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This report details work performed and results obtained in a study of the water management aspects of oil shale mining and retorting in the Piceance Creek Basin. Three specific sites were investigated, and optimal water management systems for both conventional and in situ extraction processes were generated. Water-related legal and environmental constraints on development were identified and the water management schemes were developed in compliance with these regulations. Limitations on shale oil production implied by limited water supplies were evaluated. Potential basin-wide effects of development were evaluated using a computer model, and mitigation strategies were developed. Recommendations for additional investigation and analyses were presented.

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The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing Interior Department's Bureau of Mines or of U. S. Government.

FOREWORD

This report was prepared by Golder Associates, Inc., 10628 N.E. 38th Place, Kirkland (Seattle), Washington 98033, under USBM Contract Number J0265019. The contract was initiated under the Oil Shale Mining Research Program. It was administered under the technical direction of Spokane Mining Research Center with Mr. B.M. Stewart acting as the Technical Project Officer. Mr. John J. Arnold was the contract administrator for the Bureau of Mines.

This report is a summary of the work recently completed as part of this contract during the period June 30, 1976 to September 1977. This report was submitted by the authors in September 1977.

Golder Associates, Inc. certifies that no patents or inventions have resulted from this study.

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UNITS AND CONVERSION FACTORS

This report uses the U.S. system of units throughout. The following list presents approximate metric and other conversion factors for selected parameters.

PARAMETER	UNITS USED	CONVERSIONS
Volume	AF (acre-foot)	1 AF = 7,779 BBL
	BBL (barrel)	1 BBL = 42 gallons
		1 AF = 1,233 m^3
Flow Rate	AFY (acre-foot/year)	1 AF = 0.62 GPM
	GPM (US gallons/min)	= 0.040 liter/sec
	CFS (cubic foot/sec)	1 GPM = 0.063 liter/sec
		1 CFS = 449 GPM
		= 28.25 liter/sec
Permeability*	FT./DAY (foot/day)	1 FT./DAY = 3.5x10^4 cm/sec
		= 7.5 gal/day/$ft.^2$
		= 350 millidarcy*

* "Permeability" in this report refers to permeability coefficient, or hydraulic conductivity. It assumes that water is the fluid, and conversion to absolute permeability (above) assume an ambient temperature of 20°C.

CHAPTER 1
MANAGEMENT SUMMARY

1.1 OBJECTIVE

The objective of this study is to devise the most economical, technically feasible, and environmentally acceptable methods of water management for shale oil industries of various sizes and methods at three different locations in the Piceance Creek Basin (Figure 1-1).

1.2 METHOD

The approach adopted in the study has been to divide up the various aspects of the water management system, and to focus on each part in detail. The resulting building blocks are then integrated into technically feasible, economically rational, and environmentally acceptable water management strategies. Cost figures used in this summary are in 1974 dollars. To obtain approximate 1977 dollars multiply by 1.3.

1.3 THE STUDY SETTING

The study is set in the Piceance Basin, in northwest Colorado. This Basin is rich in oil shale and evaporite minerals, and has the potential to supply a significant part of future U.S. oil needs. The Basin averages 7,000 feet elevation, with a semi-arid climate and relatively sparse vegetation.

The upper 1,500 feet of the Basin rocks are in general relatively permeable (with horizontal permeability averaging 0.5 ft./day or 150 millidarcies). The rocks are highly stratified, which leads to a very much lower permeability

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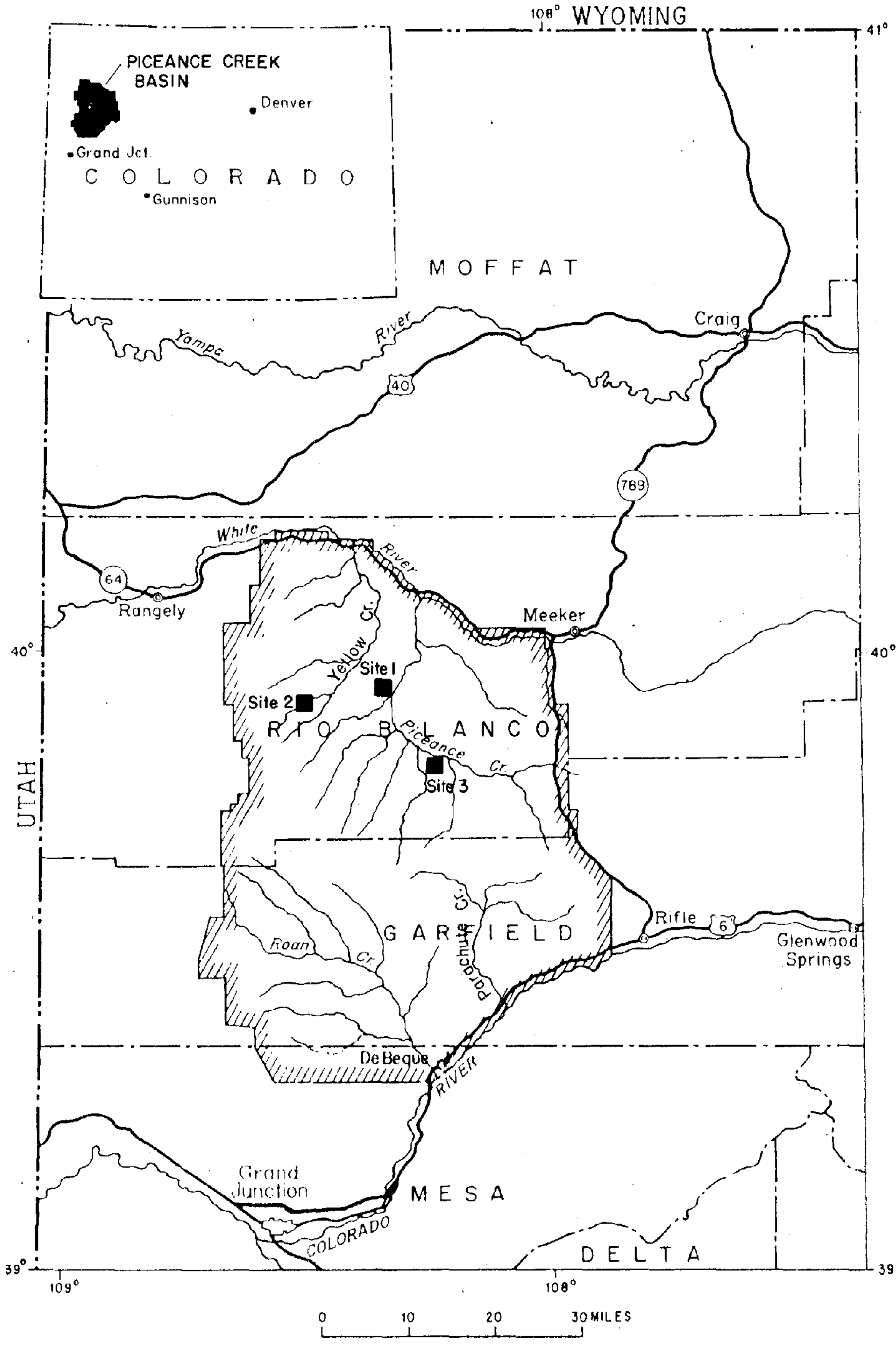
Figure I-1 LOCATION OF THE PICEANCE CREEK BASIN AND STUDY SITES



PICEANCE CREEK BASIN
Denver
Grand Jct.
COLORADO
Gunnison
108° WYOMING
41°
MOFFAT
Yampa River
40
Craig
789
White River
64
Rangely
Meeker
40°
Yellow Cr.
Site 1
Site 2
RIO BLANCO
Piceance Cr.
Site 3
UTAH
Rifle
6
Glenwood Springs
Roan Cr.
GARFIELD
Parachute Cr.
DeBeque
RIVER
Grand Junction
MESA
COLORADO
DELTA
39°
109°
108°
0 10 20 30 MILES

After Coffin, et al., 1971

normal to the stratification. The streams of the Basin are primarily intermittent with the few perennial streams being fed mainly by groundwater.

Within the Basin the Bureau has selected three specific sites for detailed evaluation. They are shown on Figure 1-1.

Site 1 is at the location of the proposed U.S.B.M. Demonstration Mine, and is close to the depositional center of the Basin. In this location the geology is characterized by some 700 feet of sandstone of the Uinta formation overlying 1,600 feet of oil shale (kerogen-rich marlstone) of the Green River formation. The lower 900 feet of the oil shale is very rich in saline minerals, whereas the upper 700 feet is leached. The permeability of the upper 1,400 feet of rock in this location is high (averaging 1.6 ft./day). Beneath 1,400 feet the rock is virtually impermeable. The upper 150 feet of material at this Site is unsaturated.

Site 2 is coincident with Federal Tract C-a. It is on the western flank of the Basin, and is considered to be relatively deficient in groundwater resources. In the location chosen for detailed study the Uinta sandstone is only 150 feet thick and is unsaturated. It overlies 1,000 feet of saturated oil shale of the Parachute Creek member of the Green River formation. The Site is characterized by an unusual geohydrologic system (for the Piceance Basin) with a permeable zone in the upper part of the oil shale member, and another permeable zone close to its base. The two permeable zones seem to be only slightly connected.

Site 3 is coincident with Federal Tract C-b, which is on the eastern side of the Basin, close to Piceance Creek. At this location the Uinta sandstone is 900 feet thick, with the oil shale of the Parachute Creek member extending 1,600 feet below the sandstone. Significant permeability of the rocks appears to cease about 1,500 feet below surface. The upper 400 feet of the sandstone is unsaturated.

1.4 WATER USE IN A CONVENTIONAL SHALE OIL INDUSTRY

A conventional shale oil industry is defined here as an industry where the oil shale is mined, transported to a surface retorting facility, retorted, the crude oil upgraded to pipelineable standards, and the spent shale placed in a permanent disposal area. In order to present the results in a form which allows evaluation of the water requirements of an oil shale industry of any size, the water requirements have been expressed in terms of barrels of water needed per barrel of oil produced. The total net water requirement for a conventional industry is about 5 barrels per barrel of oil, which is made up as follows.

The first significant water use in developing a shale oil industry is for site development. Averaged over the life of the mine this use is equilavent to 0.05 barrels of water per barrel of product oil. This water is used mainly for dust suppression and for sanitary and drinking water systems for the retorting plant and mine complex.

The water used in mining depends only slightly on the method of mining chosen. The study evaluated room and pillar, chamber and pillar, sublevel stoping, block caving, and open pit mining methods, and the overall requirement for water was about 0.2 barrels of water per barrel of product crude. Water is mainly used for drilling, dust control, and washing down equipment.

Once the ore has been mined it will be crushed, transported out of the mine to a stockpile, reclaimed, given secondary crushing to reduce it to plant feed size, and transported to the retort. All of these operations generate considerable quantities of dust, and there is thus a dust supression water requirement of 0.3 barrels of water per barrel of crude oil produced.

The major water-consumptive activity is conventional shale oil production is the retorting/upgrading step. The study evaluated three retorting/upgrading system: Paraho, Union, and TOSCO II. In terms of water consumption, the Paraho and Union systems were virtually identical, requiring 2.35 barrels of water per barrel of product oil (note that this excludes water used in spent shale wetting, to be considered later). The TOSCO II system is somewhat more consumptive of water, as it uses indirectly heated ceramic balls to provide the heat required for retorting. TOSCO II water use is estimated at 2.7 barrels of water per barrel of oil produced. It should be noted that the oil shale itself produces nearly 1 barrel of water per barrel of oil during the retorting cycle, partly by release of water from within the rock matrix, and partly from combustion of hydrocarbons in direct retorting. Thus the actual consumption of water is 3.35 and 3.7 barrels of water per barrel of oil produced for Paraho/Union and TOSCO II processes respectively, but the apparent consumption is 1 barrel per barrel less.

The waste product from the retorting process is hot spent shale. This material is quenched, and enough moisture is added to it to make it transportable. In all, this requires about 0.7 barrels of water per barrel of oil produced, and leaves the spent shale with a moisture content of about 8%. This material can be readily compacted on a spent shale disposal pile. If it is desired to transport the spent shale as a slurry, and to recycle reclaimed water, it is estimated that the net water use will be 4.9 barrels of water per barrel of oil. Both because of the heavy water requirement, and for environmental reasons, this option looks very unattractive.

Any surface waste pile will have to be reclaimed and revegetated. This generally requires leaching of the soluble salts from the upper surface of the pile, planting appropriate ground cover, and irrigating for two growing seasons. In all, the average water requirement for this activity is expected to be 0.2 barrels of water per barrel of product oil.

The major ancillary service which has a substantial water usage is electrical power generation. It is likely that a commercial shale oil industry will generate electrical power on-site, to take advantage of the abundant supply of low BTU off-gas. The net water use for this activity will be 0.6 barrels of water per barrel of oil. (Whether the generation is on-site or off-site, this extra water usage will be incurred, so it should be included in either case.)

Finally, we have added a miscellaneous water use of 0.64 barrels of water per barrel of oil, or 15% of the total of the items above. This is to allow for unaccounted uses, evaporation from holding ponds, and losses. All of the water uses listed above have assumed minimum requirements; as no human system is completely efficient, it is prudent to allow a substantial contingency.

Table 1-1 summarizes the expected water usage of a conventional shale oil industry. The total consumptive use is 5 barrels of water per barrel of product oil.

TABLE 1-1
WATER USE IN A CONVENTIONAL SHALE OIL INDUSTRY

PROCESS STEP	WATER USE (Barrels of water per barrel of oil)
BASE CASE	
Site Development	.05
In-Mine Use	.2
Raw Shale Delivery	.3
Retorting and Upgrading	2.3
Disposal of Spent Shale	.7
Reclamation and Revegetation	.2
Power Generation	.6
Miscellaneous	.6
BASE CASE TOTAL	5.0
INCREMENTS TO BASE CASE	
TOSCO II Retorting	+ .4
Slurry Spent Shale Disposal	+ 4.9

NOTE: To obtain usage, add any required increment to base case total.

1.5 WATER USE IN AN IN-SITU SHALE OIL INDUSTRY

In-situ retorting of oil shale involves rubblization of the oil shale in the ground, in-place retorting, surface upgrading of the oil, and surface disposal of any waste materials. Two types of in-situ retorting have been evaluated in this report: true in-situ and modified in-situ. True in-situ retorting involves rubblizing the oil shale from the surface, generally with conventional or nuclear explosives. Modified in-situ retorting involves mining a proportion of the oil shale (usually around 20%) and rubblizing the remaining oil shale into the voids thus created. For clarity the water management aspects of each system will be presented separately.

1.5.1 True In-Situ Retorting

The total water use for true in-situ retorting can be as high as 1.6 barrels of water per barrel of oil; in the minimum-use case water is produced at the rate of 0.8 barrels of water per barrel of oil. Details of each case are as follows.

The water use for site development in the true in-situ case is about the same as for conventional mining. While the surface construction for the industry will be substantially less, the number of access roads (for drilling) and pipe networks will be substantially greater. It is estimated that the site development water use will be 0.04 barrels of water per barrel of oil produced. This water will be used primarily for dust control and sanitary and drinking water systems.

The rubblizing phase of true in-situ retort development often includes hydraulic fracturing of the shale as a preliminary to blasting. Although this activity uses water as the fracturing fluid, we have assumed that this water, or equivalent water, is recovered from the groundwater system for re-use, and so the water involved is recycled rather than consumptively used.

The quantity of water used during retorting depends upon the method chosen. As a minimum, no water need be added to the retorts, in which case the retorting process makes about 1 barrel of water for each barrel of oil produced. As mentioned above, some of this water is trapped in the kerogen-rich rock, while the remainder is derived from the combustion of residual hydrocarbons in the rock during the retorting phase.

There is, however, considerable economic advantage to be gained in a commercial industry by injecting steam into the retorts. This produces considerably higher BTU off-gas, allowing its use for on-site power generation. As the in-situ technology currently proposed is very power consumptive, this system seems likely to be implemented. The steam injection requires the consumptive use of 1.3 barrels of water per barrel of oil produced, and the power generation requires the use of a further 1.1 barrels of water per barrel of oil produced, so that the net water requirement for this option is 1.4 barrels of water per barrel of oil (after subtracting the water produced by retorting).

Once the oil has been retorted, it is pumped to the surface, separated from the entrained water developed in retorting, and is upgraded. All that is required for upgrading to pipelineable standard is visbreaking or mild heating, so that no water is consumed in this step.

As in the previous case, an allowance of 0.2 barrels of water per barrel of oil for water losses, unaccounted uses, evaporation, and other miscellaneous uses has been made. This seems warranted considering the early stage of development of this technology.

The total water usage for true in-situ retorting is summarized in Table 1-2. The minimum water use case produces a water gain of 0.8 barrels of water for each barrel of oil produced, while the maximum water use case (which is most likely) has a consumptive use of 1.6 barrels of water per barrel of oil produced.

1.5.2 Modified In-Situ Retorting

The water use aspects of modified in-situ retorting are similar to those for true in-situ, except that the mining necessary for the modified in-situ method uses water, and creates a disposal and reclamation water use on the surface.

Site development water use is 0.04 barrels of water per barrel of oil produced, as in the previous case. In-mine use is 0.35 barrels of water per barrel of oil produced, which is somewhat higher than for convention mining because of the large amount of drilling needed in the preparation of blastholes for the modified in-situ system.

Rock removed from the mine prior to rubblizing is given primary crushing, and then hoisted to the surface and transported to the waste pile. The major water use in this phase is for dust suppression, which consumes 0.1 barrels of water per barrel of oil.

TABLE 1-2
WATER USE IN A TRUE IN-SITU SHALE OIL INDUSTRY

PROCESS STEP	WATER USE (Barrels of water per barrel of oil)
OFF-SITE POWER GENERATION	
Site Development	.04
Retorting	(1.0)
Upgrading	-
Miscellaneous	.2
TOTAL	(.8)
ON-SITE POWER GENERATION INCREMENTS	
Steam Injection to Retorts	1.3
On-site Power Generation	1.1
TOTAL	2.4
TOTAL WITH ON-SITE POWER GENERATION	1.6

NOTE: The material in this table is based on untried technology - see text for description of the development of these values.

The rubblizing phase of development requires no water, as it is performed using explosives. Retorting water-use considerations are the same as for true in-situ mining, with the minimum water use case producing 1 barrel of water per barrel of oil, and the maximum water use case requiring a net water supply of 1.4 barrels of water per barrel of oil. Upgrading of the product oil is not consumptive of water, as in the true in-situ case.

Revegetation of the spoil material removed from the mine requires some leaching, planting, and irrigation. As the volume of material is less than spent shale from conventional retorting, and the salt content lower, less water is used: 0.04 barrels of water per barrel of product oil. Once again a miscellaneous water allowance of 0.2 barrels of water per barrel of oil is made, to cover losses.

The total water use for modifed in-situ oil shale retorting is presented in Table 1-3. Minimum water use produces a slight net water gain of 0.3 barrels of water per barrel of oil, while an on-site power generation strategy results in net water use of 2.1 barrels of water per barrel of oil produced.

1.6 WATER SUPPLY OPTIONS

There are three major raw-water supply options for oil shale developments in the Piceance Basin: mine inflow water, groundwater, and river water.

Mine inflow will occur for all the mines considered in this study. The quantity of inflow is highly dependent on site, mine type, and stratigraphic location, and ranges from 20,000 BWPD (barrels of water per day) to 2 million BWPD,

TABLE 1-3
WATER USE IN A MODIFED IN-SITU SHALE OIL INDUSTRY

PROCESS STEP	WATER USE (Barrels of water per barrel of oil)
OFF-SITE POWER GENERATION	
Site Development	.04
In-Mine Use	.3
Rock Transport	.1
Retorting	(1.0)
Upgrading	-
Revegetation	.04
Miscellaneous	.2
TOTAL	(.3)
ON-SITE POWER GENERATION INCREMENTS	
Steam Injection to Retorts	1.3
On-site Power Generation	1.1
TOTAL	2.4
TOTAL WITH ON-SITE POWER GENERATION	2.1

with a median value of 200,000 BWPD. This water will average 1,500 mg/l total disolved solids (TDS) for the 3 sites considered, and is available without direct charge to the project, as it must be pumped to the surface in any case.

Groundwater is the second supply option. In cases where insufficent groundwater is obtained from mine inflow, this flow may be augmented by groundwater wells. The cost of producing water by this method is 0.4¢ per barrel of water at Sites 1 and 2, and 1.2¢ per barrel of water at Site 3. (Note: all cost figures are in terms of 1974 dollars.) The difference occurs because of the lower average permeability of rock at Site 3. Average quality of this water is also 1,500 mg/l TDS.

River water may be imported to the Basin from either the White River to the north, or the Colorado River to the south. Lengthy pipelines and multiple pumping stations would be required, and so this is the most expensive form of water supply for these projects. For large flow rates, the cost of supply averages 1.8¢ per barrel of water. Quality of the water varies, but averages 350 mg/l TDS and 1,000 mg/l suspended solids.

1.7 WATER TREATMENT

There is a variety of required water qualities for oil shale processing. The most pure water is needed for boiler feedwater, for which less than 100 mg/l TDS is required. Service water must be less than 750 mg/l TDS, while wastewater input need only be free of settleable particulate matter.

Three input qualities are available: groundwater, with an average at the three sites of 1,500 mg/l TDS; river water, with an average of 350 mg/l TDS plus 1,000 mg/l suspended solids; and process wastewater, with approximately 25,000 mg/l TDS plus some suspended solids.

It is clear that some water treatment will be necessary, and that the type and cost will depend on the input quality and the required output quality. Of the many treatment options available for reducing inorganic TDS in water, the most promising for large-scale water purification of the type required in oil shale processing appears to be the reverse osmosis method. In this method a semipermeable membrane separates purified water from filtered raw water. On application of pressure in excess of the osmotic potential to the raw water, purified water permeates from the raw water side to the purified water side.

The cost of this process is primarily a function of the input water quality. Table 1-4 sets out the treatment strategy and cost for the various water supply/water use combinations. As can be seen, treatment to produce one barrel of service or boiler feed water averages 2¢ for river water, 3¢ for groundwater, and 10¢ for wastewater.

1.8 WATER DISPOSAL

Although the Piceance Basin is in a water deficient area, there are three shale oil processing scenarios where water disposal is necessary. First, in the cases where foul water produced in retorting exceeds the water quantity required for consumptive use in the rest of the system, the excess wastewater will have to be disposed of. Second, in the cases where wastewater is produced by the process in greater volume than wastewater can be used in the other parts of the process it may be economically attractive to dispose of the

TABLE 1-4
SUMMARY OF WATER TREATMENT STRATEGIES AND COSTS
(Costs in ¢/BBL Water)

WATER USE CATEGORY	WATER SOURCE RIVER WATER	GROUNDWATER	WASTEWATER
Boiler Feed	R/O 2.8¢/BBL	R/O 3.6¢/BBL	R/O 10.8¢/BBL
Service Water	Filtration 1.1¢/BBL	R/O 2.4¢/BBL	R/O 9.3¢/BBL
Wastewater	No Treatment --	No Treatment --	No Treatment --
Direct Disposal	No Treatment --	R/O 4.7¢/BBL	R/O 10.5¢/BBL

NOTES:
1. Costs in 1974¢ per barrel of treated water.
2. R/O denotes reverse osmosis.

wastewater rather than to treat it to boiler or service use standards. Third, in the cases where mine inflow water exceeds water demand it will be necessary to dispose of the excess. There are four methods of disposal commonly considered: disposal in spent shale piles, injection into subsurface strata, evaporation, and direct discharge.

Disposal in spent shale piles is an attractive option for wastewater disposal in conventional shale oil industries. The capacity of the spent shale to hold additional water is considerable: the optimum moisture content for compaction is about 23% moisture by weight. The difference between the minimum water content necessary to allow bulk handling of the material (8%) and the prudent maximum water content for good compaction (say 20%) allows the disposal of about 1 barrel of wastewater in the spent shale pile for every barrel of crude oil produced by the process. Environmentally this disposal system is attractive, as testing indicates that a compacted shale pile is virtually impervious, and the wastewater does not seep out of the pile under gravity.

Re-injection of wastewater into subsurface strata seems acceptable only if the water quality is in all respects equal to or better than the water already in the target injection strata, and if it can be shown that the resulting pressure changes are not to the detriment of the groundwater system. Thus re-injection of clean mine inflow water into the strata from which it came is probably acceptable, as is injection of purified wastewater. However, deep injection of high TDS wastewater is almost certainly unacceptable. The cost of injection is estimated at about 0.7¢ per barrel of water injected at Sites 1 and 2, and 4¢ per barrel of water injected at Site 3.

Evaporation of high TDS wastewater is an attractive strategy where spent shale pile capacity is lacking. Evaporation would be from lined ponds, with sufficient capacity to contain effluent in the low evaporation winter months. Cost of this option is estimated at 8.9¢ per barrel of wastewater, and as such is competitive with purification.

Direct discharge of water to surface streams will only be allowed when the quality of the water is in all respects equal to or better than existing receiving stream quality, and in addition the toxicity of the discharge water meets or exceeds drinking water standards. As water meeting these standards has a market value of 4¢ per barrel, it would seem irrational to discharge it except to maintain required stream flows as part of an augmentation scheme. As noted in Section 1.7, the cost of treating wastewater to these standards is 10.5¢ per barrel of wastewater, so it is not economic to treat the wastewater for sale.

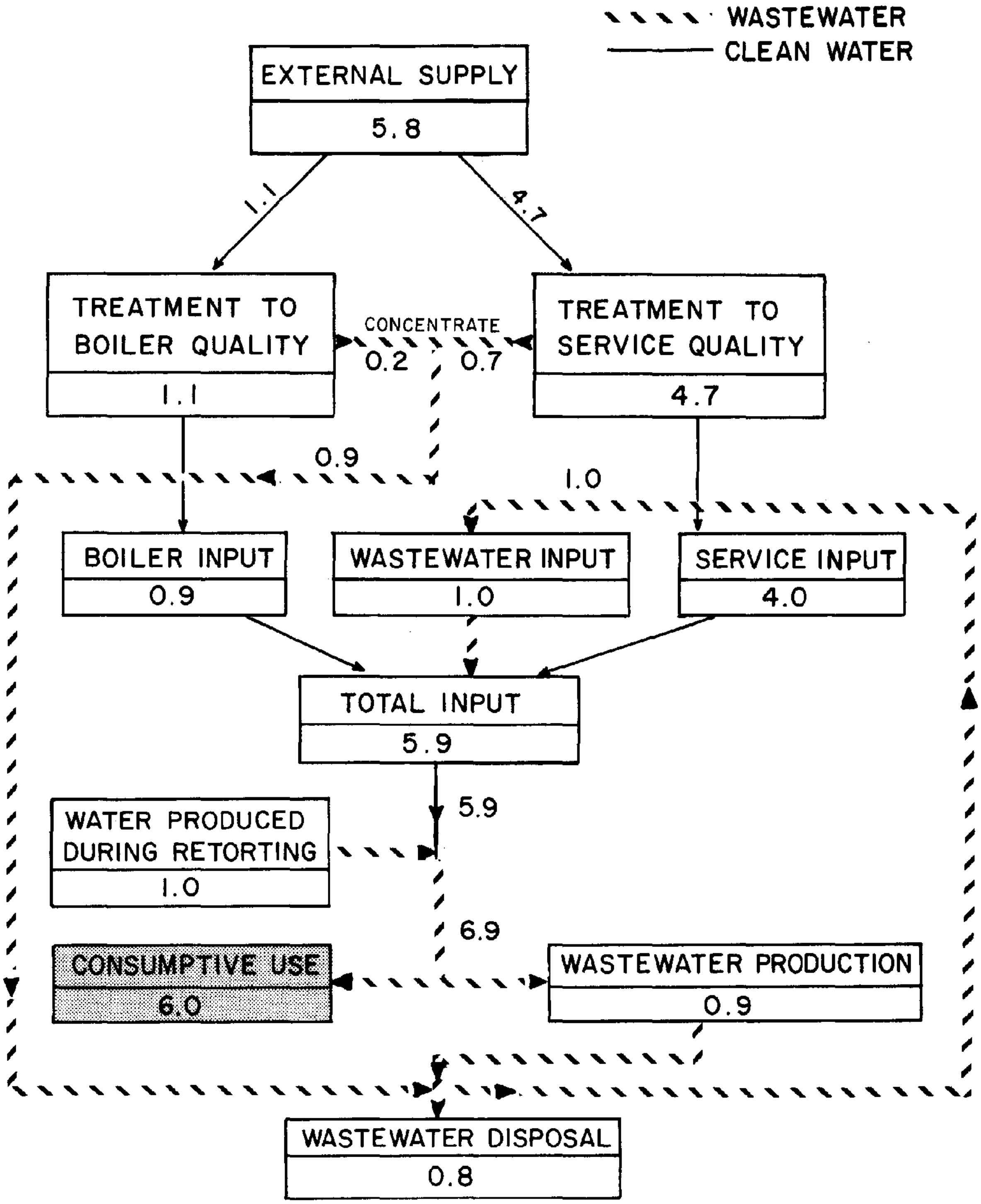
1.9 WATER MANAGEMENT SYSTEMS

It is now possible to assemble the water management systems required for exploitation of oil shale. The range of possible water management cases is covered by three systems: conventional, minimum in-situ, and maximum in-situ.

The water management system for conventional processing is shown in Figure 1-2. Consumptive use is 6 barrels of water per barrel of oil produced, supply is 5.8 barrels per barrel, and wastewater disposal is 0.8 barrels per barrel. The disposal is not included in consumptive use at this point as it could be reclaimed if desired. The overall cost of water supply per barrel of product oil for conventional retorting averages 14¢ if mine inflow is the water source,

Figure I-2 WATER MANAGEMENT SYSTEM FOR CONVENTIONAL PROCESSING – GENERALIZED

(Flows expressed in barrels of water per barrel of oil produced)



WASTEWATER
CLEAN WATER
EXTERNAL SUPPLY
5.8
1.1
4.7
TREATMENT TO BOILER QUALITY
1.1
CONCENTRATE
0.2
0.7
TREATMENT TO SERVICE QUALITY
4.7
0.9
1.0
BOILER INPUT
0.9
WASTEWATER INPUT
1.0
SERVICE INPUT
4.0
TOTAL INPUT
5.9
5.9
WATER PRODUCED DURING RETORTING
1.0
6.9
CONSUMPTIVE USE
6.0
WASTEWATER PRODUCTION
0.9
WASTEWATER DISPOSAL
0.8

17¢ if river water is the water source, 16¢ at Sites 1 and 2 if pumped groundwater is the water source, and 21¢ at Site 3 if pumped groundwater is the water source. Thus it can be seen that there is little difference between water sources other than mine inflow, providing relatively large industries are considered. Note that these costs are a small proportion of the 1974 price of oil of about $10 per barrel.

The water management system for true in-situ processing with minimum water use is shown in Figure 1-3. Note that true consumptive use is shown rather than net consumption, which is negative. In this case the process is more than self sufficient in water, and 0.5 barrels of water per barrel of product oil is available for disposal. The overall cost of the water management system in this case is 9¢ per barrel of oil produced. It should be noted, however, that there would be significant water use external to the project for power generation.

The water management system for modifed in-situ processing with maximum water use is shown in Figure 1-4. In this case water input is 2.5 barrels of water per barrel of oil produced. The overall cost of the water management system in this case is 20¢ per barrel of oil produced.

1.10 AVAILABILITY OF WATER

The availability of water to the shale oil industry depends upon the physical existence of water, and upon legally acquiring right to that water.

Groundwater can be obtained at each site in varying quantities for the assumed 30-year mine life. At Site 1 it is possible to withdraw on the order of 500,000 barrels of water per day (BWPD), at Site 2 withdrawal is limited to

Figure 1-3 WATER MANAGEMENT SYSTEM FOR TRUE IN-SITU PROCESSING – MINIMUM WATER DEMAND
(Flows expressed in barrels of water per barrel of oil produced)

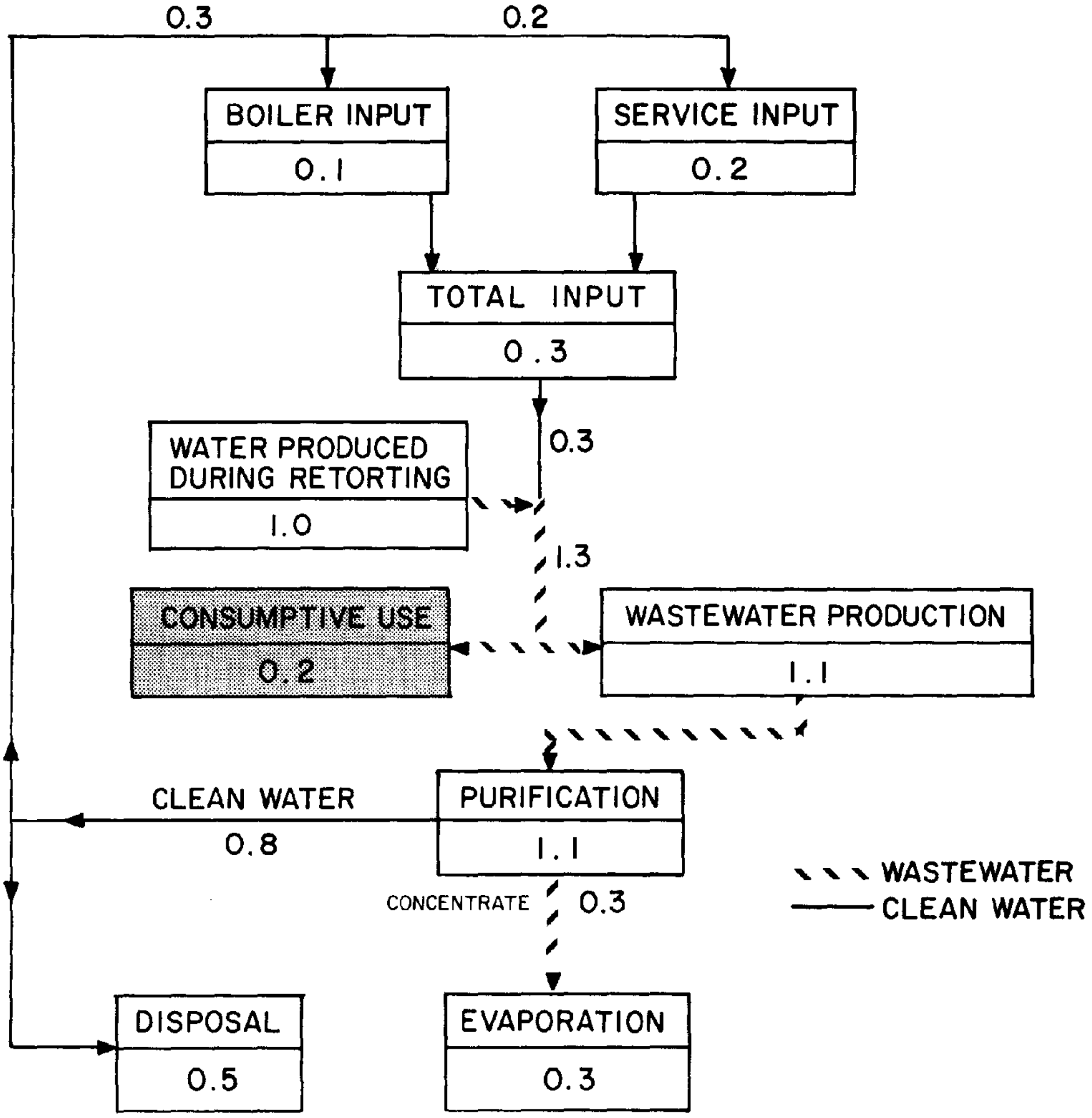
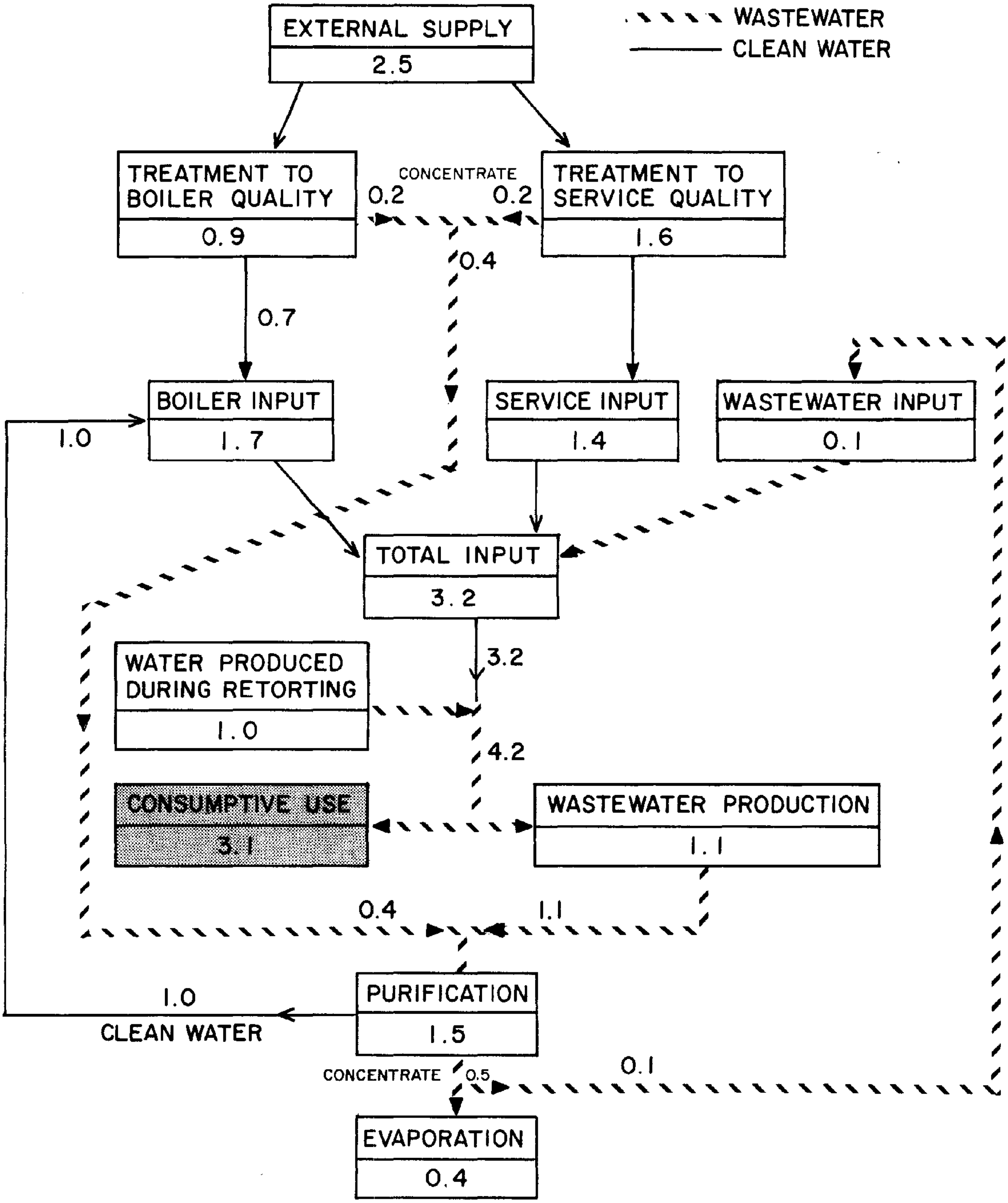

0.3
0.2
BOILER INPUT
0.1
SERVICE INPUT
0.2
TOTAL INPUT
0.3
0.3
WATER PRODUCED DURING RETORTING
1.0
1.3
CONSUMPTIVE USE
0.2
WASTEWATER PRODUCTION
1.1
CLEAN WATER
0.8
PURIFICATION
1.1
CONCENTRATE
0.3
WASTEWATER
CLEAN WATER
DISPOSAL
0.5
EVAPORATION
0.3

Figure 1-4 WATER MANAGEMENT SYSTEM FOR MODIFIED IN-SITU PROCESSING WITH ONSITE POWER GENERATION
(Flows expressed in barrels of water per barrel of oil produced)


WASTEWATER
CLEAN WATER
EXTERNAL SUPPLY
2.5
TREATMENT TO BOILER QUALITY
0.9
CONCENTRATE
0.2
0.2
TREATMENT TO SERVICE QUALITY
1.6
0.4
0.7
BOILER INPUT
1.7
1.0
SERVICE INPUT
1.4
WASTEWATER INPUT
0.1
TOTAL INPUT
3.2
3.2
WATER PRODUCED DURING RETORTING
1.0
4.2
CONSUMPTIVE USE
3.1
WASTEWATER PRODUCTION
1.1
0.4
1.1
PURIFICATION
1.5
1.0
CLEAN WATER
CONCENTRATE
0.5
0.1
EVAPORATION
0.4

150,000 BWPD, and at Site 3 withdrawal is limited to about 300,000 BWPD. The withdrawal which could be sustained for longer periods is, of course, lower.

River water imports are limited to the available water in excess of present use. This places a limit on imports of 17 million BWPD, and a practical long term limit of perhaps 4 million BWPD.

The more significant limitation is, perhaps, legal. Colorado water law is based on appropriative right, determined on a first in time, first in right basis. Absolute and conditional rights exist today which are sufficient to entirely use the flow of the rivers in the vicinity of the Basin. Further, as the Basin groundwater is, in general, tributary to the surface streams, it falls under the same appropriation doctrine and is thus potentially fully appropriated.

There are two principal methods available to those who wish to obtain water for oil shale development. First, rights to the water may be purchased from the current holders, and the use may, with some difficulty, be switched to the oil shale industry. Second, water supply may be purchased from major rights holders (for example the U.S. Bureau of Reclamation) and either transported to the site, or used to augment downstream supplies in order to allow diversion of surface water or groundwater at the site.

Presuming that the legal restrictions are not the determining factor in oil shale development, Table 1-5 sets out the limitations on development of a shale oil industry based on industry type, and water supply type. As can be seen, conventional processing appears limited to about 1 million barrels of oil per day, and modified in-situ processing with

TABLE 1-5
LIMITATIONS ON OIL SHALE DEVELOPMENT DUE TO PHYSICAL WATER AVAILABILITY

(Total Production in Barrels/Day)

	INDUSTRY TYPE	
WATER SUPPLY	CONVENTIONAL MINING/RETORTING	IN-SITU WITH ON-SITE POWER GENERATION
SITE GROUNDWATER		
Site 1 (500,000 BWPD)	90,000 BPD	200,000 BPD
Site 2 (150,000 BWPD)	25,000 BPD	60,000 BPD
Site 3 (300,000 BWPD)	50,000 BPD	120,000 BPD
TOTAL (950,000 BWPD)	165,000 BPD	380,000 BPD
EXTERNAL RIVER WATER		
TOTAL (4 million BWPD)	700,000 BPD	1,600,000 BPD

NOTES:

i. Groundwater availability based on 30 years supply at each site. Longer periods of supply would produce lower average flow rates.

ii. River water supply assumed to be 200,000 AFY, or one quarter of the presently uncommitted flow.

on-site power generation is limited to about 2 million barrels of oil per day. The production rate in the case of minimum water use in-situ retorting is unlimited, as it produces water. However, the electrical generation required off-site, and the waste of hydrocarbon resource implied on-site, suggest that this mode of development is impractical for a large scale industry.

1.11 MINE INFLOW

A major concern of developers has been the quantity of mine inflow which may occur at each site, and the economic impact of an excess of mine inflow water on the project.

Mine inflow is strongly dependent on the type of mining, rate of mine expansion, and the permeability and porosity of the materials in which the mine is located. Two of the most critical parameters for inflow evaluation (vertical permeability and material porosity) are very ill-defined at present, and this makes inflow analysis extremely difficult. Using the present best estimate of these parameters, average inflows to conventional mines or in-situ retort areas are on the order of 200,000 BWPD, which is sufficient to sustain a conventional processing system of 35,000 barrels of oil per day, or a modified in-situ processing system of 80,000 barrels of oil per day.

For schemes where the water usage rate is less than the inflow amounts (which probably includes all presently proposed pilot schemes), re-injection of excess water is the most economic method of disposal. This will involve intercepting inflow at the mine periphery, either in wells or specially constructed drives and drainage systems, and removing it to the surface, where that portion not used will be transported to a ring of injection wells sited in excess of a mile away from the interceptor system. The cost per barrel of oil of such a scheme depends upon industry size and actual inflow. For example, a 30,000 BPD (50,000 TPD) industry using the modified in-situ technology and encountering mine inflow of 200,000 BWPD would add about 3¢ per barrel of oil produced at Sites 1 and 2, and 8¢ per barrel of oil produced at Site 3 due to the cost of re-injecting 125,000 BWPD.

1.12 BASIN-WIDE IMPACTS OF GROUNDWATER USE

Although detailed evaluation of the Basin-wide impact of the schemes developed in this report is beyond the scope of the study, some evaluation was carried out in the process of establishing the technical feasibility of reliance on groundwater supply. These evaluations comprised the computer analysis of a relatively simple model of the total Basin hydraulics, including groundwater recharge, groundwater flow, and surface water flow. Impacts were developed for both the groundwater system and the surface water system.

The major impact of large scale development on the groundwater regime is to reduce piezometric pressures in the near mine region, and to de-saturate some of the surface rock sequence above and adjacent to the mine. It is likely that this will reduce or eliminate flows from most springs in the zone where any significant drawdown occurs. The only other significant impact will be an increase in the head against which other deep groundwater users will have to pump to obtain water.

The major impact on the surface water regime will be a reduction in streamflows adjacent to, and downstream of, the developments. While more work needs to be done in evaluating the degree of connection of the streams to the deep aquifers, it seems likely that water will be drawn from Piceance and Yellow Creeks into the groundwater system if piezometric heads are lowered significantly.

The extent of the impacts depends upon the net quantity of groundwater removed from the system, and the rate and location(s) of that removal. Figure 1-5 shows a typical set of results from the simulation for a 50,000 TPD (30,000 BPD) conventional industry, or a 60,000 BPD modified in-situ industry, at Site 3. Corresponding figures for all sites and expected groundwater usage are presented in the body of the report.

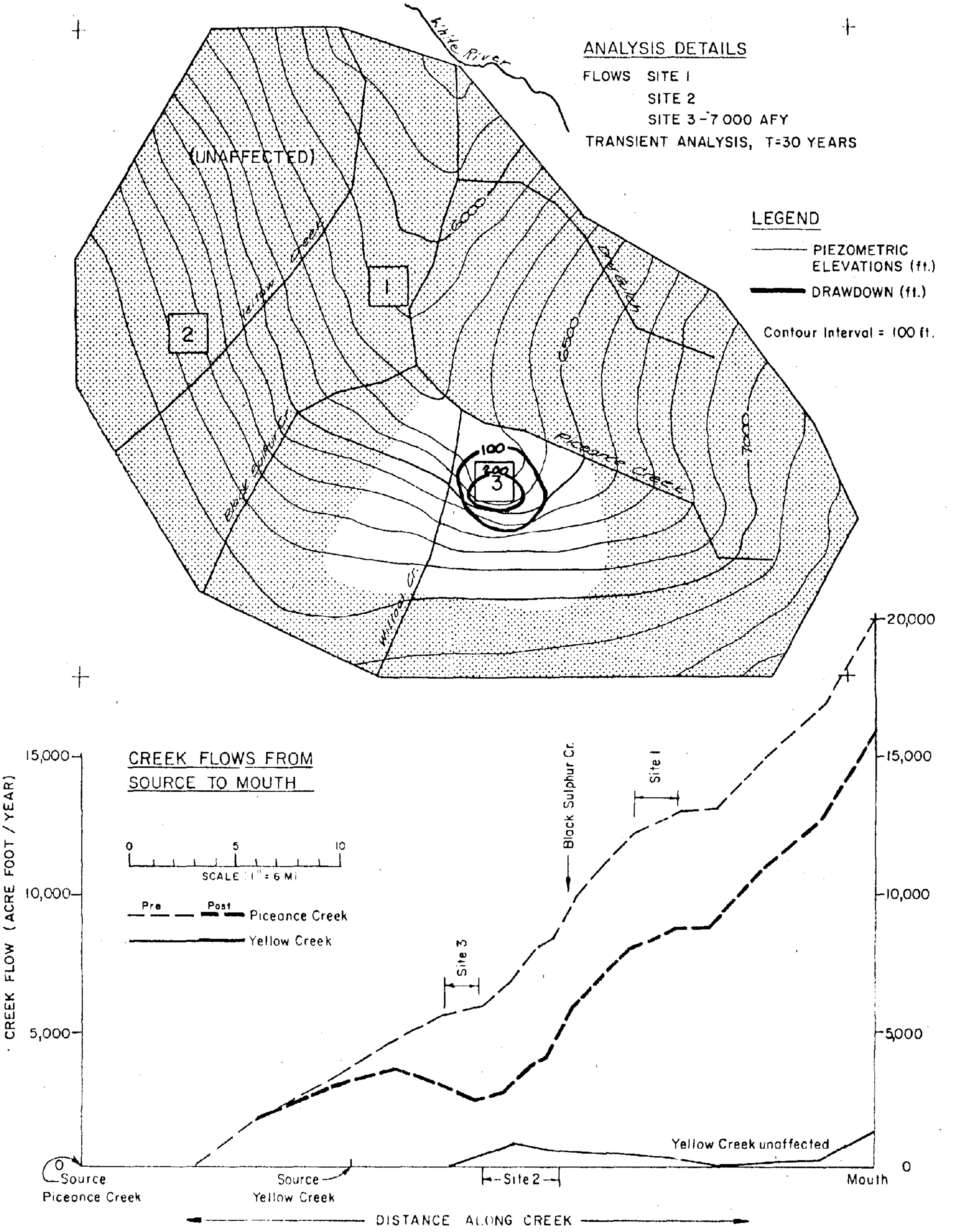
1.13 POST-MINING IMPACTS ON THE HYDROLOGIC SYSTEM OF THE BASIN

After mining ceases at any location, the mine workings provide the opportunity for communication between water-bearing zones which were poorly connected prior to mining. The water quality in near surface zones could be degraded by poorer quality water from deeper zones if head conditions created upward flow. However at the three sites studied, the water quality appears to be relatively constant with depth, and the existing head regime appears in general to favor downward flow in the rock strata. Accordingly this kind of impact is not expected to be a problem at the study sites, although it may be a problem in the northern part of the Basin.

A more serious potential impact is posed by the leaching of a backfilled conventional mine, or of spent in-situ retorts. After activity ceases at a minesite, water re-enters the workings, and the pre-mining groundwater flow conditions are (approximately) re-established. Any soluble materials in

BASIN-WIDE ANALYSIS RESULTS
50,000 TPD MINING AT SITE 3

FIGURE I-5



the workings are then transported by the groundwater flow, resulting in degradation of the flow. The detailed analysis of this impact is beyond the scope of this study, but an initial evaluation suggests that substantial degradation of the groundwater and surface water resources of the Basin may result. An investigation of the cost of leaching spent retorts prior to abandonment suggests that this would add perhaps 50¢ to the cost of each barrel of oil produced, and as such may be a viable mitigation measure.

1.14 RECOMMENDATIONS FOR FUTURE WORK

In the course of the study several areas which need additional study have been identified, using the criteria that the present level of understanding is inadequate, and that the knowledge is necessary. Details of the recommended programs are given in Chapter 16, and the primary recommendations are as follows.

i. Data Assembly. It is recommended that a data and information bank be set up to make material related to oil shale more readily available.

ii. Mine Inflow Study. It is recommended that a methodology for predicting inflow in oil shale mines be developed and validated, and estimates of inflow generated for different sites in the Basin.

iii. In-Situ Retorting Study. It is recommended that a study of the water-related aspects of in-situ retorting be conducted.

iv. Basin-Wide Impact Evaluation. It is recommended that a more detailed evaluation of Basin-wide impacts of large-scale development be conducted, especially with respect to aquifer interconnection, post-mining retort and backfill leaching, and evaluation of the adequacy of the present Basin geohydrology data.

v. Geohydrology Data Collection Methodology. It is recommended that a program to develop an effective, simple, relatively inexpensive methodology for determining mining-related geohydrology data be performed, and tested in the field.

vi. Study of Stream/Groundwater Interaction. It is recommended that a study be performed to determine the relationship between streamflow and groundwater piezometric pressures, particularly with respect to:
   a. streamflow depletion due to groundwater pressure reduction
   b. origin of springs and stream baseflow.

vii. Water Management Study for Total Basin Development. It is recommended that a study of the water management aspects of total development of the Basin resources be made.

Many of these recommendations can be put into effect at the site of the proposed USBM demonstration mine, and would thus form part of the proposed demonstration project. The total effort required to perform all of the recommendations is relatively large, but the resulting understanding of oil shale mining and retorting systems and their effects on the Basin would provide a firm basis for long-range decision making on water-related aspects of development.

1.15 CONCLUSIONS

The general water management system developed in this study has been presented in Section 1.9.

Other general conclusions of this study are as follows:

1. Shale oil production is in general very water consumptive: conventional mine/retort complexes require the supply of 5 barrels of water to produce 1 barrel of oil, while in-situ retorting complexes require the supply of 2.5 barrels of water to produce 1 barrel of oil.

2. All of the shale oil production systems in which on-site power generation is included achieve zero discharge of water. Consumption goes primarily to steam and evaporation.

3. Because of the high level of water consumption and the limited water available, it seems likely that an oil shale industry in the Piceance Basin will be limited to an output of about 2 million barrels of oil per day.

4. It seems clear that the first oil shale developers will seek to use the limited groundwater resource of the Basin as a water supply. However, significant development of the Basin's oil shale resources will require imports of water from outside the Basin.

5. Consumptive groundwater use will have a significant and widespread impact on piezometric pressures, spring flows, and streamflows in the Basin. Augmentation and/or damage payments will probably be required to mitigate these effects.

6. Mine inflow will in general exceed the consumptive use requirements of shale oil industries in the 50,000 barrels of oil per day range or less. Re-injection of the excess into the aquifers from which the water originated seems the most economical and environmentally acceptable disposal strategy.

7. Water resources in and near the Piceance Basin are virtually fully committed. Thus developers in the Basin will have to purchase water rights, or purchase direct water supplies from rights holders.

8. There are no major negative post-mining impacts of development upon the hydrology of the Basin which cannot be economically mitigated by appropriate activities during the mining phase. However, spent shale backfilling of underground mines in oil shale aquifers may not be environmentally acceptable.

9. Although the general level of understanding of the water-related aspects of the Basin is adequate for evaluations of the type performed in this study, it is clear that a considerable amount of additional work will be necessary before effective regulation of the water-related aspects of Basin development can be achieved. Recommendations for a number of studies have been made.

We hope that this report helps to define the water management parameters and analytic tools as they presently exist. Many of the questions which might be asked about the Basin's hydrologic system can be answered, and future impacts of planned events can be determined with entirely adequate precision using existing technology. It is clear from this study that there are still a broad range of unresolved questions relating to water management in a shale oil industry. However, it can now fairly be said that there is no reason why any action in the Basin should have a major unexpected hydrologic impact.

CHAPTER 2
INTRODUCTION

2.1 OBJECTIVE

This report details work performed and results obtained during the performance of United States Bureau of Mines Contract J0265019 - "Water Management in Oil Shale Mining". The objective of this project is stated in the contract as follows:

> "The objective of the contract is to devise methods of water management with cost data, which are technically feasible and environmentally acceptable for three different locations in the Piceance Creek Basin and for various mine sizes and methods."

In order to provide a background against which the project was set, the Bureau provided the following notes:

> "When commercial oil shale operations begin in the Piceance Creek Basin of Colorado, initial development will probably take place in the upper oil shale zone which contains the Basin's most easily accessible rich oil shale (Cameron Engineer report, 1975). Mining this zone, from the surface or underground, will require control of influxing water from aquifers above and below the upper oil shale sequence. Surface water shortages in the Piceance Creek Basin (Cameron Engineer report, 1975) and restricted use of water from the Colorado River (U.S.D.I. final Environmental Statement, 1973) will make it necessary to use ground water for mining, disposal, upgrading, power generation, revegetation, sanitary and domestic purposes.
>
> To date, no systems, methods, or detailed economic studies for coping with an excess or lack of water and water quality control have been determined for commercial oil shale development. To do this, it is necessary to first determine quality and quantity of water needed for a full scale mining venture, water sources, quality and quantity of water from the sources, fluctuations, costs

Precedin

> and Federal and state regulations. Water management is a major concern for the oil shale industry and will be a factor in determining the feasibility of a full scale mining venture."

2.2 SCOPE

The contract sets out the required project scope in great detail, which has provided the major framework for the study. In order to simplify the 17 work items, Golder Associates divided the task into four phases, which are briefly described below:

Stage I. Assembly: Assembly of all available information relating to water management in oil shale, from public and private sources.

Stage II. Analysis: Analysis of water inflows, water availability, water requirements, water loss and use, dewatering strategies, and water disposal associated with various oil shale development techniques.

Stage III. Evaluation: Integration of systems and selection of optimal water management strategies based on cost, impact, and feasibility.

Stage IV. Report: Presentation of findings.

As it was finally constituted, the contract broadly calls for the evaluation of the water management aspects of any combination of the following systems:

i. Location: Three specific locations for the studies were selected in the Piceance Basin. These were:

   a. Site 1 - Horse Draw, T1S, R97W, Secs 29 & 30. This is the location of the proposed U.S.B.M. Demonstration Mine.

Preceding page

b. [illegible] 2 - This was finally chosen to coincide [illegible] C-a Tract in light of the large quan[illegible] of data available at that location.

Site 3 - This was finally chosen to coincide with C-b Tract, also on the grounds of data availability.

ii. Mining Type: The evaluations called for various mining types at the different locations. These are summarized in Table 2-1.

TABLE 2-1

MINING TYPES CONSIDERED

Mine Type	Site 1	Site 2	Site 3
Room & Pillar	X	X	X
Chamber & Pillar	X		
Sublevel Stoping	X		
Sublevel Stoping with Spent Shale Backfill	X		
Block Caving	X		
Open Pit		X	
True In-Situ	X	X	X
Modified In-Situ	X	X	X

iii. Mining Rate: The rates of extraction called for in the contract were 50,000 and 100,000 ton/day at all sites, and in addition 200,000 ton/day for open pit mining at Site 2. (Note: 50,000 TPD mining is equivalent to a production of approximately 30,000 barrels of oil per day. In the in-situ cases the oil production was used as a measure of size.)

iv. Processing Methods: The Bureau requested that three conventional retorting methods be evaluated, namely:

   a. Paraho IH Process
   b. TOSCO II Process
   c. Union B Process

In addition, all true and modified in-situ processes were to be evaluated. (This in-situ section of the program was incrementally funded by the Area Oil Shale Supervisor's Office of the U. S. Geological Survey.)

In addition to the major variables, the contract called for consideration of a number of other alternatives, including:

i. Source of Water Supply
   a. Groundwater
   b. River Water
ii. Method of Spent Shale Handling
   a. Dry Handling
   b. Slurry Handling
iii. Location of Spent Shale Disposal
   a. Surface Disposal
   b. Subsurface Disposal

Finally, the contract called for the selection of optimal water management systems for each situation. These systems were to be chosen with consideration being given to economics of the system, ease of compliance with legal regulations, and technical feasibility of the systems.

2.3 APPROACH AND REPORT ARRANGEMENT

The major variables listed in the contract led to the consideration of 155 systems, and the addition of the listed minor considerations raises the number to close to 2,000. Accordingly the approach taken has been to attempt to simplify each segment of the water management system and to establish common elements in different systems in order to reduce the variables to a manageable number.

This approach has determined the arrangement of this report. The items common to any system of shale oil extraction have been presented first, and then the report splits, dealing first with conventional mine/retort complexes and then with in-situ systems. A brief description of the contents of each chapter is given below.

Chapters 3 through 6 discuss elements common to both conventional and in-situ water management systems:

> Chapter 3 - The Piceance Basin. This chapter describes the physical setting for the study, including geology, hydrology, and geohydrology.
>
> Chapter 4 - Specific Geohydrology Models. This chapter describes the geology and hydrology of each site in detail and also presents a model of the surface and subsurface hydrology of the entire Basin.
>
> Chapter 5 - Water Supply to the Sites. This chapter describes the physical availability and quality of water in the region, and the cost of supplying water to the sites by various methods.

Chapter 6 - Water Disposal and Treatment. The disposal of water and the treatment of water to use or discharge standards are matters of central importance in the water-deficient study area. Water quality is usually sufficiently low to require treatment before it is suitable for any use. This chapter describes the quality requirements for various use and discharge categories, the method and costs of treating water to those standards, and methods of disposal.

Chapters 7 through 11 describe elements which are largely specific to conventional mining/retorting systems:

Chapter 7 - Conventional Mining Systems. This chapter describes the five mining systems used in calculating conventional mine/surface retort systems. A brief review of each method is given, plus an evaluation of water consumption in mining. Also the geometric parameters of the mining system necessary for later mine inflow evaluations are presented.

Chapter 8 - Inflow to Conventional Mines. The inflows to the specific conventional mines nominated in the contract are presented in this chapter, together with analytical details.

Chapter 9 - Surface Retorting. The three conventional retorting techniques are described in this chapter, with emphasis on the water usage and requirement aspects of each step in the processing activity.

Chapter 10 - Solid Waste Disposal. This chapter evaluates the water-related aspects of spent shale disposal and of other solid waste disposal. It also discusses reclamation and revegetation of disposal areas.

Chapter 11 - Water Management Systems for Conventional Shale Oil Industries. This chapter presents an integration of all information presented in the preceding chapters and produces four basic water management systems. This contrasts favorably with the 2,000 systems identified above.

Chapters 12 through 14 repeat the evaluation steps performed in Chapters 7 through 11, but this time considering the water management aspects of in-situ shale oil recovery technologies.

Chapter 12 - In-Situ Shale Oil Recovery. This chapter reviews the technology of in-situ recovery and attempts to identify the water usage involved. The mine geometrics are presented to aid subsequent inflow evaluations.

Chapter 13 - Dewatering Flows for In-Situ Retorts. The flows necessary to dewater the in-situ retorts are calculated and presented in this chapter.

Chapter 14 - Water Management Systems for In-Situ Shale Oil Industries. This chapter presents an integration of the material on in-situ recovery of shale oil. The water management aspects of four basic systems are adequate to describe the range of likely developments.

Chapters 15 through 17 complete the report, presenting a brief assessment of Basin-wide considerations and our recommendations and conclusions, respectively.

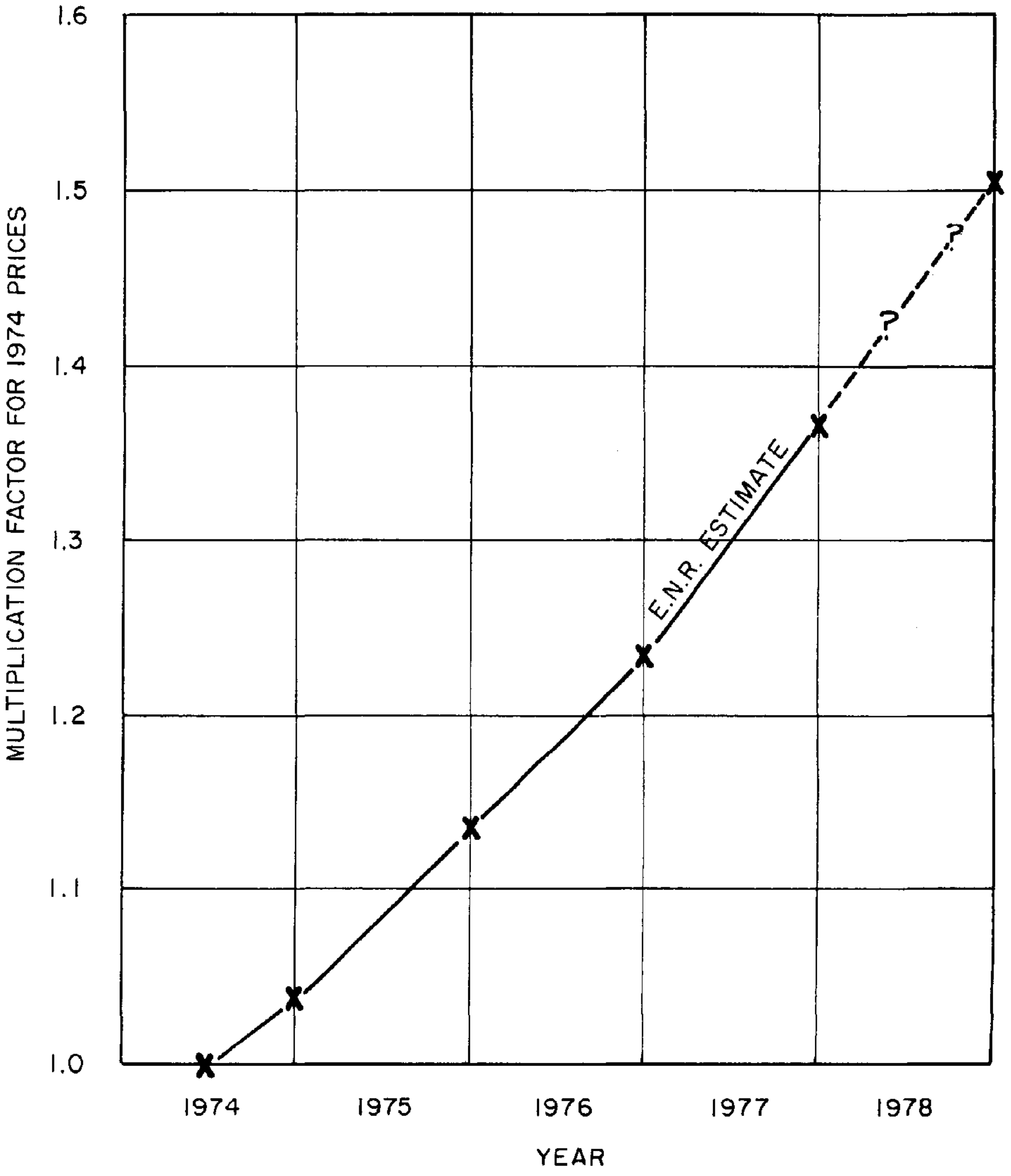
> Chapter 15 - Basin-Wide Considerations. This chapter reviews the Basin-wide effects of groundwater withdrawal for processing of shale oil. Computer simulations of impacts are presented. The water-related environmental impacts of the post-mining phase are also evaluated. Particular emphasis is placed on evaluation of post-mining leaching of spent in-situ retorts and feasible mitigation procedures.
>
> Chapter 16 - Recommendations. This chapter details recommended activities which we feel still need to be performed in the evaluation of water management problems in the Piceance Basin. Some attempt has been made to define needs, reasons, and required level of effort for the various recommended programs.
>
> Chapter 17 - Conclusions. This final chapter summarizes our conclusions.

2.4 ECONOMIC DATA BASIS

Throughout this report reference is made to economic data. By chance, almost all of this data is available in terms of 1974 dollars, in the many reference sources used. As a result we have chosen to retain 1974 dollars as our economic basis, and provide the reader with adjustment factors to arrive at 1977 prices.

We have used the Engineering News Record construction price index trend as a means of estimating the appropriate price escalation factor. Figure 2-1 shows this index for the period 1974-1978, with the 1977 year based on the ENR estimated increase, and 1978 extrapolated. From this

Figure 2-1 CONSTRUCTION PRICE INDEX TRENDS 1974 - 1978



Source: Engineering News Record, December 23, 1976, p.51

figure it can be seen that an escalation factor of 1.3 is appropriate to convert mid-1974 dollars to mid 1977 dollars.

2.5 STUDY TEAM

This project has been performed by a small core of Golder Associates technologists, aided by two external consultants.

Project Manager was Adrian Brown, Associate Partner and Head of Golder Associates' Geohydrology section. The task team comprised Bryan Brooking, Jerry Rowe, and Marie Schauer of Golder Associates, and William Heley, who is a private consultant. Information services and bibliographic searching were performed by Roberta Bradley. Computer programming and analysis was performed by Ian Miller with assistance from Ron Ungless.

Project Director was Allen Gass, President of Golder Associates Inc. Specialist guidance was provided by David Pentz, Principal, Golder Associates; Jose F. T. Agapito, Private Mining Consultant; and Rudolf Kvapil, Specialist Consultant, Golder Associates.

The report was written by Adrian Brown, Marie Schauer, Jerry Rowe, and William Heley. The report was typed by Hilda deGraaff and Marie Monroe, and the figures were drafted by Susan Mullarky and Joanne Naganawa.

We have written the report largely in the first person in order to ease the task of reading a text of this length. We hope this does not offend those more used to third-person presentation.

2.6 ACKNOWLEDGEMENTS

There are a large number of people who have contributed infor-

mation, ideas, and encouragement in the performance of this project. To all we collectively extend our thanks and appreciation. While to single out a few for special thanks is somewhat arbitrary, to fail to acknowledge special assistance would be unacceptable. Accordingly we would like to thank the following:

- Bill Stewart (USBM, Spokane) who has been an outstanding and involved technical project officer for this project.

- Jack Weeks (USGS, Denver) who provided information and advice on Basin geohydrology.

- Eric Hoffman (AOSSO, USGS, Grand Junction) who initiated the inclusion of consideration of in-situ technologies in this study.

- Harry Carpenter (ERDA, Laramie) who provided us with a personal introduction to true in-situ processing.

- Al Ireson (Shell Oil, Denver) for his time and enthusiasm.

- Jack Cotter (TRW, Redondo Beach, California) for input on processing technology.

- Herb Dishlip (U. S. Bureau of Reclamation, Grand Junction) for invaluable aid with water supply aspects.

- Sue Terry, John Cashion, and John Donnell (USGS, Denver) for geological information and assistance.

- Bob Crookston (TOSCO, Los Angeles) for information on processing.

- Jay Hill (Ashland Oil, Denver) for encouragement, and

discussions on C-b Tract.

- Larry Trudell (ERDA, Laramie) for resource and stratigraphic data.

We hope that the material presented in this report justifies the time and effort which they provided.

CHAPTER 3
THE PICEANCE BASIN

The Piceance Creek Basin is a 1,600 square mile elevated basin located in northwestern Colorado between the White and Colorado Rivers. It stands 1,000 to 4,000 feet above the surrounding lowlands, with the land surface sloping gently downward from the rim toward the center of the Basin.

The rocks exposed range in age from Late Cretaceous to Quaternary. The conformable stratigraphic sequence reaches a maximum thickness of 15,800 feet, and consists primarily of sandstone, shale, marlstone, kerogen-rich marlstone, and, in the central part of the Basin, the sodium minerals nahcolite, dawsonite, and halite. The economic resources of the Basin include kerogen-rich dolomitic marlstone or "oil shale", the sodium minerals nahcolite, dawsonite, and halite, and minor natural gas, oil, and coal. As well as being a physiographic and stratigraphic basin, the Piceance Creek Basin is a large northwest-trending structural basin.

The climate of the Basin is semi-arid, with winter and late spring snowfall, late summer thunderstorms and flash floods, and high evapotranspiration during the summer months. The northern part of the Basin is drained by the White River and its tributaries, principally Piceance and Yellow Creeks. The southern part is drained by the Colorado River and its tributaries, principally Parachute and Roan Creeks.

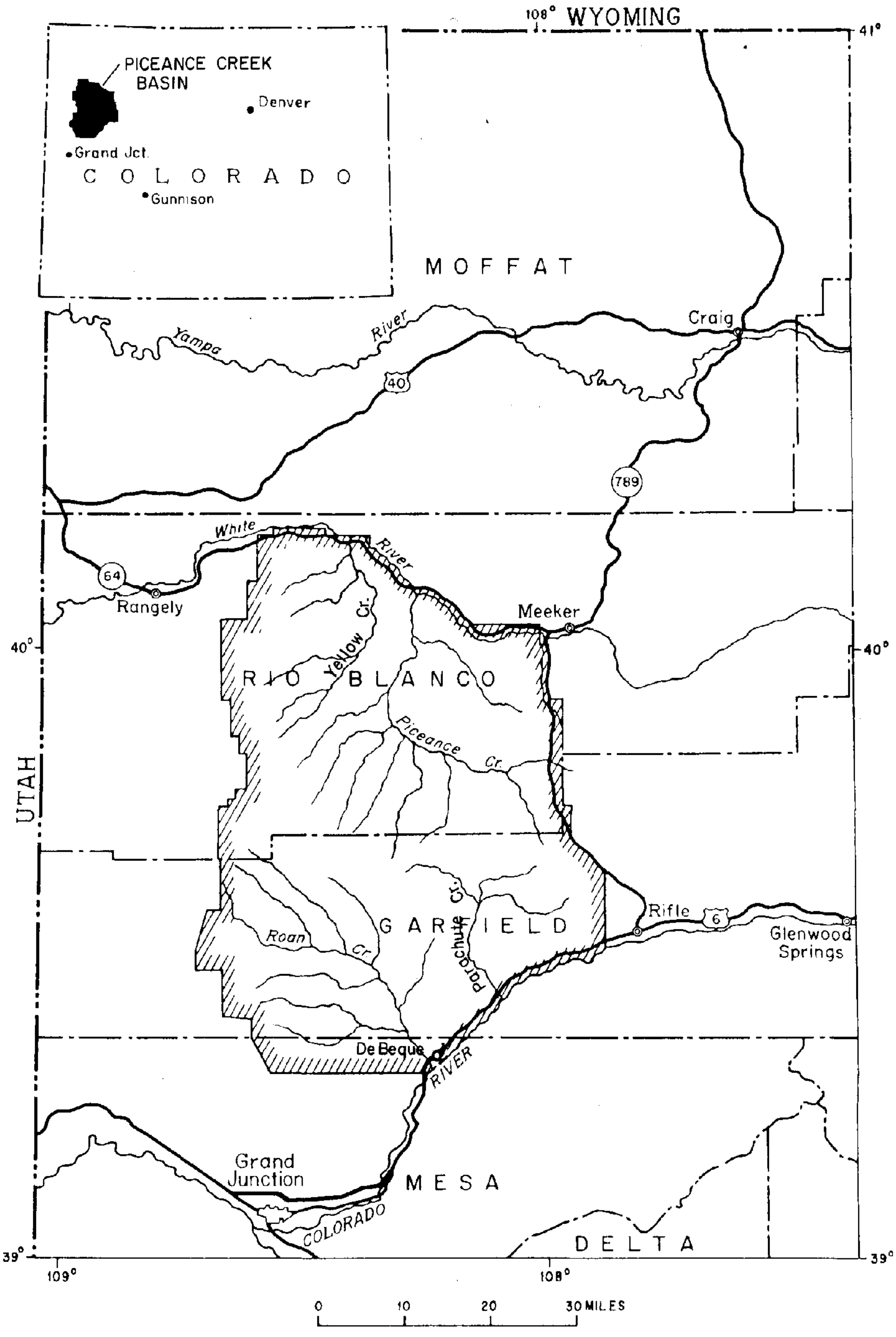
The Basin rocks are characterized by moderate permeability along the bedding, and very low permeability normal to the bedding. Significant permeabilities occur only in the top 1,500 feet of the Basin rocks, which is considered to be the main groundwater-bearing zone. Recharge to the geohydrologic system occurs at the higher elevations around the margins of the Basin. Groundwater quality is low, with the concentration of dissolved solids increasing in the direction of groundwater flow.

3.1 GEOLOGY

3.1.1 PHYSIOGRAPHY

The Piceance Creek Basin is located in northwestern Colorado between the White and Colorado Rivers, as shown in Figure 3-1. It occupies an area of 1,600 square miles in Rio Blanco, Garfield, and Mesa Counties. Elevations range from 4,900 feet on the Colorado River near De Beque to 9,400 feet at the crests of the cliffs northwest of Rifle. Most of the area is a plateau that stands 1,000 to 4,000 feet above the surrounding lowlands. The southern and highest part of the plateau has been deeply dissected and terminates in the Roan Cliffs, a very irregular line of high, precipitous cliffs, with talus slopes at the base. Other parts of the plateau rim are more regular, lower, and less precipitous, except for the Cathedral Bluffs in the northwest. In general, the land surface slopes gently downward from the rim toward the central part of the plateau, with the greatest dips occurring on the eastern and northern slopes. The central part of the plateau is characterized by north- to northeast-trending parallel ridges and valleys that have a local relief of 200 to 600 feet and are asymmetric in nature, with long gentle slopes toward the plateau interior and short steep slopes facing the rim. The differential resistance to erosion is reflected here also. The Roan Plateau, a lightly dissected divide separating the White and Colorado drainages, crosses the south central part of the plateau from east to west.

Figure 3-1 INDEX MAP SHOWING THE PICEANCE CREEK BASIN


PICEANCE CREEK BASIN
Denver
Grand Jct.
COLORADO
Gunnison
108° WYOMING
41°
MOFFAT
Yampa River
40
Craig
789
White River
64
Rangely
Meeker
40°
40°
UTAH
RIO BLANCO
Yellow Cr.
Piceance Cr.
GARFIELD
Roan Cr.
Parachute Cr.
Rifle
6
Glenwood Springs
De Beque
RIVER
Grand Junction
MESA
COLORADO
DELTA
39°
39°
109°
108°
0
10
20
30 MILES

After Coffin, et al., 1971

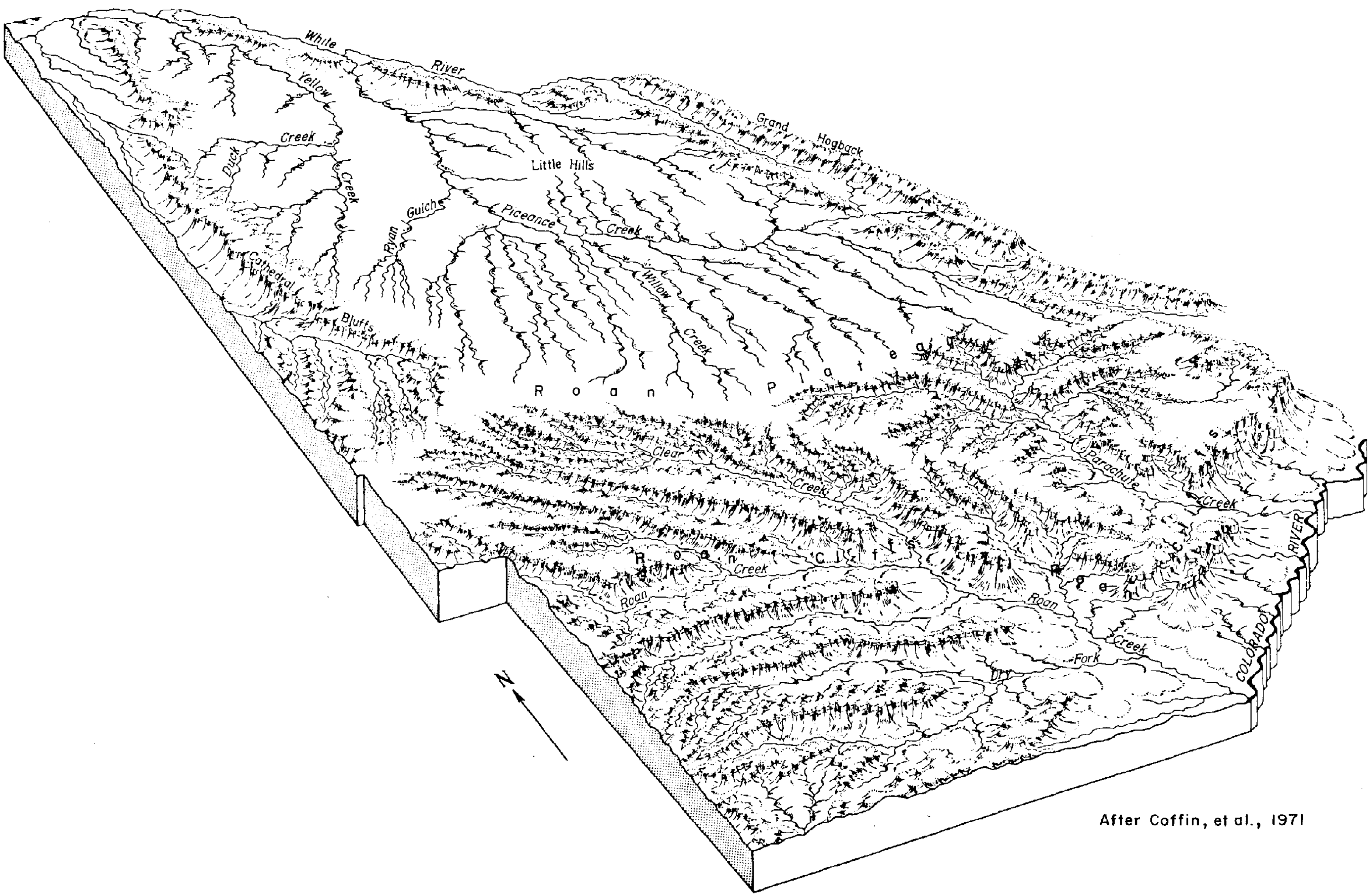
The major rivers in the vicinity of the Piceance Creek Basin are the Colorado, White, and Yampa Rivers, which flow westward from their headwaters on the western slope of the Rocky Mountains in Colorado. The Yampa joins the Green River, which flows southward from Wyoming, in Dinosaur National Monument in Colorado. The White joins the Green River near Ouray, Utah, and the Green flows south to join the Colorado River near Moab, Utah.

The northern and larger part (887 square miles) of the Basin is drained by the White River and its tributaries, principally Piceance and Yellow Creeks. Piceance Creek drains 629 square miles, with 485 square miles being above Ryan Gulch. Yellow Creek drains 258 square miles. Streams in this part are numerous, relatively long, have gentle gradients, and valleys have alluvial deposits. The southern part of the Basin is drained by the Colorado River and its tributaries, principally Parachute and Roan Creeks. Streams in this part are few, relatively short, have steep gradients, and may occur in canyons. In the west central part of the Basin, drainage appears to be structurally controlled, with patterns ranging from trellis to parallel.

Figure 3-2 shows the physiography of the Basin.

3.1.2 STRATIGRAPHY

The rocks exposed in the Piceance Creek Basin range in age from Late Cretaceous to Quaternary. The maximum thickness is 15,800 feet. All contacts are conformable and often gradational. Donnell (1961) believes that local unconformities may exist at the base of and within the Uinta formation.


White River
Yellow Creek
Duck Creek
Grand Hogback
Little Hills
Ryan Gulch
Piceance Creek
Cathedral Bluffs
Willow Creek
Roan Plateau
Clear Creek
Parachute Creek
Roan Cliffs
Roan Creek
Roan Creek
Fork
Dry
COLORADO RIVER
N

After Coffin, et al., 1971

Figure 3-2 BLOCK DIAGRAM OF PICEANCE CREEK BASIN

The oldest rocks exposed in the Piceance Creek Basin are the Mesaverde group of Late Cretaceous age. It consists of tan to brown fine- to coarse-grained sandstone interbedded with shale and several coal beds, and outcrops along the Basin margins forming erosion-resistant cliffs, benches, or ridges. The maximum thickness is 5,600 feet at the eastern margin and thins to the west. Fresh, brackish, and saltwater fossils indicate deposition at or near ancient strand lines.

The Ohio Creek conglomerate, probably of Paleocene age, overlies the Mesaverde group. It consists of black and red chert and quartzite pebbles in a white sandstone matrix, and outcrops along the eastern margin of the Basin. It reaches a maximum thickness of 20 feet in the northeast. No fossils have been reported.

An unnamed unit of Paleocene age overlies the Ohio Creek conglomerate. It consists of brown ledge-forming sandstone, dark-colored shale, and a few thin coal beds, and outcrops along the Basin margins. The maximum thickness is 500 feet in the east. Plant and nonmarine mollusk fossils indicate deposition in a continental environment; the local presence of thin coal beds indicates the existence of scattered short-lived swamps.

The Wasatch formation of early Eocene age overlies the unnamed unit. It consists of buff lenticular sandstone and irregularly-bedded brightly-colored shale with minor amounts of limestone, conglomerate, coal, and black carbonaceous shale. It outcrops along the Basin margins forming nonresistant lowlands. There is great variability in thickness, with a maximum of 5,500 feet in the east and an overall thinning toward the west. The many fossils indicate a fluviatile environment.

The Green River formation of middle Eocene age overlies the Wasatch formation. It is of fluviatile and lacustrine origin. The maximum thickness is in the east and it thins towards the west. The Green River formation has been subdivided into the Douglas Creek, Garden Gulch, Anvil Points, and Parachute Creek members.

The basal member is the Douglas Creek member. It consists of brown to buff crossbedded and ripplemarked sandstone, algal and ostracodal limestone, and oolitic sandstone and limestone, with minor gray shale. It outcrops along the southern and western margins of the Basin forming an erosion-resistant series of benches. The maximum thickness is 800 feet in the west.

The Garden Gulch member overlies the Douglas Creek member. It consists of dark, finely laminated, papery to flaky shale and dolomitic marlstone, generally barren of kerogen. Thin beds of sandstone, breccia, and algal, oolitic, and ostracodal limestone are locally present. It outcrops along the Basin margins, except in the east, and forms gray steep slopes. The maximum thickness is 900 feet in both the southwest and northwest.

In the eastern margin of the Basin the Anvil Points member is the lateral equivalent of the Douglas Creek, Garden Gulch, and lower Parachute Creek members. It consists of a near-shore facies of gray shale, interbedded gray shale and brown and gray sandstone, massive brown and gray sandstone, and light brown marlstone, generally barren of kerogen. Minor amounts of siltstone and algal and oolitic limestone are present. It outcrops in benches and cliffs, and reaches a maximum thickness of 1,870 feet in the southeast.

The Parachute Creek member overlies the Garden Gulch or Anvil Points member. It consists of white to gray varved dolomitic marlstone with alternating dark kerogen-rich and light barren zones, and sodium minerals, principally nahcolite, dawsonite, and halite. It outcrops along the Basin margin forming whitish cliffs. The maximum thickness is 1,230 feet in the southeast. There is a general increase in thickness and richness of kerogen-rich marlstone towards the center of the basin and a corresponding increase in thickness of saline minerals. A particularly kerogen-rich zone is the Mahogany Zone which occurs in the upper part of the Parachute Creek member and forms a prominent resistant ledge in the outcrop, bounded below and above by the barren nonresistant B- and A-grooves, respectively. Within the Mahogany Zone is a thin analcitized tuff and ash bed called the Mahogany Marker that is used as a stratigraphic marker throughout the Basin.

The Uinta formation of late Eocene age overlies the Green River formation. It consists of fine- to medium-grained, lenticular, massive, brown sandstone, white to gray lenticular siltstone, white to gray marlstone, generally barren of kerogen and shale. Sandstone becomes increasingly prominent towards the top of the member, while kerogen-containing marlstone beds are present near the base. It outcrops in the central part of the Basin and forms buff to light brown rounded receding caps on the plateau rim and rough hilly topography in the central part of the Basin. The top of the formation is eroded but the approximate maximum thickness is 1,250 feet in the east. The depositional environment of this unit became progressively more fluviatile.

Alluvium of Quaternary age occurs as stream valley deposits in the northern part of the Basin. This consists mainly of unconsolidated gravel, sand, and clay derived from the Uinta formation. Maximum thickness is 200 feet.

A small erosional remnant of a basaltic flow is present on the summit of Mount Callahan in the extreme southeastern part of the Basin. The rock consists principally of labradorite with a high percentage of mafic minerals. Donnell (1961) states that this may be a part of the extensive lava flow covering mesas to the south that has been isolated by erosion of the Colorado River and its tributaries.

Table 3-1 summarizes Basin stratigraphy, and Figure 3-3 shows a generalized cross-section of the Basin.

3.1.3 STRUCTURAL GEOLOGY

The Piceance Creek Basin is a large northwest-trending structural downwarp. It is asymmetric, with gently dipping limbs on the south and west and more steeply dipping limbs on the north and east. The northwest-trending axis is offset to the east in the subsurface. The Basin is bordered on the northeast and east by the Axial Basin anticline and the White River uplift, on the southwest by the Uncompahgre uplift--an ancient feature of low topography but high structural relief--, on the west by the Douglas Creek arch, and on the northwest by the Blue Mountain and Rangely anticlines and the Uinta uplift. The structural features of the Basin and surrounding areas are shown in Figure 3-4.

The most prominent evidence of folding is the Piceance Creek dome in the northeastern part of the Basin. This dome is 10 miles long and has a structural relief of 200 to 250 feet. Numerous small, parallel, northwest-trending plunging anticlines and synclines are also present throughout the Basin. Donnell (1961) believes that there may also be folding of the Green River formation that is not reflected in the surficial Uinta formation.

TABLE 3-1 - STRATIGRAPHIC SECTION OF PICEANCE CREEK BASIN

GEOLOGIC AGE			GEOLOGIC UNIT		TOPOGRAPHIC EXPRESSION	LITHOLOGY	DEPOSITIONAL ENVIRONMENT	THICKNESS (FEET)
ERA	PERIOD	EPOCH						
Cenozoic	Quaternary	Recent and Pleistocene	Alluvium		Stream valleys	Unconsolidated gravel, sand, and clay.	Fluviatile	0-200
	Tertiary	Pliocene	Basalt flow		Summit of Mount Callahan	Labradorite with a high percentage of mafic minerals.	Volcanic	Small
		Eocene	Uinta Formation		Buff to brown rounded receding caps on the plateau rim and rough hilly topography in the central part of the Basin	Fine to medium-grained, lenticular, massive, brown sandstone, white to gray lenticular siltstone, white to gray marlstone, generally barren of kerogen and shale.	Fluviatile-Lacustrine	0-1,250
			Green River Formation	Parachute Creek Member	Whitish cliffs	White to gray varved dolomitic marlstone with alternating dark kerogen-rich and light barren zones, and sodium minerals, principally nahcolite dawsonite, and halite.	Lacustrine	500-1,230
				Anvil Points Member (lateral equivalent to Douglas Creek, Garden Gulch, and lower Parachute Creek Members in the eastern part of the Basin)	Benches and cliffs	Gray shale, interbedded gray shale and brown and gray sandstone, massive brown and gray sandstone, light brown marlstone, generally barren of kerogen. Minor amounts of siltstone and algal and oolitic limestone.	Lacustrine (near-shore facies)	0-1,870
				Garden Gulch Member	Gray steep slopes	Dark, finely laminated, papery to flaky shale and dolomitic marlstone, generally barren of kerogen. Locally thin beds of sandstone, breccia, and algal, oolitic, and ostracodal limestone.	Lacustrine	0-900
				Douglas Creek Member	Benches	Brown to buff cross-bedded and ripple-marked sandstone, algal and ostracodal limestone, and oolitic sandstone and limestone with minor gray shale.	Lacustrine	0-800
			Wasatch Formation		Lowlands	Buff lenticular sandstone and irregularly-bedded brightly-colored shale with minor amounts of limestone, conglomerate, coal, and black carbonaceous shale.	Fluviatile	300-5,500
		Paleocene	Unnamed unit		Ledges	Brown sandstone, dark-colored shale, and a few thin coal beds.	Continental with scattered short-lived swamps	500
			Ohio Creek conglomerate			Black and red chert and quartzite pebbles in a white sandstone matrix.	Continental	20
Mesozoic	Cretaceous	Late Cretaceous	Mesaverde Group		Prominent cliffs, benches, or ridges	Tan to brown fine to coarse-grained sandstone interbedded with shale and several coal beds.	Fresh water, brackish and marine at or near ancient strand lines	5,600

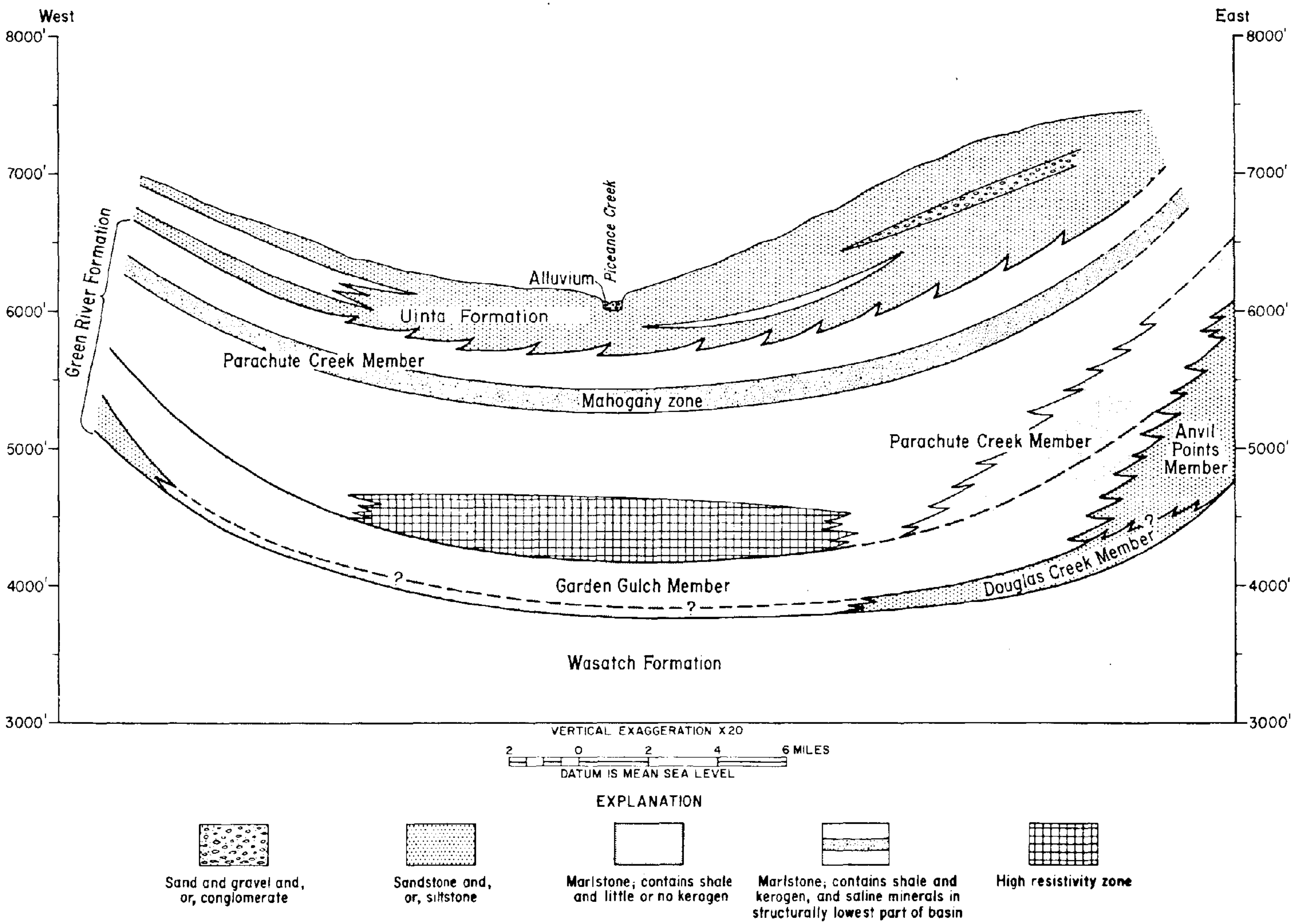
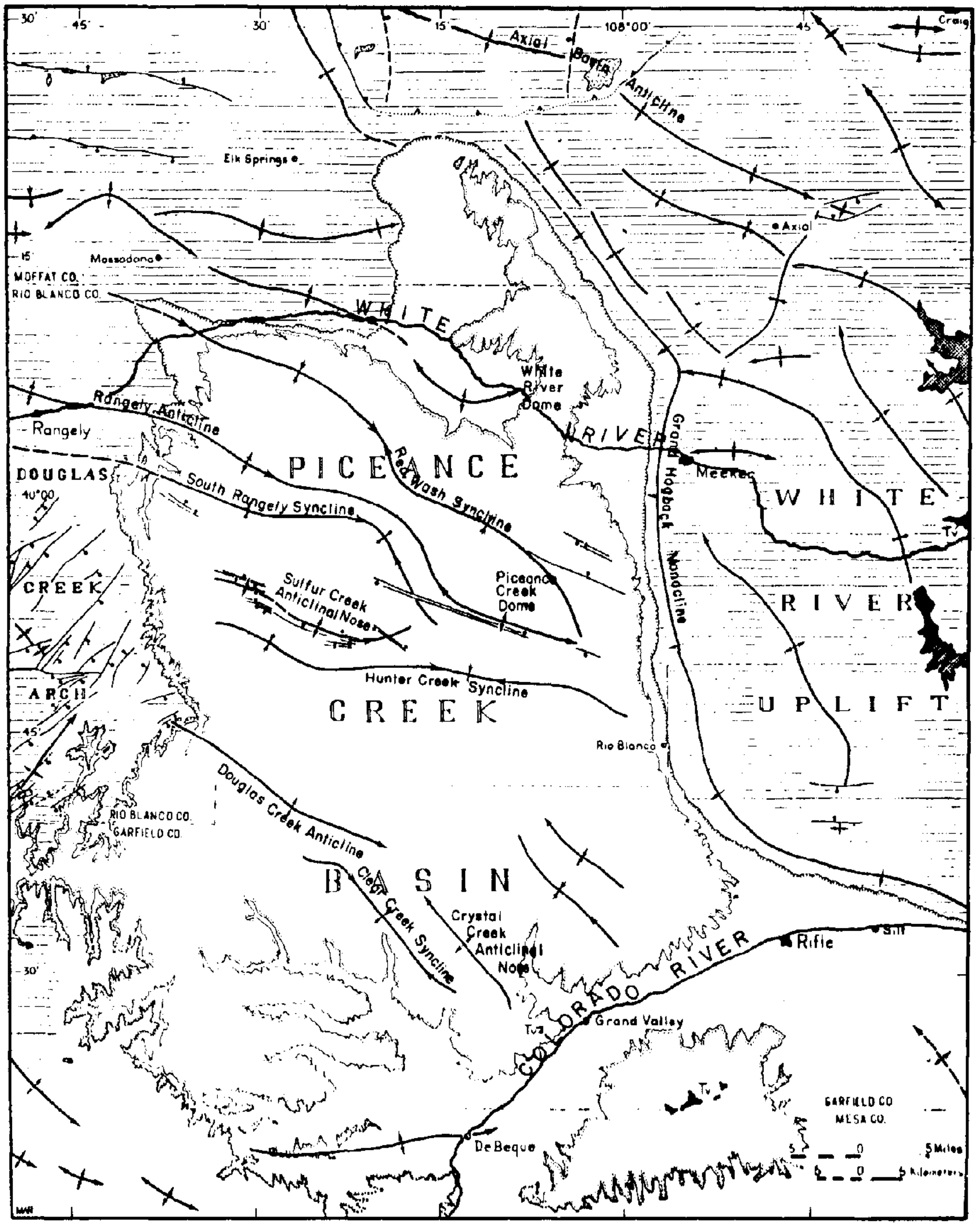

West
East
8000'
7000'
6000'
5000'
4000'
3000'
Green River Formation
Piceance Creek
Alluvium
Uinta Formation
Parachute Creek Member
Mahogany zone
Parachute Creek Member
Anvil Points Member
Garden Gulch Member
Douglas Creek Member
?
Wasatch Formation
VERTICAL EXAGGERATION X20
2 0 2 4 6 MILES
DATUM IS MEAN SEA LEVEL
EXPLANATION
Sand and gravel and, or, conglomerate
Sandstone and, or, siltstone
Marlstone; contains shale and little or no kerogen
Marlstone; contains shale and kerogen, and saline minerals in structurally lowest part of basin
High resistivity zone

Figure 3-3 DIAGRAMMATIC SECTION ACROSS PICEANCE CREEK BASIN After Coffin, et al., 1971

Figure 3-4 STRUCTURAL GEOLOGIC MAP OF PICEANCE CREEK BASIN


30'
45'
30'
15'
108°00'
45'
Craig
Axial Basin Anticline
Elk Springs
Axial
15'
Massadona
MOFFAT CO.
RIO BLANCO CO.
WHITE RIVER
White River Dome
Rangely Anticline
Rangely
PICEANCE CREEK BASIN
DOUGLAS CREEK ARCH
40°00'
Red Wash Syncline
South Rangely Syncline
Grand Hogback Monocline
Meeker
WHITE RIVER UPLIFT
Tv
Piceance Creek Dome
Sulfur Creek Anticlinal Nose
Hunter Creek Syncline
45'
Rio Blanco
RIO BLANCO CO.
GARFIELD CO.
Douglas Creek Anticline
Clear Creek Syncline
Crystal Creek Anticlinal Nose
COLORADO RIVER
Rifle
Silt
30'
Grand Valley
Tv
DeBeque
GARFIELD CO
MESA CO.
5 0 5 Miles
5 0 5 Kilometers
MAR

After M W Reynolds in Murray and Haun, in Murray (ed.), 1974, pp. 34-35

EXPLANATION

OUTCROP SYMBOLS

▩ Tv Miocene(?) and Pliocene volcanic rocks

☐ Mesozoic and Paleozoic rocks (locally includes Tertiary Browns Park Formation)

Base of Eocene Green River Formation

Precambrian rocks

Base of Eocene and Paleocene Wasatch Formation

STRUCTURE SYMBOLS

FOLDS

Anticline - showing direction of plunge

Syncline - showing direction of plunge

Monocline

FAULTS

Normal fault - bar and ball on downthrown side

Reverse fault - dotted where concealed or inferred

Numerous northwest-trending, high-angle normal faults are present in the northeast part of the Basin, on and just to the west of the Piceance Creek dome. These commonly occur in pairs with a down-dropped block or graben between them. The maximum vertical displacement is 200 feet with 50 feet being the norm. Numerous minor faults of small displacement are found on the graben surface. Similar parallel or en echelon faulting is sometimes present on the crest and flanks of plunging anticlines. The faults are often filled with calcite.

An extensive system of joints and fractures exists in the Basin, with well-defined primary trends to the northeast and northwest and a secondary east-west trend. There is a regularity in lateral variation of joint density within individual rock units and vertical discontinuity in joint density between rock units. Some of the joints are calcite-filled, and all tend to close with depth in the lower portions of the Green River formation. In the west central part of the Basin, there appears to be a partial adjustment of streams to the joint system, producing a trellis to parallel drainage pattern. Streams are aligned with the primary joint trends where the regional surface dip direction parallels a joint trend.

3.1.4 GEOLOGIC HISTORY

In the Late Cretaceous the sea had withdrawn for the final time to the north and east of the Piceance Creek Basin, resulting in marine sedimentation followed by deltaic and paludal deposition. The uplift of the Douglas Creek arch on the west and uplift in the south and east (with which the Paleocene

Ohio Creek conglomerate is associated) resulted in the formation of a depositional basin by the early Eocene. Deposition in and around the Basin was primarily fluviatile. Late in the early Eocene the outlet of the stream system was blocked either by subsidence of the Basin, uplift of the Uinta mountains to the north, or both, and Lake Uinta was formed. The Douglas Creek arch was inundated and the lake covered most of northwestern Colorado and northeastern Utah.

Sediment that accumulated near the shore on the floor of Lake Uinta consisted primarily of sand, while sediment that accumulated far from the shoreline consisted primarily of clay and dolomitic marl. The lake contained abundant plant and animal life. A large amount of carbonate, bicarbonate, and sodium existed in solution in the lower water layers. Decomposition of organics that died and sank to the lake floor lowered the pH of the water and caused the sodium minerals nahcolite, dawsonite, and halite to be precipitated in the central part of the lake. As depositional and water-chemical conditions varied because of climatic changes, various amounts of organic matter and salts accumulated on the lake bottom. After some time the lake rapidly expanded to its maximum size, salinity decreased, and organics increased. This resulted in an increase in the deposition of undecomposed organics and a decrease in the precipitation of sodium minerals. From time to time nearby volcanic activity deposited ash and tuff layers in the lake. Downwarping of the lake and intraformational folding kept pace with continued deposition.

In the late Eocene the greatest effects of the Laramide orogeny were felt and the surrounding land was uplifted, causing stream influx to fill the lake with clastics first in the northwest and then the southern part of the lake.

The weight of the overlying sediments consolidated the lake deposits into rock and converted the organic matter to kerogen, a solid hydrocarbon. Folding, faulting, jointing, and fracturing also took place during the Laramide orogeny. Fracturing exposed the upper part of the sodium mineral-rich zone in the Green River formation to solution by groundwater, leaving a very porous leached zone that is a permeable aquifer filled with highly saline water.

In the Pliocene basalt flows were extruded onto the surface in the extreme southeastern part of the Basin from the south. Post-Laramide epeirogeny occurred; consisting of continued uplift, downcutting of streams down into the Mesaverde group, and surficial erosion.

In the Quaternary alluvium is being deposited in stream valleys, talus slopes are forming at the base of the cliffs around the margins of the Basin, and surficial erosion continues.

3.1.5 ECONOMIC GEOLOGY

Kerogen-rich dolomitic marlstone is also known as "oil shale". Kerogen is only slightly soluble in ordinary petroleum solvents but can be converted to oil by destructive distillation. Eighty percent of the oil shale resources of the Eocene Green River formation occur in the Piceance Creek Basin, with 75% of the land being owned by the Bureau of Land Management of the federal government and 25% by private sources. The thickest and richest of these oil shale deposits are in the Parachute Creek member and tend to be thicker and richer towards the center of the Basin. Donnell (1961) estimates reserves of oil shale averaging 25 gallons per ton and at least 15 feet thick at 260,000 million tons of oil shale or 155,000 million barrels of oil in the Mahogany Zone and adjacent areas, and at 264,000 million tons of oil shale or 157,000 million barrels of oil in the northern and deeper parts of the Basin, all estimates not taking into account loss in mining and processing.

Nahcolite, $NaHCO_3$ or sodium bicarbonate, occurs in the sodium mineral-rich zone in the central part of the Basin in the lower Parachute Creek member of the Green River formation. The sodium mineral-rich zone reaches a maximum thickness of 1,000 feet in the northeast. Nahcolite occurs mostly as irregular to roughly spherical brown crystalline aggregates. It is also found as fine crystals disseminated in the oil shale matrix or in fractures and as brown microcrystalline or white coarse-bedded deposits that may be associated with halite. It is highly water soluble. It is a source of soda ash and sodium bicarbonate, which is used in glass production and in atmospheric emission control systems to remove sulfur from emission gases. It is estimated that 29,000 million tons of nahcolite are present in the Basin.

Dawsonite, $NaAl(OH)_2 CO_3$ or dihydroxy sodium aluminum carbonate, occurs in the sodium mineral-rich zone. It occurs as finely disseminated crystals in the oil shale matrix or in fractures. It is not water soluble. Dawsonite is a source of alumina. It is estimated that 19,000 million tons of dawsonite containing 6,500 million tons of alumina are present in the Basin.

Halite, NaCl or sodium chloride, occurs in the sodium mineral-rich zone. It occurs interbedded with oil shale and may be associated with nahcolite. It is highly water soluble. Halite is a source of common table salt, but there has been little or no interest in mining it in the Basin.

Gas has been produced in commercial quantities from the Douglas Creek member of the Green River formation at the Piceance Creek dome. The gas is stratigraphically trapped in sandstone lenses 12 to 230 feet thick. There is no history of sustained production. Other minor gas and oil shows have been produced from the Douglas Creek member and sandstones of the Wasatch formation and the Mesaverde group. It is expected that exploration for stratigraphically and structurally trapped oil and gas in the Basin will continue.

Known deposits of coal are found in the Mesaverde group, the unnamed unit of Paleocene age, and the Wasatch formation where these outcrop around the margins of the Basin. In the rest of the Basin the coal beds are covered by 4,500 feet or more of overburden. The coal is generally high volatile and B or C bituminous in rank. There has been only minor interest in mining the coal due to the overburden thickness and concentration on oil shale development.

3.2 SURFACE HYDROLOGY

3.2.1 HYDROLOGIC SETTING

The major rivers in the vicinity of the Piceance Creek Basin are the Colorado, White, and Yampa Rivers, which flow westward from their headwaters on the western slope of the Rocky Mountains in Colorado. The Yampa joins the Green River, which flows southward from Wyoming, in Dinosaur National Monument in Colorado. The White joins the Green River near Ouray, Utah, and the Green flows south to join the Colorado River near Moab, Utah.

The northern and larger part (887 square miles) of the Basin is drained by the White River and its tributaries, principally

Piceance and Yellow Creeks. Piceance Creek drains 629 square miles, with 485 square miles being above Ryan Gulch. Yellow Creek drains 258 square miles. Streams in this part are numerous, relatively long, have gentle gradients, and valleys have alluvial deposits. The southern part of the Basin is drained by the Colorado River and its tributaries, principally Parachute and Roan Creeks. Streams in this part are few, relatively short, have steep gradients, and may occur in canyons. In the west central part of the Basin, drainage appears to be structurally controlled, with patterns ranging from trellis to parallel.

Figure 3-2 shows the physiography of the Basin.

3.2.2 CLIMATOLOGY

The climate of the Piceance Creek Basin is semi-arid, and at the higher elevations almost sub-humid. Summers are warm and mild with the maximum temperature of 100°F. occurring in July. Winters are cold with the minimum temperature of minus 40°F. occurring in January. The average annual number of frost-free days ranges from 50 at the higher elevations to 120 at the lower elevations. Temperature also varies inversely with elevation.

Two types of wind occur in the basin: regional or gradient winds are gentle southwesterlies, and local or drainage winds vary in speed and direction due to topography, diurnal temperature change, and seasonal change. In the morning solar heating warms the air in the valleys of the Basin and it expands and rises causing first up-valley and then up-slope winds which reach their maximum intensity in the afternoon. In the evening cool denser air from the higher elevations sinks into the valleys, causing first down-valley and then down-slope winds which reach their maximum intensity at night. This diurnal thermal convection process is often disrupted in the winter due to snow cover preventing significant surface heating and expansion of the morning air; the inversion from the previous night is persistent.

The average annual precipitation measured at the low elevation Little Hills weather station is 12.9 inches. The range for the Basin is 12 to 20 inches with as much as 25 inches at the highest elevations; precipitation and relative humidity vary directly with elevation. The annual precipitation is spread uniformly over the months.

The general weather pattern consists of stationary warm, dry high pressure systems that occur because both close and distant surrounding mountains to the west and south deflect cool, wet low pressure systems from the southwest around the Basin or cause them to lose their moisture content through precipitation before reaching the Basin. Mountains to the east, both in the immediate area and farther away like the Rocky Mountains, block the movement of the high pressure systems that are formed. As a result days are usually clear, sunny, and of moderate humidity. Two types of storm systems occur to disrupt this general pattern. In the winter low pressure frontal systems from the Gulfs of Mexico, California, and Alaska often resist deflection or reduction in moisture content and move into the Basin along the Colorado River drainage. The resulting storms are regional and uniform, of long duration of a week or so, and low in precipitation intensity. The snow or rain that falls makes up 50% or more of the annual precipitation, and it goes mostly for evapotranspiration and for stream runoff and groundwater recharge. In the late summer thermal convection system sometimes cause thunderstorms that are local and erratic, of short duration, high in precipitation intensity, and have strong turbulent winds. The rain makes up 50% or slightly less of the annual precipitation, and it goes mostly for evapotranspiration (which occurs at a higher rate than in the winter) and for stream runoff in the form of flash floods.

3.2.3 STREAMFLOW

Rivers and streams in and around the Piceance Creek Basin can be classified as either perennial or intermittent. The Colorado, White, and Yampa Rivers, Piceance Creek, and lower Yellow and Roan Creeks are perennial and always have some streamflow due to groundwater discharge. In addition streamflow is augmented by runoff from snowmelt in winter and early spring and flash floods in late summer. Upper Yellow and Roan Creeks, Parachute Creek, and all the other minor streams are intermittent and have a streamflow that is seasonally dependent on runoff for their existence. In general, 80% of the volume of annual streamflow in the Basin is due to groundwater discharge and 20% is due to stream runoff. Minimum flows occur in late spring and summer and peak flows in winter and early spring and in late summer. Irrigation diversions from March to November serve to reduce flow minima below their natural levels, and to reduce the effect of peak flows; diversions are greater in Piceance Creek than Yellow Creek.

Flow gaging in the Basin is complicated by irrigation diversions, erratic records, and diversions around the gaging point. Piceance Creek at White River has a measured mean annual discharge of 17,345 AFY (24 cubic feet per second), plus an estimated 4,740 AFY diverted for irrigation. Records include 1965-1966, and 1971-1976 water years. Piceance Creek at Ryan Gulch has a measured mean annual discharge of 13,948 AFY

(19.3 cubic feet per second), plus an unknown irrigation diversion. Records span the 1965-1976 water years. Yellow Creek near White River has a mean annual discharge of 1,265 AFY (1.75 cubic feet per second), plus an estimated 60 AFY for irrigation. Records include 1965-1966 (unpublished) and 1973-1976 water years. Total discharge from the Basin is thus 18,610 AFY (25.75 cubic feet per second), plus in-Basin use of 4,800 AFY. Figures 3-5 and 3-6 show respectively mean monthly and mean annual discharge for Piceance and Yellow Creeks.

Reference to Figure 3-6 shows a fairly marked increase in the flow of Piceance Creek after 1972. This increase coincides with the Rio Blanco Nuclear Shot, and it has been suggested that the shock from the blast may have significantly altered the rock permeability, allowing a more rapid discharge of groundwater to the stream. It is likely that any effect of this sort will be of limited duration, and that streamflows will return to their pre-1973 levels after a few years or decades.

Streamflow quality in the Basin depends on quality and quantity of groundwater discharge to a given reach of a stream, on quantity of irrigation diversions or return flow, and on evapotranspiration. A seasonal determinant of streamflow quality is the ratio of stream runoff to groundwater discharge, with the relationship being a direct one. Disregarding seasonal variations in stream runoff, quality of streamflow and groundwater discharge and sediment load generally decrease downstream, while quantity of groundwater discharge and irrigation diversions or return flow, total dissolved solids content, specific conductance, sodium, chloride, and fluoride content, and salinity (due to salt loading/adding salts or salt concentrating/removing salts) increase downstream.

Figure 3-5 MEAN DISCHARGE RATE OF PICEANCE AND YELLOW CREEKS

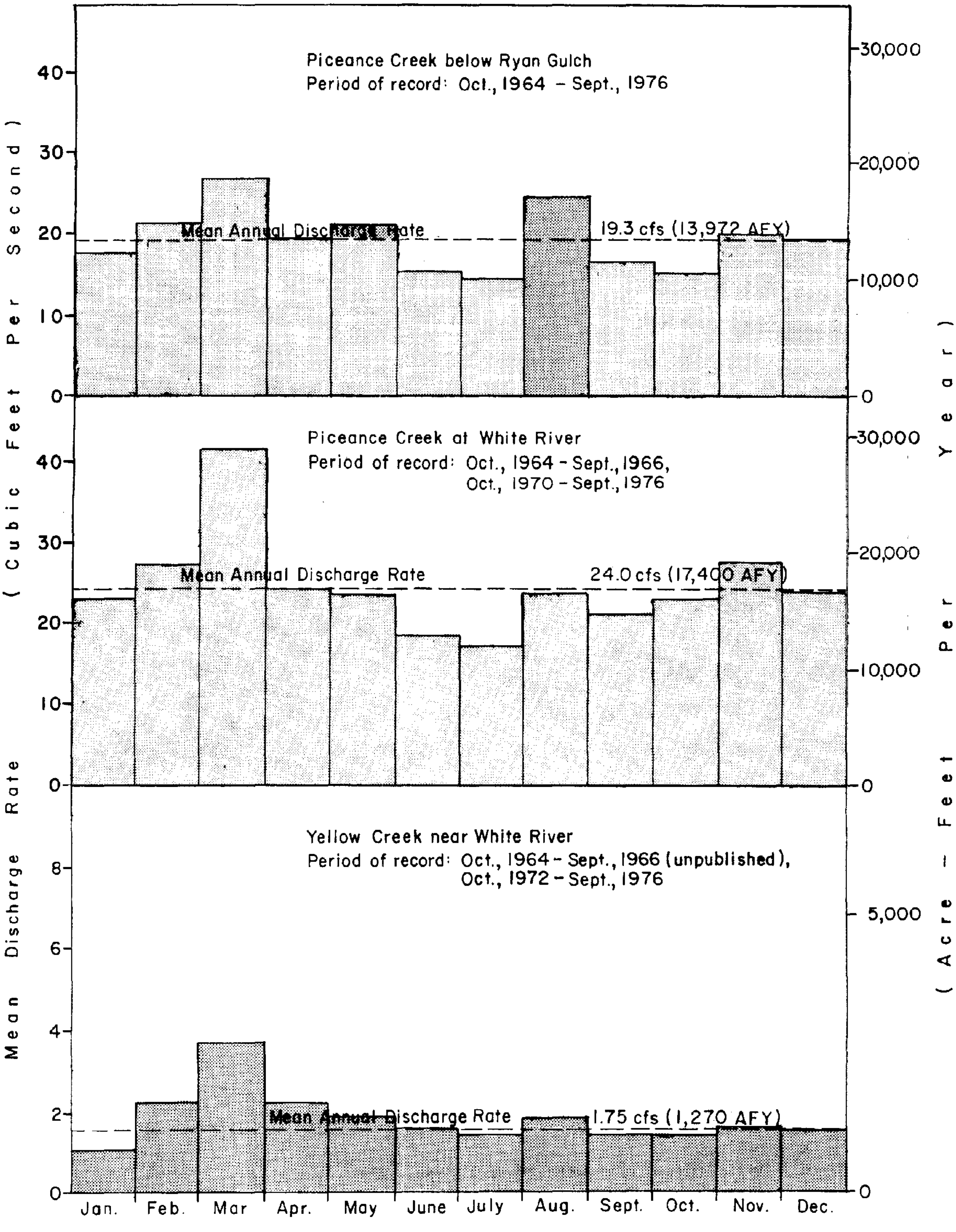
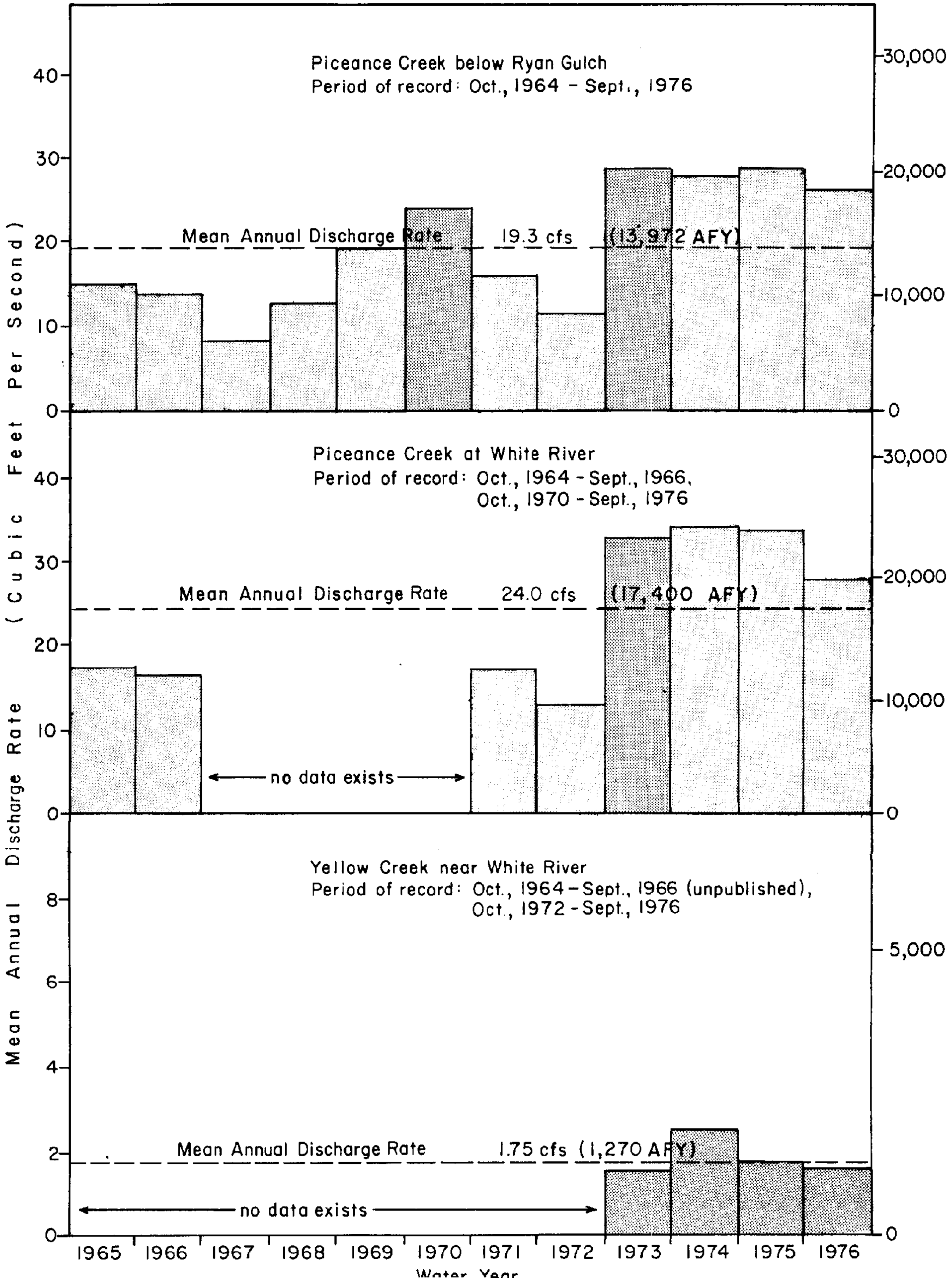


Figure 3-6 MEAN ANNUAL DISCHARGE RATE OF PICEANCE AND YELLOW CREEKS



Quality grades from a mixed bicarbonate type to a sodium bicarbonate type downstream. Surface water of the Basin is not considered potable but is acceptable for livestock watering. Salinity and sodium content are quite high for irrigation diversions.

Tables 3-2, 3-3, and 3-4 present typical water quality data for the gaging sites on Piceance and Yellow Creeks. In addition to the ionic salt loading, the creeks carry significant quantities of sediment into the White River.

3.2.4 SPRINGS AND SEEPS

Springs and seeps in the Piceance Creek Basin can also be classified as either perennial or intermittent. Perennial springs have as their source oil shale aquifer groundwater discharge. Intermittent springs have as their source alluvial and perched aquifer discharge. Although there is a diversity of opinion on the genesis of the springs of the Basin, it seems likely that both types are well represented in the Basin. Springs and seeps occur on stream valley floors and along valley sides, and are most numerous on lower Piceance Creek between Ryan Gulch and the White River. A total dissolved solids content of 22,000 milligrams per liter was measured at one of these springs during the 1973 water year. The total dissolved solids content of the springs increases and thus the water quality decreases in a downstream direction.

3.3 GEOHYDROLOGY

The geohydrology of the Piceance Basin has been extensively investigated. The major reference works are those by Coffin, et al. (1971) and Weeks, et al. (1974). Data has been presented in four Basic-Data Releases of the Colorado Water

TABLE 3-2

WATER QUALITY OF PICEANCE CREEK BELOW RYAN GULCH

PERIOD OF RECORD.--Chemical analyses: December 1970 to September 1973.
Sediment records: October 1972 to September 1973.

EXTREMES, 1972-73.--Sediment concentrations: Maximum daily, 4,000 mg/l May 14; minimum daily, 65 mg/l Oct. 3.
Sediment loads: Maximum daily, 1,430 tons (1,300 t) May 26; minimum daily, 0.97 tons (0.88 t) Oct. 3.

WATER QUALITY DATA, WATER YEAR OCTOBER 1972 TO SEPTEMBER 1973

DATE	DISCHARGE (CFS)	DISSOLVED SILICA (SIO2) (MG/L)	DISSOLVED IRON (FE) (UG/L)	DISSOLVED MANGANESE (MN) (UG/L)	DISSOLVED CALCIUM (CA) (MG/L)	DISSOLVED MAGNESIUM (MG) (MG/L)	DISSOLVED SODIUM (NA) (MG/L)	DISSOLVED POTASSIUM (K) (MG/L)	BICARBONATE (HCO3) (MG/L)	CARBONATE (CO3) (MG/L)	ALKALINITY AS CACO3 (MG/L)	DISSOLVED SULFATE (SO4) (MG/L)
OCT.												
05...	8.3	17	40	63	73	93	220	3.8	671	0	550	420
NOV.												
10...	17	18	30	70	85	81	170	3.1	620	0	509	350
DEC.												
07...	17	17	50	70	80	75	160	3.1	637	0	522	320
JAN.												
16...	11	19	70	40	79	84	200	3.0	697	4	578	390
FEB.												
08...	15	19	40	30	80	77	180	3.1	658	0	540	350
MAR.												
08...	18	16	80	30	81	77	160	3.4	634	0	520	340
APR.												
05...	13	15	60	50	84	90	180	2.6	635	0	521	420
MAY												
24...	82	18	30	10	79	66	120	3.5	523	0	429	290
JUNE												
14...	43	16	30	40	89	90	190	3.1	664	0	545	400
JULY												
12...	26	20	40	70	100	110	210	3.4	750	0	615	500
AUG.												
30...	51	20	30	20	86	78	150	2.5	554	0	454	370

DATE	DISSOLVED CHLORIDE (CL) (MG/L)	DISSOLVED FLUORIDE (F) (MG/L)	DISSOLVED NITRITE PLUS NITRATE (N) (MG/L)	DISSOLVED ORTHO. PHOSPHORUS (P) (MG/L)	DISSOLVED SOLIDS (SUM OF CONSTITUENTS) (MG/L)	DISSOLVED SOLIDS (TONS PER DAY)	HARDNESS (CA,MG) (MG/L)	NON-CARBONATE HARDNESS (MG/L)	SODIUM ADSORPTION RATIO	SPECIFIC CONDUCTANCE (MICROMHOS)	PH (UNITS)	TEMPERATURE (DEG C)
OCT.												
05...	25	1.0	.00	.03	1180	26.4	560	15	4.0	1691	8.1	9.5
NOV.												
10...	17	.8	.26	.01	1030	47.3	550	37	3.2	1510	8.0	2.5
DEC.												
07...	16	.9	.39	.01	987	45.3	510	0	3.1	1450	7.7	.0
JAN.												
16...	16	.8	.41	.04	1140	33.9	540	0	3.7	1610	8.4	.0
FEB.												
08...	13	.8	.50	.05	1050	42.5	520	0	3.4	1510	8.2	.0
MAR.												
08...	15	.8	.42	.04	1010	49.1	520	0	3.1	1480	8.0	1.0
APR.												
05...	14	.6	.28	.03	1120	39.3	580	59	3.3	1350	7.9	6.5
MAY												
24...	12	.6	.87	.05	851	188	470	40	2.4	1230	8.0	10.0
JUNE												
14...	13	.9	.44	.02	1130	131	590	48	3.4	1630	8.1	11.5
JULY												
12...	17	.8	.31	.05	1330	93.4	700	87	3.4	1910	8.2	14.0
AUG.												
30...	12	.4	.70	.02	995	137	540	81	2.8	1440	8.0	13.5

SOURCE: Weeks and Welder, 1974, p. 70.

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TABLE 3-3

WATER QUALITY OF PICEANCE CREEK AT WHITE RIVER

PERIOD OF RECORDS.--Chemical analyses: December 1970 to September 1973.
Water temperatures: January 1971 to September 1973.

EXTREMES, 1972-73.--Specific conductance: Maximum daily, 5,800 micromhos Feb. 15; minimum daily, 1,330 micromhos May 11, 12, 13, 14.
Water temperatures: Maximum, 21°C Oct. 3, July 26, 27, 28; minimum, freezing point on many days during November to march.
Period of record.--Specific conductance: Maximum daily, 9,500 micromhos July 16, 1972; minimum daily, 687 micromhos Mar. 23, 1971.
Water temperatures: Maximum, 26°C June 6, 1972; minimum, freezing point on many days during the winter months.

WATER QUALITY DATA, WATER YEAR OCTOBER 1972 TO SEPTEMBER 1973

DATE	DISCHARGE (CFS)	DISSOLVED SILICA (SIO2) (MG/L)	DISSOLVED IRON (FE) (UG/L)	DISSOLVED MANGANESE (MN) (UG/L)	DISSOLVED CALCIUM (CA) (MG/L)	DISSOLVED MAGNESIUM (MG) (MG/L)	DISSOLVED SODIUM (NA) (MG/L)	DISSOLVED POTASSIUM (K) (MG/L)	BICARBONATE (HCO3) (MG/L)	CARBONATE (CO3) (MG/L)	ALKALINITY AS CACO3 (MG/L)	DISSOLVED SULFATE (SO4) (MG/L)
OCT. 05...	8.6	14	60	8	34	80	810	4.4	1540	143	1500	510
NOV. 10...	20	17	70	50	68	84	360	3.6	1050	15	886	380
DEC. 07...	18	18	70	50	59	92	690	3.9	1790	0	1470	450
JAN. 16...	12	17	120	40	71	79	480	4.1	1210	55	1080	400
FEB. 08...	16	18	60	30	76	74	200	3.1	708	0	581	350
MAR. 06...	27	15	60	20	34	79	400	6.2	1080	0	886	370
APR. 05...	18	15	40	0	67	88	380	3.0	1020	0	837	450
MAY 24...	75	17	50	10	69	66	210	4.0	701	0	575	300
JUNE 14...	47	19	50	20	68	88	390	4.5	1040	0	853	460
JULY 12...	19	16	150	20	58	100	580	4.8	1460	0	1200	580
17...	42	20	100	10	74	110	460	4.5	1070	0	878	580
27...	63	20	120	20	77	89	290	3.3	802	0	658	420
AUG. 30...	49	20	40	10	68	82	300	3.4	788	0	646	440

DATE	DISSOLVED CHLORIDE (CL) (MG/L)	DISSOLVED FLUORIDE (F) (MG/L)	DISSOLVED NITRITE PLUS NITRATE (N) (MG/L)	DISSOLVED ORTHO. PHOSPHORUS (P) (MG/L)	DISSOLVED SOLIDS (SUM OF CONSTITUENTS) (MG/L)	DISSOLVED SOLIDS (TONS PER DAY)	HARDNESS (CA,MG) (MG/L)	NONCARBONATE HARDNESS (MG/L)	SODIUM ADSORPTION RATIO	SPECIFIC CONDUCTANCE (MICROMHOS)	PH (UNITS)	TEMPERATURE (DEG C)
OCT. 05...	110	7.0	.01	.08	2470	57.4	410	0	17	3531	8.7	8.5
NOV. 10...	50	1.2	.30	.03	1500	81.0	520	0	6.9	2240	8.5	.0
DEC. 07...	120	2.2	.55	.08	2320	113	530	0	13	3360	7.9	.0
JAN. 16...	69	1.6	.50	.07	1770	57.3	500	0	9.3	2570	8.4	.0
FEB. 08...	16	.8	.58	.05	1090	47.1	490	0	3.9	1640	8.2	.0
MAR. 06...	53	1.4	.45	.06	1490	109	410	0	8.6	2200	8.1	5.0
APR. 05...	55	1.3	.29	.06	1560	75.8	530	0	7.2	2210	8.1	1.0
MAY 24...	27	.8	.65	.03	1040	211	440	0	4.3	1460	8.0	12.0
JUNE 14...	41	1.3	.40	.09	1590	202	530	0	7.4	2280	8.3	14.5
JULY 12...	75	1.7	.13	.06	2140	110	560	0	11	3070	8.3	15.0
17...	46	1.3	.27	.05	1830	208	640	0	7.9	2500	8.2	20.0
27...	31	.8	.79	.03	1330	226	560	0	5.3	1900	8.1	17.0
AUG. 30...	35	.9	.71	.05	1340	177	510	0	5.8	1860	8.1	13.0

SOURCE: Weeks and Welder, 1974, p. 78.

TABLE 3-4

WATER QUALITY OF YELLOW CREEK NEAR WHITE RIVER

PERIOD OF RECORD.--October 1972 to September 1973.

DATE	SPECIFIC CONDUCTANCE (MICROMHOS)	DISSOLVED SOLIDS (SUM OF CONSTITUENTS) (MG/L)	ALKALINITY AS CACO3 (MG/L)	DISSOLVED SILICA (SIO2) (MG/L)	TOTAL ALUMINUM (AL) (UG/L)	DISSOLVED ALUMINUM (AL) (UG/L)	TOTAL IRON (FE) (UG/L)	DISSOLVED IRON (FE) (UG/L)	DISSOLVED MANGANESE (MN) (UG/L)	DISSOLVED CALCIUM (CA) (MG/L)	DISSOLVED MAGNESIUM (MG) (MG/L)	DISSOLVED SODIUM (NA) (MG/L)
MAY , 1972 16...	3920	--	--	--	--	--	--	10	0	--	--	--
AUG., 1973 01...	3900	3070	1920	2,9	20	20	140	120	30	10	120	1000

DATE	DISSOLVED LEAD (PB) (UG/L)	DISSOLVED MERCURY (HG) (UG/L)	DISSOLVED NICKEL (NI) (UG/L)	DISSOLVED SILVER (AG) (UG/L)	DISSOLVED ZINC (ZN) (UG/L)	TOTAL BARIUM (BA) (UG/L)	DISSOLVED BORON (B) (UG/L)	TOTAL LEAD (PB) (UG/L)	TOTAL LITHIUM (LI) (UG/L)	TOTAL MOLYBDENUM (MO) (UG/L)	DISSOLVED SELENIUM (SE) (UG/L)	TOTAL STRONTIUM (SR) (UG/L)
MAY , 1972 16...	2	.0	2	0	10	--	--	--	--	--	--	--
AUG., 1973 01...	--	--	--	--	--	0	920	<50	180	26	4	2800

DATE	DISSOLVED POTASSIUM (K) (MG/L)	BICARBONATE (HCO3) (MG/L)	CARBONATE (CO3) (MG/L)	DISSOLVED SULFATE (SO4) (MG/L)	DISSOLVED CHLORIDE (CL) (MG/L)	DISSOLVED FLUORIDE (F) (MG/L)	BROMIDE (BR) (MG/L)	DISSOLVED NITRITE PLUS NITRATE (N) (MG/L)	DISSOLVED ORTHO, PHOSPHORUS (P) (MG/L)	DISSOLVED ARSENIC (AS) (UG/L)	DISSOLVED CADMIUM (CD) (UG/L)	DISSOLVED COPPER (CU) (UG/L)
MAY , 1972 16...	--	--	--	660	--	--	--	--	--	4	0	2
AUG., 1973 01...	4,6	1690	323	590	180	3.0	.400	.01	,00	8	--	--

SOURCE: Weeks and Welder, 1974, p. 83.

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Conservation Board (Nos. 12, 31, 35, and 37). In addition, data relating to the two Federal Tracts, C-a and C-b, has been presented by the leasees, and is held at the Area Oil Shale Supervisor's Office in Grand Junction, Colorado. This information has been summarized in the Detailed Development Plans of each project. Three other significant geohydrologic investigations of parts of the Basin are known to have been performed.

i. Proposed USBM Demonstration Mine Site, Horse Draw. This investigation was performed in 1975 and 1976, and provides some data on conditions in the center of the Basin. Data is available, although not yet in published form.

ii. Superior Oil Studies. These studies were performed on Superior's properties in the north of the Basin between Piceance and Yellow Creeks. Some information is available in a paper (Weichman, 1974) but basic information is proprietary.

iii. Atomic Energy Commission Studies. As a part of the investigation for project Rio Blanco, extensive testing was performed in the south central area of the Basin, to the south of the junction of Piceance and Black Sulphur Creeks. Several published accounts of this study exist (e.g. Knutson, et al., 1973).

The general geohydrology of the Piceance Basin is that of a flat-lying sedimentary deposit. The main rock types making up the deposit (fine-grained sandstone, marlstone, kerogen-rich marlstone, and evaporites) have low to very low intact-rock permeabilities, and thus almost all permeability observed in the Basin rocks is fracture permeability or permeability caused by leaching of soluble salts from the rock mass. Permeabilities are somewhat anisotropic (different in different directions) along the bedding plane, and permeability normal to the bedding plane is believed to be several orders of magnitude less than that along the bedding. Significant permeabilities in the rock mass apparently occur only in the top 1,500 feet of the deposit. It is postulated that stresses at greater depth are high enough to seal any fractures which might occur as a result of tectonic movements.

In addition to the rock aquifers there are very limited unconsolidated aquifers in the alluvium of the creek valleys and gulches. However these are of very minor significance as far as the present study is concerned.

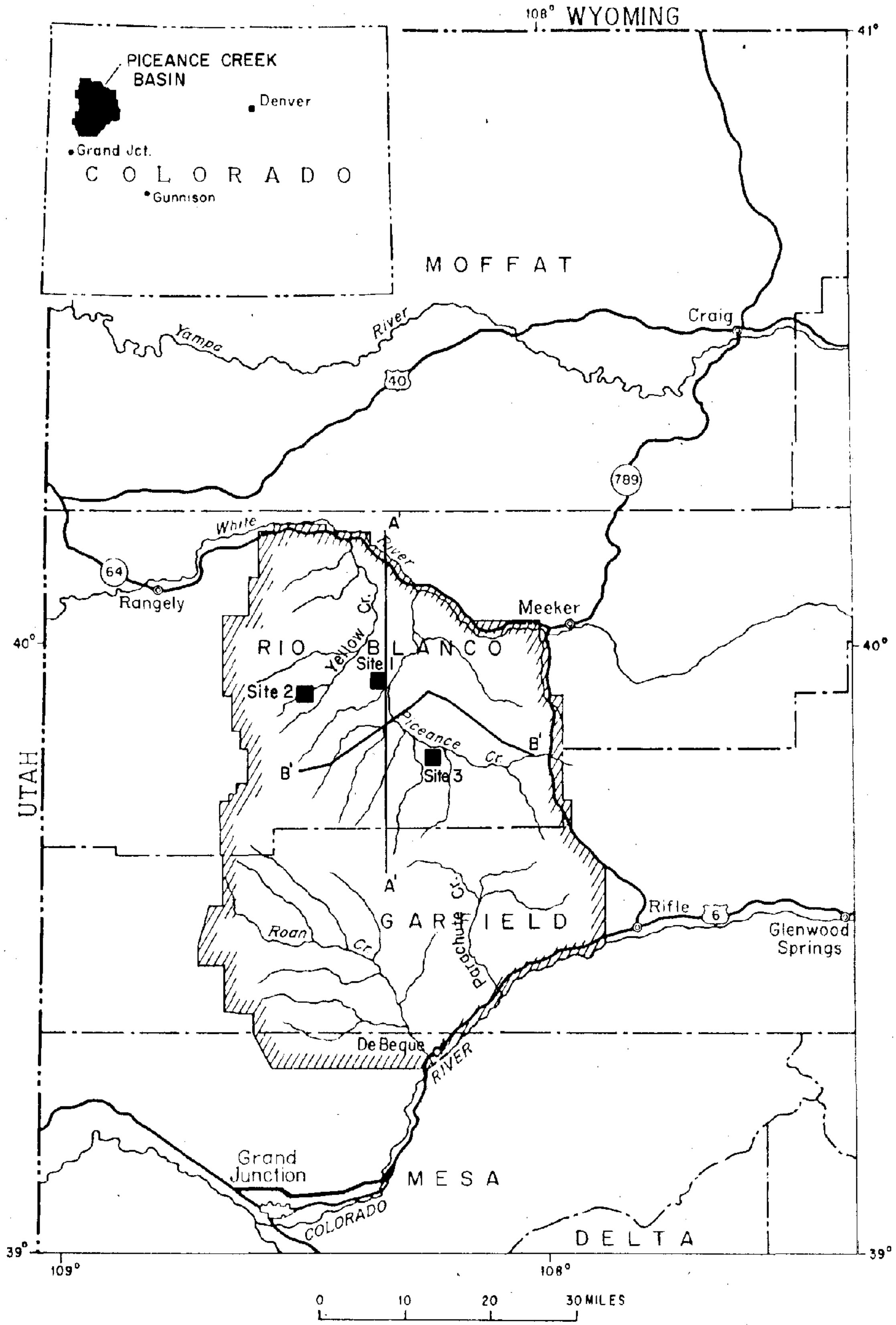
This section evaluates the general geohydrology of the Basin. Details of the data available at specific locations of the Basin, and numerical parameters to characterize the geohydrology models, are presented in Chapter 4.

Figure 3-7 shows a plan of the Basin and the locations of two sections. Section AA' is in a north-south direction, and Section BB' is approximately east-west. Figure 3-8 shows Section AA', while Figure 3-9 shows Section BB'. All three figures are generally as shown in Weeks, et al. (1974). The major elements of Basin geohydrology are evident from these sections.

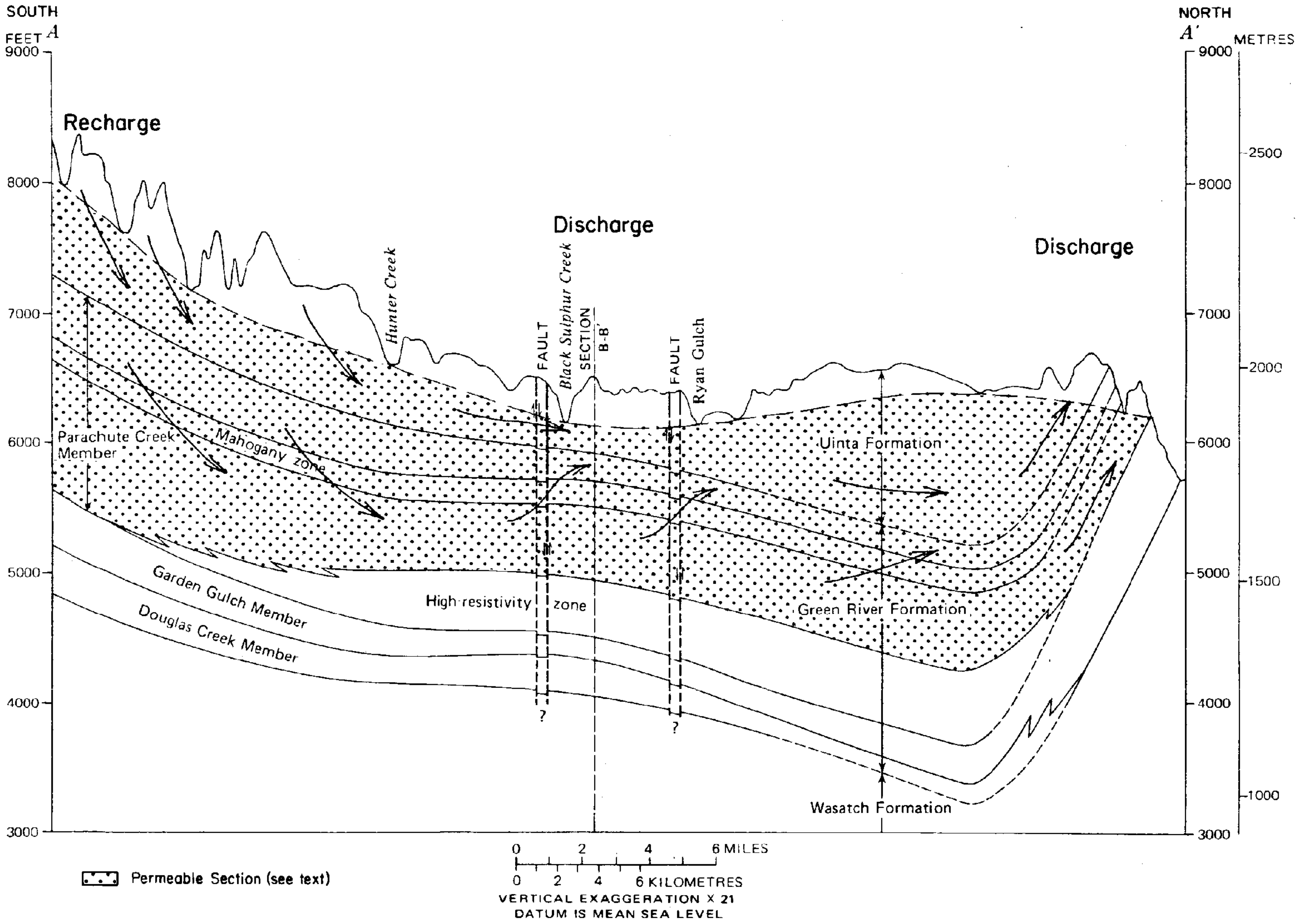
3.3.1 PERMEABILITY

The significantly permeable regions of the sections are shown shaded. They comprise the Unita formation sandstones, plus most of the marlstones of the Parachute Creek member of the Green River formation. In the center of the Basin there is

Figure 3-7 LOCATION OF THE PICEANCE CREEK BASIN AND STUDY SITES

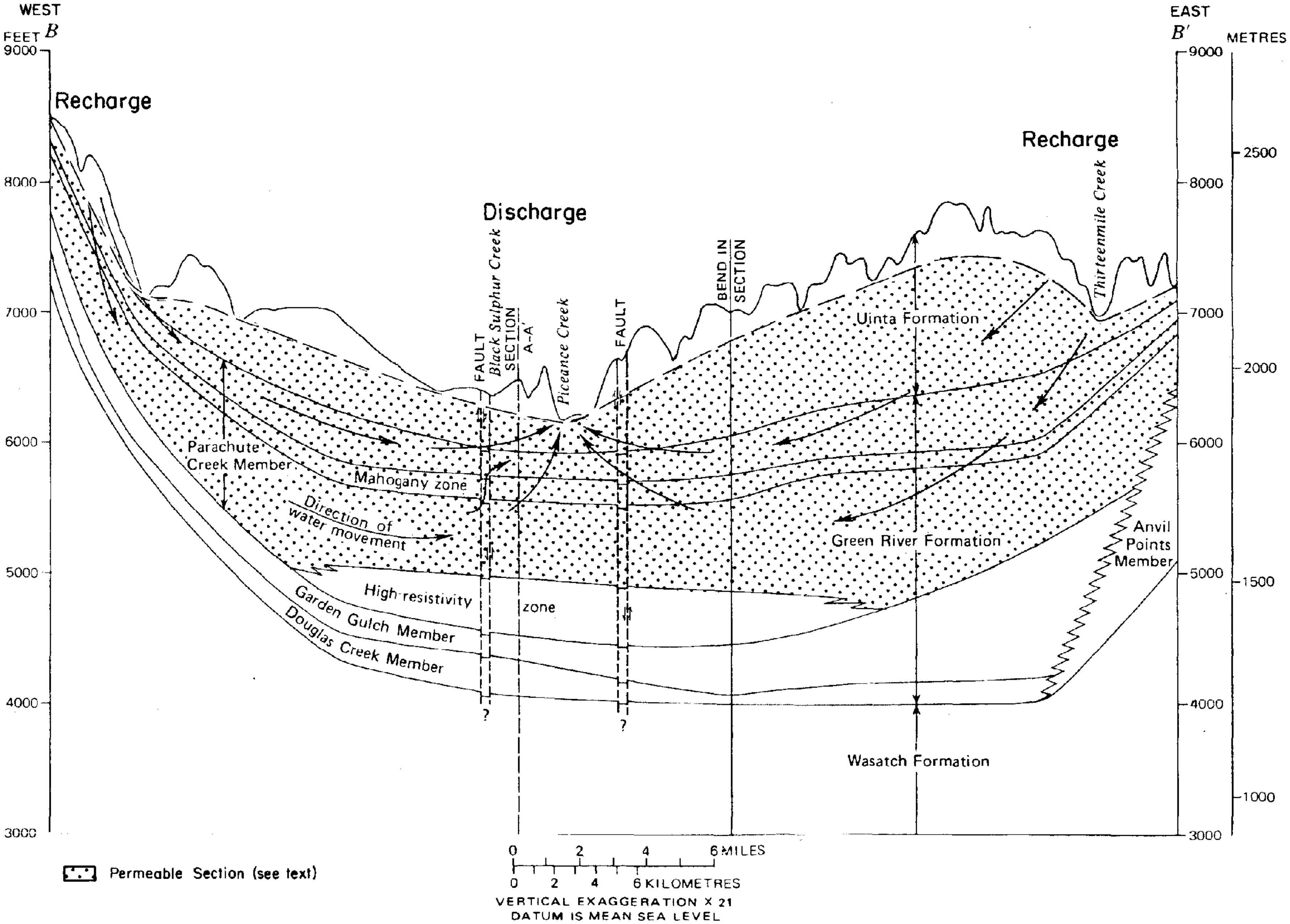

PICEANCE CREEK BASIN
Denver
Grand Jct.
COLORADO
Gunnison
108° WYOMING
41°
MOFFAT
Yampa River
Craig
40
789
White River
64
Rangely
Meeker
A'
Yellow Cr.
RIO BLANCO
Site 1
Site 2
Piceance Cr.
Site 3
B'
B'
UTAH
40°
40°
A'
Roan Cr.
GARFIELD
Parachute Cr.
Rifle
6
Glenwood Springs
De Beque
RIVER
Grand Junction
MESA
COLORADO
DELTA
39°
39°
109°
108°
0
10
20
30 MILES

After Coffin, et al., 1971


SOUTH
FEET A
9000
8000
7000
6000
5000
4000
3000
NORTH
A'
METRES
2500
2000
1500
1000
Recharge
Discharge
Discharge
Hunter Creek
FAULT
Black Sulphur Creek
SECTION B-B'
FAULT
Ryan Gulch
Parachute Creek Member
Mahogany zone
Uinta Formation
Green River Formation
High-resistivity zone
Garden Gulch Member
Douglas Creek Member
Wasatch Formation
?
?
Permeable Section (see text)
0 2 4 6 MILES
0 2 4 6 KILOMETRES
VERTICAL EXAGGERATION X 21
DATUM IS MEAN SEA LEVEL

After: Weeks, et al., 1974, p.6.

Figure 3-8 GEOHYDROLOGIC SECTION THROUGH THE PICEANCE BASIN (Section AA' in Figure 3-7)


WEST
B
FEET
9000
8000
7000
6000
5000
4000
3000
Recharge
Discharge
Recharge
EAST
B'
METRES
9000
8000
7000
6000
5000
4000
3000
2500
2000
1500
1000
FAULT
Black Sulphur Creek
SECTION A-A'
Piceance Creek
FAULT
BEND IN SECTION
Thirteenmile Creek
Uinta Formation
Parachute Creek Member
Mahogany zone
Direction of water movement
Green River Formation
Anvil Points Member
High-resistivity zone
Garden Gulch Member
Douglas Creek Member
?
?
Wasatch Formation
0 2 4 6 MILES
0 2 4 6 KILOMETRES
VERTICAL EXAGGERATION X 21
DATUM IS MEAN SEA LEVEL
Permeable Section (see text)

After : Weeks, et al., 1974, p.26.

Figure 3 – 9   GEOHYDROLOGIC SECTION THROUGH THE PICEANCE BASIN (Section BB' in Figure 3-7)

a highly saline zone at the base of the Parachute Creek member which shows up on resistivity logs as a high resistivity zone. Testing has demonstrated that this zone has very low permeability, and so this material is not included in the permeable section of the Basin.

The Garden Gulch member of the Green River formation lies beneath the Parachute Creek member. It is composed of a clayey oil shale, and is generally regarded as functionally impervious. The few meaningful tests of permeability of this unit support this interpretation.

Within the Parachute Creek member of the Green River formation there are numerous very persistent layers of high grade oil shale. The mechanical properties of oil shale suggest that joints which exist in high grade zones (30 gallon/ton or higher) may seal themselves due to creep. For this reason the Mahogany Zone, which is the thickest high grade zone in the Basin, has generally been regarded as a major aquitard, separating two "aquifers" of material with much higher vertical permeability than the Mahogany Zone. Although this is an attractive hypothesis, the testing performed on the Federal lease tracts suggests that the entire Parachute Creek member has very low vertical permeability, and that the Mahogany Zone vertical permeability is similar to that of the rest of the unit. Clearly more evaluation is required to confirm this theory, but it has important implications for analytical and conceptual evaluation of matters relating to Basin geohydrology.

The shape of the permeable zone is of considerable significance in this study. Section AA' shows the Basin rising gently southward from the depocenter, and rising abruptly northwards.

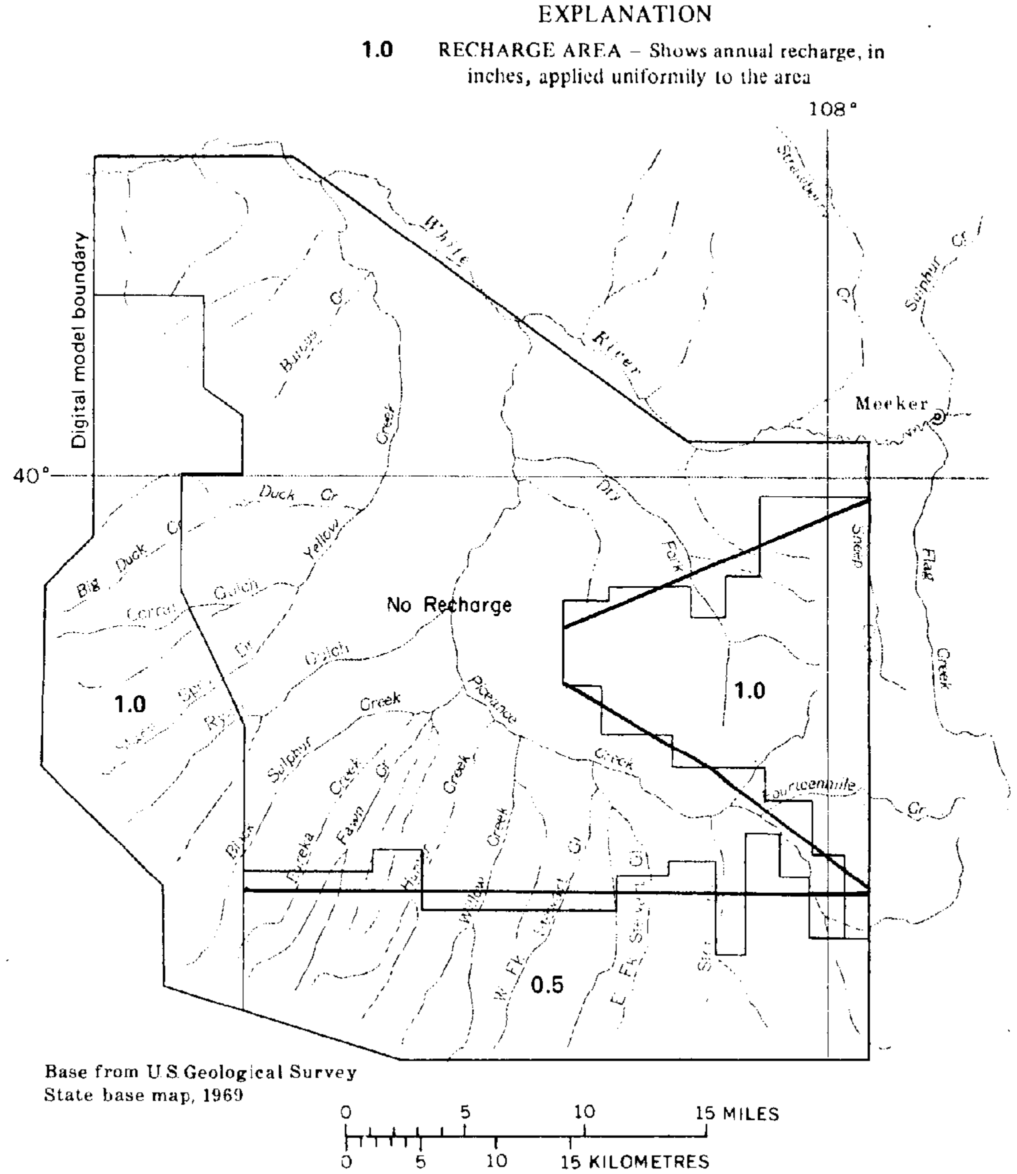
The base of the permeable unit is flatter than the Basin stratigraphy, due to the presence of the high resistivity saline zone. The impact of this northern upsweep in the Basin is to force groundwater flow to the surface, so that it flows out of the Basin primarily in the creeks, rather than by subsurface infiltration to White River to the north. Section BB' indicates that the permeable section is also dished in the east-west direction.

The sections show two faults. Once again it is not clear how significant these faults are from a geohydrologic standpoint. They are shown fully penetrating the Green River formation, but drilling on Tract C-a suggests that these features may not, in fact, penetrate further than the Mahogany Zone. If this were the case, their geohydrologic impact would be small, as they would not disturb the relatively low vertical permeability picture which has been demonstrated remote from the fault locations. It is quite possible that the few surface fault expressions in the Basin are relatively superficial remnants of differential rock consolidation and subsurface leaching.

3.3.2 RECHARGE AND DISCHARGE

As noted in Weeks, et al. (1974), the majority of the precipitation which falls in the Basin falls at higher elevations. An extensive study of groundwater recharge, performed by the Weeks group, concluded that the bulk of the infiltration of surface water to the groundwater system occurs at elevations above 7,000 feet. Some subsequent information gathered on C-b tract suggests that significant infiltration also occurs at lower elevations, but for the purposes of the present study the infiltration evaluation presented by Weeks, et al. (1974) will be used. Figure 3-10 shows the recharge pattern determined by Weeks, et al. (1974).

Figure 3-10 ESTIMATED RECHARGE RATES FOR PICEANCE BASIN


EXPLANATION
1.0 RECHARGE AREA – Shows annual recharge, in inches, applied uniformly to the area
108°
40°
Digital model boundary
White River
Meeker
Sulphur Cr
Strawberry Cr
Flag Creek
Sheep
Dry Fork
Duck Cr
Big Duck Cr
Yellow Creek
Corral Gulch
Ryan Gulch
Black Sulphur Creek
Eureka Creek
Fawn Cr
Hunter Creek
Willow Creek
Piceance Creek
Fourmile Cr
W. Fk. Stewart Gulch
E. Fk. Stewart Gulch
No Recharge
1.0
1.0
0.5
0 5 10 15 MILES
0 5 10 15 KILOMETRES

Base from U.S. Geological Survey
State base map, 1969

After: Weeks, et al., 1974, p.68.

The location and movement of recharge water is shown in the two sectional figures (Figures 3-8 and 3-9). The illustrated water movements have significant implications for piezometric conditions in the Basin, which are discussed in the next section.

Discharge of groundwater from the Basin occurs in creeks and gulches, with some discharge directly to the White River to the north of the Basin. The mechanism of discharge is self-evident from the sections.

3.3.3 PIEZOMETRIC CONDITIONS

The top of the zone of saturated rock will, for the purposes of this report, be termed the "water table". The reason for this somewhat circumspect definition of the concept is that the highly anisotropic nature of the Basin materials renders the term "water table" in its normal sense somewhat meaningless. What probably exists in reality are a series of perched aquifers of relatively small thickness (perhaps averaging tens of feet) separated by highly impervious, but very thin, rich oil shale stringers. Accordingly, there are unquestionably relatively high vertical head gradients in parts of the Basin, particularly in the recharge and discharge zones.

The "water table" location is largely conditioned by the elevation of the deeper gulches of the Basin, and by the major flowing creeks (Piceance, Yellow, Black Sulphur). The "water table" has been sketched on Section AA', but it must be cautioned that the actual field measurements of its location are very limited.

Head differences measured between different stratigraphic layers within the same borehole in the Basin tend to be low;

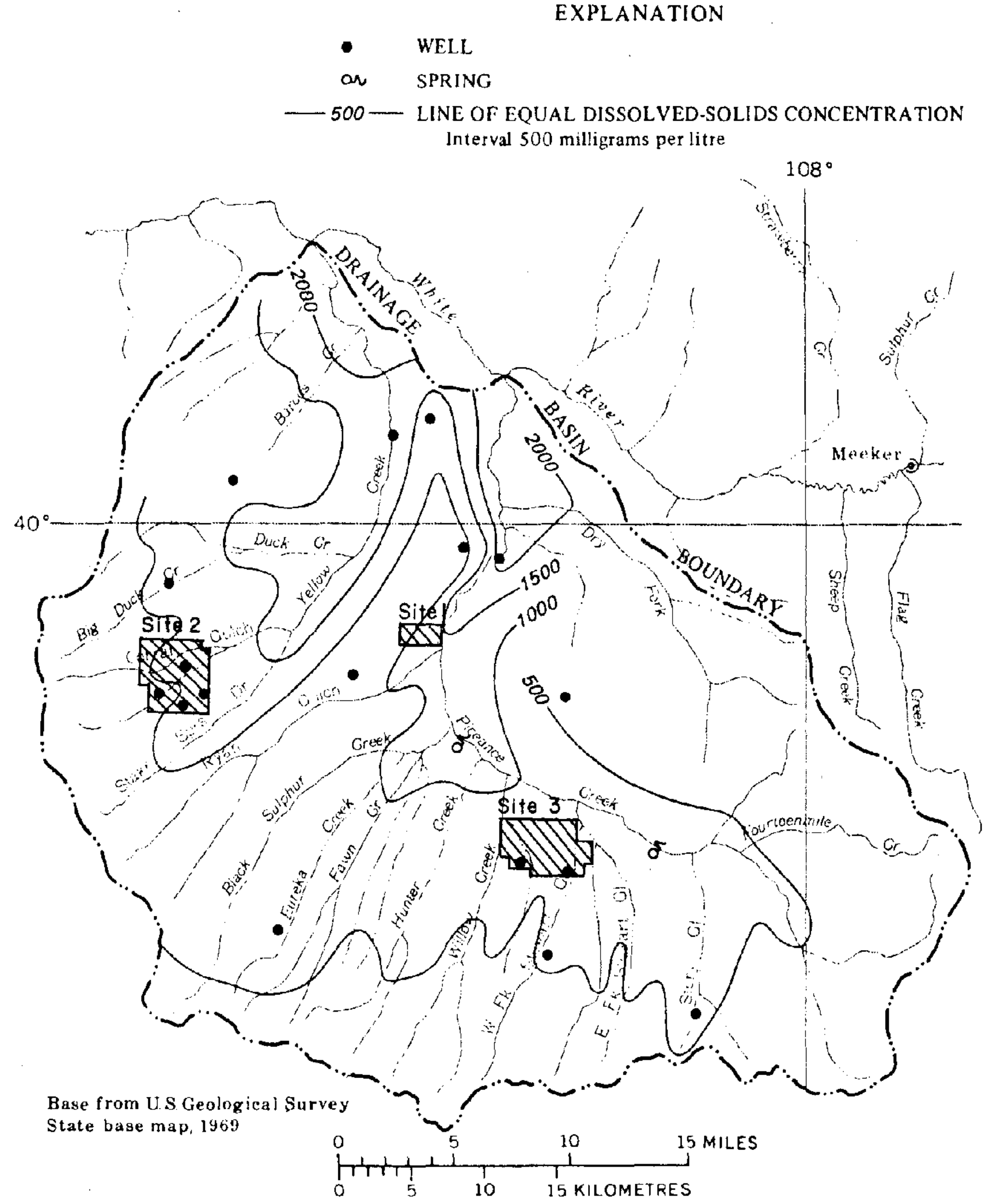
generally less than 100 feet. This is, perhaps, not a fair representation of the true position, as most of the few reliable measurements from which such a statement can be made are located midway between recharge and discharge areas, and thus it would not be expected that large head differences should exist. The major observed exception to this is found on the western edge of C-a tract, where the head difference between the top and bottom of the Parachute Creek member is of the order of 400 feet, with the upper piezometric elevation being higher. As this location is clearly in a recharge zone of the Basin, this result is in accordance with expectation.

3.3.4 GROUNDWATER QUALITY

As the Piceance Basin is made up of a saline mineral suite, it is hardly surprising to find that the quality of the groundwater is frequently not high. Weeks, et al. (1974) present contours of water quality for the stratigraphic layers above and below the Mahogany Zone, and these are presented in Figures 3-11 and 3-12 respectively. It should, however, be noted that the contoured values do not agree with those observed at Site 1 of this study (the proposed USBM demonstration mine site) so they should be treated with considerable caution. As can be seen, the concentration of dissolved solids increases in the direction of groundwater flow, presumably due to active dissolution of the saline mineral-bearing rocks present in the Basin.

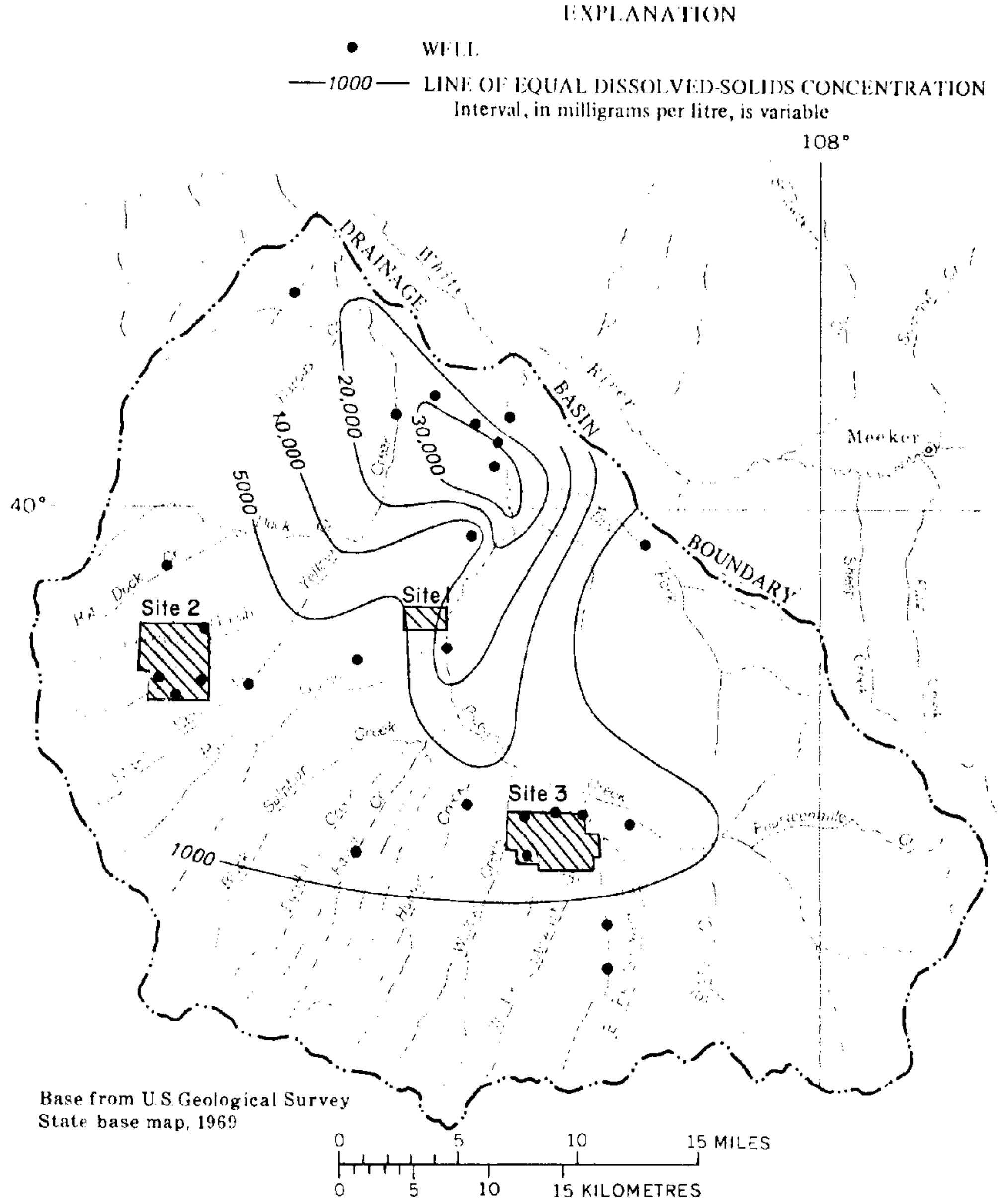
The principal cation is bicarbonate, and the principal anions are sodium and magnesium. Table 3-5 presents typical water chemistry data for the Basin. The fluoride ion concentration is of concern from an environmental and public health standpoint, and is a critical determinant in the cost of groundwater purification (see Chapter 6).

Figure 3-11 CONCENTRATION OF DISSOLVED SOLIDS IN THE UPPER AQUIFER, MAY-SEPTEMBER 1973.


EXPLANATION
● WELL
SPRING
—500— LINE OF EQUAL DISSOLVED-SOLIDS CONCENTRATION
Interval 500 milligrams per litre
108°
40°
DRAINAGE
BASIN
BOUNDARY
White River
Meeker
Strawberry Cr
Sulphur Cr
Sheep Creek
Flag Creek
Dry Fork
Fourteenmile Cr
2000
1500
1000
500
Site 1
Site 2
Site 3
Big Duck Cr
Duck Cr
Barcus Creek
Yellow Creek
Gulch
Stake Springs Draw
Ryan Gulch
Piceance Creek
Black Sulphur Creek
Eureka Cr
Fawn Cr
Hunter Creek
Willow Creek
W. Fk
E. Fk
Stewart Gl
Base from U.S. Geological Survey
State base map, 1969
0 5 10 15 MILES
0 5 10 15 KILOMETRES

Source: Weeks, et al., 1974, p.40.

Figure 3-12 CONCENTRATION OF DISSOLVED SOLIDS IN THE LOWER AQUIFER, MAY-SEPTEMBER 1973.


EXPLANATION
● WELL
—1000— LINE OF EQUAL DISSOLVED-SOLIDS CONCENTRATION
Interval, in milligrams per litre, is variable
108°
40°
DRAINAGE
BASIN
BOUNDARY
White
River
Meeker
30,000
20,000
10,000
5000
1000
Site 1
Site 2
Site 3
Creek
Base from U.S. Geological Survey
State base map, 1969
0 5 10 15 MILES
0 5 10 15 KILOMETRES

Source: Weeks, et al., 1974, p. 42.

TABLE 3-5

SUMMARY OF WATER-CHEMISTRY DATA FROM WELLS IN THE ALLUVIAL, UPPER, AND LOWER AQUIFERS, PICEANCE BASIN

Chemical Constituent	Concentrations (mg/l) in each aquifer[1] Alluvial[2]	 Upper[3]	 Lower[4]
Potassium	2.5	1.5	11
Sodium	490	210	3,980
Calcium	57	50	7.4
Magnesium	80	60	9.5
Bicarbonate	1,220	550	9,100
Chloride	42	16	690
Sulfate	430	320	80
Fluoride	4.6	1.4	28
Dissolved solids	1,750	960	9,400

[1] Data from Ficke, et al. (1974) and from Weeks and Welder, 1974.

[2] Based on 27 samples from wells located in Figure 25 in Weeks, et al., 1974.

[3] Based on 17 samples from wells located in Figure 27 in Weeks, et al., 1974.

[4] Based on 27 samples from wells located in Figure 29 in Weeks, et al., 1974.

SOURCE: Weeks, et al., 1974, p.35.

CHAPTER 4
SPECIFIC GEOHYDROLOGY MODELS

Throughout this project it is necessary to make quantitative evaluations of the geohydrologic effects of mining and groundwater extraction. For this purpose four geohydrology models have been developed.

The first three models are intended to characterize the geohydrologic conditions local to each of the three sites specified in the contract. This chapter explains the basis for the choice of each specific site area, details the available information, and presents the resulting geohydrologic model for the site locality.

In addition to local analyses, it is necessary to perform Basin-wide analyses to check the validity of the local analysis boundary conditions, and to evaluate Basin-wide impacts of the various mining, dewatering and abandonment plans. Accordingly, the fourth model is a simple Basin model, which integrates surface and subsurface flows.

This chapter begins by explaining the general data requirements for these models and then presents each model in turn.

4.1 DATA REQUIREMENTS AND AVAILABILITY

In order for this study to be successfully performed, it is necessary to have an adequate understanding of the geohydrology of the Basin, in particular the following parameters:

i. Horizontal Permeability. "Horizontal" permeability is defined, for the purposes of this study, as the permeability of the rock units parallel to bedding. In general, the bedding in the Basin is approximately horizontal, locally reaching 15° inclination. Horizontal permeability is an important determinant of mine inflow and of regional effects of mining. The horizontal permeability in the Basin is anisotropic (that is the horizontal permeability is greater in some directions than in others) and this has some effect on the results of analyses.

ii. Vertical Permeability. "Vertical" permeability is defined, for the purposes of this study, as the permeability of the rock units normal to the bedding. Vertical permeability is a very important parameter in mine inflow and creek impact evaluations.

iii. Specific Yield. This parameter relates to the amount of available water in the formation, and thus is a critical parameter for this study.

iv. Specific Storage. This parameter influences flows to the mine at early times, or where a high degree of confinement of water-bearing formations occurs.

v. Recharge Rate. This defines the amount of water which is influent to the Basin system, which in turn defines the maximum amount of water which can be removed from the mines in the steady state condition.

The available information relating to the Basin geohydrology has been obtained using a variety of testing techniques, some more satisfactory than others.

4.1.1 Permeability Testing

The permeability of the formations in the Basin has been evaluated by the following methods:

i. Pumping Tests. This method involves pumping water from one hole (or well) and observing the response to this pumping at another well or piezometer. It is the most sensitive and, when properly analyzed, the most reliable measure of bulk horizontal permeability of the rock. Attempts to measure vertical permeability using pump tests have also been made with some success.

ii. Injection Tests. The most reliable test of localized permeability of a specific stratum is (arguably) the injection test. In this test, water is injected into the specific portion of the formation via an isolated section of borehole. A considerable number of these tests have been performed in the Basin, with mixed success. The most thorough test was performed on Tract C-b in SG-17, where 38 tests over 2,000 feet of hole fairly accurately defined the permeability profile with depth.

iii. Informal Pumping Tests. In this test the water is blown from a drillhole using high pressure air. The recovery of the water level in the hole after the jetting is terminated is then analyzed to obtain an approximate average permeability. This test has many unmeasurable secondary influences, and is regarded as a second-order or indicative test only. However, by far the majority of testing in the Basin has been of this type.

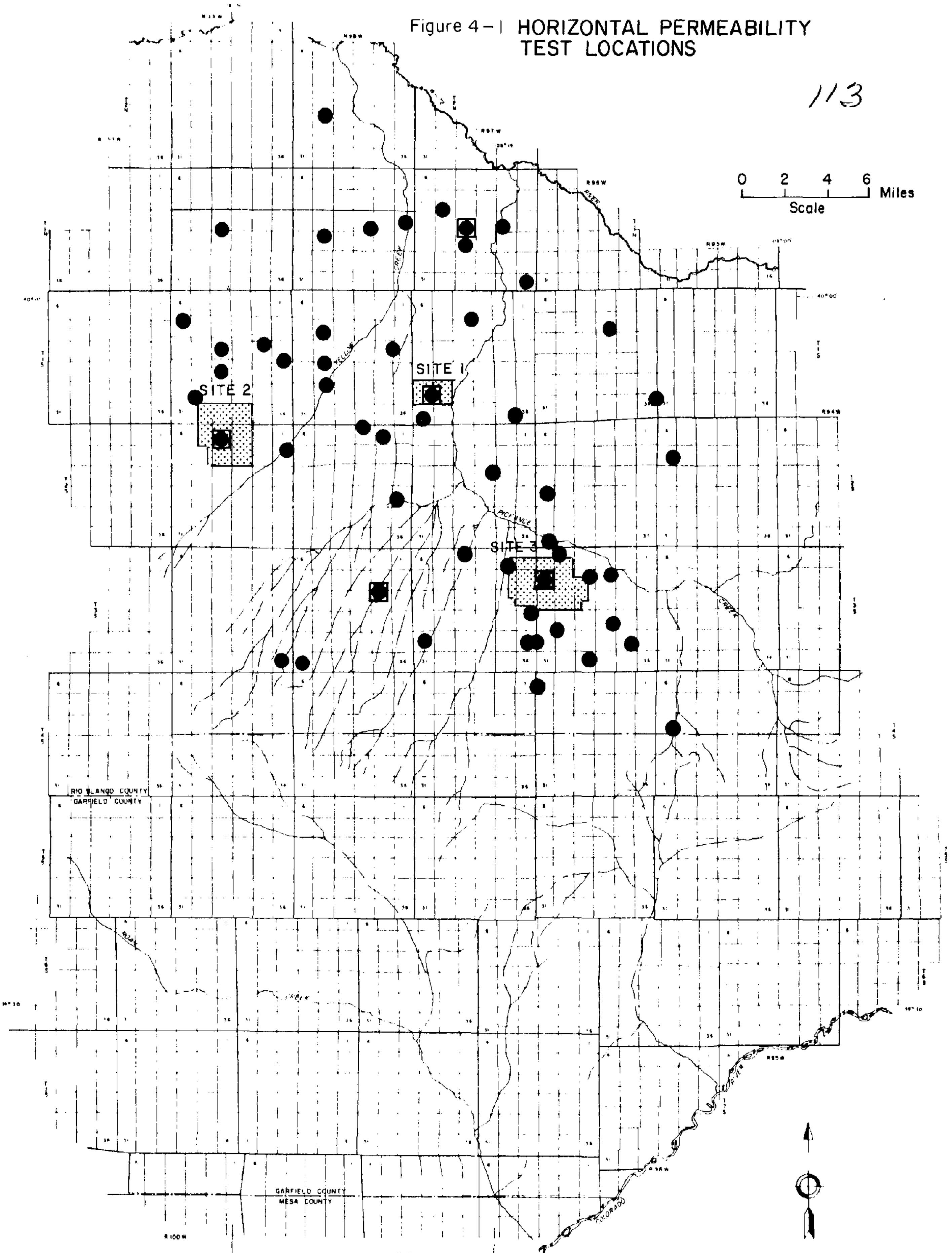
iv. Tests During Drilling. Many of the holes in the Piceance Basin were drilled using the air-mist technique. This technique blows the drilling cuttings and any inflow to the hole out at the surface using air pressure. As a result, a continuous record of water flow as a function of depth can be obtained, and changes in this flow rate can be used to indicate the zones of high permeability encountered during drilling. This information can be augmented by recording the temperature and conductivity of the expelled water as the hole is drilled, to better define the nature of changes in inflow to the hole. Again, these tests are of second-order or indicative value only.

Despite the extensive geohydrologic investigations of the Basin over the last 20 years, the reliable data from which the three dimensional geohydrology can be evaluated is very limited. Figure 4-1 shows the locations of test sites where meaningful quantitative evaluation of permeability of at least one section of the stratigraphy has been performed (pumping tests or significant injection tests). Also shown on the figure are the locations of test sites where useable secondary information has been obtained (informal pumping tests and/or water production during drilling).

A final aspect of horizontal permeability is anisotropy. Two series of tests, on the two Federal Tracts, have demonstrated significant anisotropy in the material above the Mahogany Zone. No other data is known to exist on this parameter.

The above data refers to permeability normal to the investigatory holes, which means along the bedding of the formation. However, an equally important variable is vertical permeability, and

Figure 4-1 HORIZONTAL PERMEABILITY TEST LOCATIONS


0 2 4 6 Miles
Scale
SITE 1
SITE 2
SITE 3
RIO BLANCO COUNTY
GARFIELD COUNTY
GARFIELD COUNTY
MESA COUNTY
COLORADO
R100W
R99W
R98W
R97W
R96W
R95W
R94W

LEGEND

▣ Locations with first order permeability test data

● Locations with second order permeability test data

Golder Associates

this has only been observed in three locations to our knowledge, namely Site 1, C-a Tract and C-b Tract.

In summary, the lack of believable vertical profiles of horizontal permeability, and of more than a handful of useable measures of vertical permeability, makes interpretation of the Basin geohydrology for mine inflow analysis extremely difficult. We believe that a relatively inexpensive test system for both parameters is available and should be developed and used in the Basin.

4.1.2 Piezometric Testing

Piezometric information in the Basin has been obtained from two main sources:

i. Open Holes. These holes may penetrate several thousand feet of different strata, and the water level in the hole is thus a result of the dynamic equilibrium set up by flow between strata of different static piezometric heads. Some attempt to account for this has been made by measuring the water movement in such holes, but in general the information from open holes must be regarded as of second-order accuracy.

ii. Piezometers. To our knowledge there are no true piezometers in the Piceance Basin. The closest approach to this type of completion is found in wells which are connected to only one geological formation, or part of one geological formation. In general, several hundred feet of the hole is effectively open, and thus the resulting head readings must be regarded as averages for the open

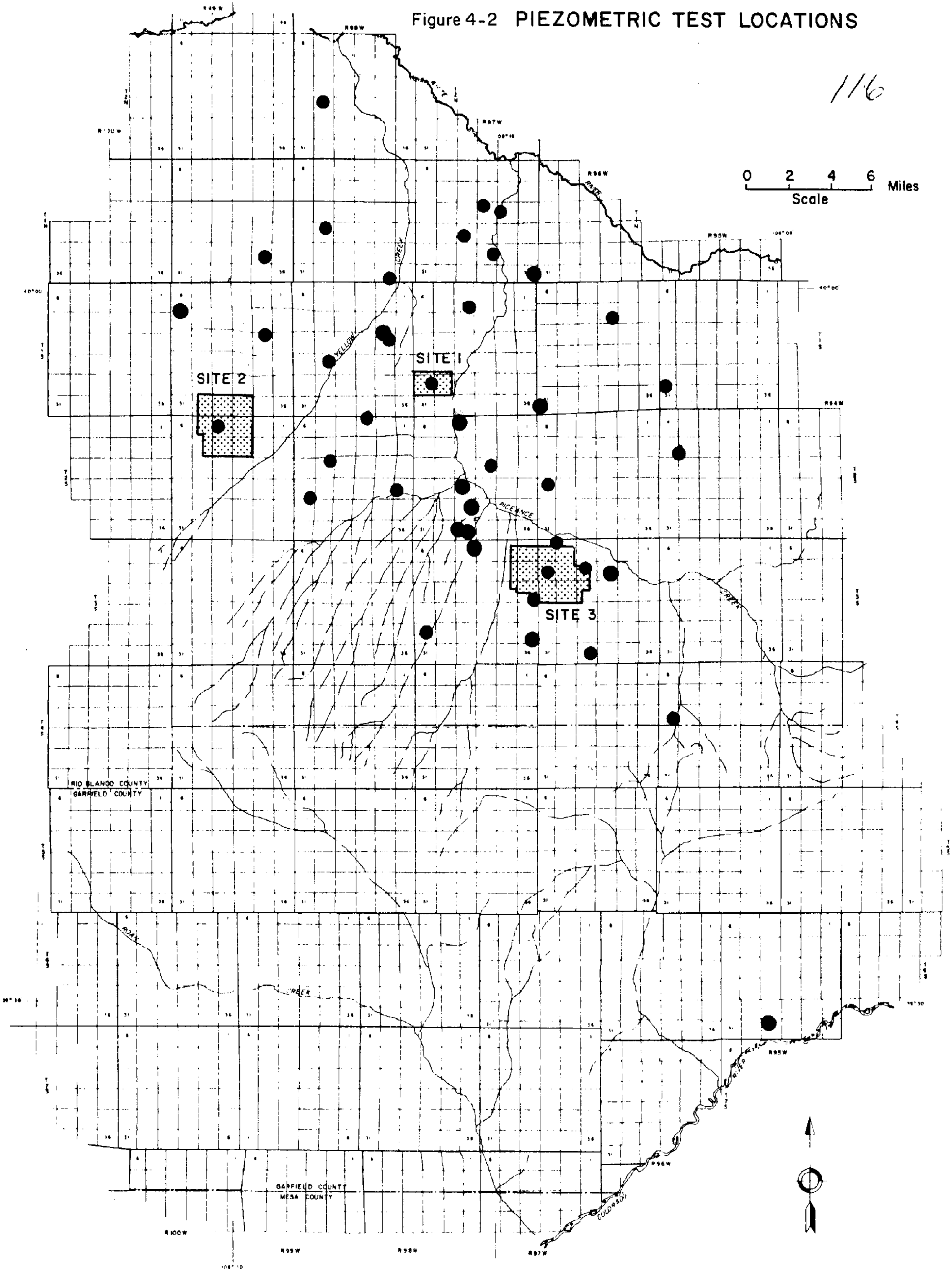
> interval. All holes in the Basin are now believed to be completed in this way, or plugged with concrete in order to prevent communication between different strata.

Piezometric data obtained in the Basin must be evaluated carefully. Particularly in the Uinta Formation, it is highly likely that a complex system of perched aquifers disguises the real piezometric conditions, especially when open holes are used to evaluate the piezometric heads in this unit. A further problem with piezometric readings is their extreme sensitivity to other drilling or pumping. In general, water pressures in the formations will not "settle down" for several months after any disturbance several miles distant from the piezometer. Thus piezometric data obtained during an on-going drilling or testing program is probably not indicative of anything approaching static conditions.

Once again, despite extensive effort, the available information on piezometric conditions in the Basin is relatively limited. Figure 4-2 shows the density of data points of reliable information.

The vertical distribution of piezometric data points is extremely poor, with most being completed either above or below the Mahogany Zone, and very few completed in any of the significantly permeable zones near the Blue Marker. Also, holes completed in the Uinta Formation alone are very uncommon, despite its obvious importance to environmental and mine inflow considerations. Recent work by the USGS to rectify this situation has been valuable, but we believe that a cheap, multiple piezometer installation must be developed and installed at a number of locations in the Basin before a good understanding of the Basin geohydrology can be obtained.

Figure 4-2 PIEZOMETRIC TEST LOCATIONS



SITE 1
SITE 2
SITE 3
0 2 4 6 Miles
Scale
YELLOW CREEK
PICEANCE CREEK
RIO BLANCO COUNTY
GARFIELD COUNTY
GARFIELD COUNTY
MESA COUNTY
COLORADO RIVER
R 100 W
R 99 W
R 98 W
R 97 W
R 96 W
R 95 W
R 94 W

4.1.3 Other Parameters

Three other parameters which are needed for meaningful characterization of the geohydrologic regime in the Basin are specific storage, specific yield and recharge rate.

i. Specific Storage. This parameter is defined as the volume of water which is released from a unit volume of material when the head of water in the material undergoes a unit change. The dimension of specific storage is reciprocal length. It is equivalent to the storage coefficient per unit thickness of aquifer for a confined aquifer situation. Accordingly, it has been evaluated in each of the pumping tests performed in the Basin (Figure 4-1), and appears to be extremely constant for all data obtained.

ii. Specific Yield. This parameter is also known as the drainable porosity of a material. It is critical in determining the extent of the available groundwater resource in the Basin, and has a significant, although somewhat indirect, impact on mine inflow. It is also important in assessing the environmental impact of the various mining schemes on the geohydrology of the Basin. No known directly-obtained information is available for this parameter in the Basin.

iii. Recharge Rate. The rate of groundwater recharge from surface sources is a critical determinant of the conditions which exist in the Basin in the steady state. This has been estimated from surface runoff/evapotranspiration studies (Weeks, et al., 1974).

4.2 SITE 1 MODEL

Site 1 was chosen by the Bureau to correspond to the location of the proposed demonstration mine which is in process of development at present. The location is shown on Figure 4-3 and is very near the depositional center of the Basin.

4.2.1 Geology of Site 1

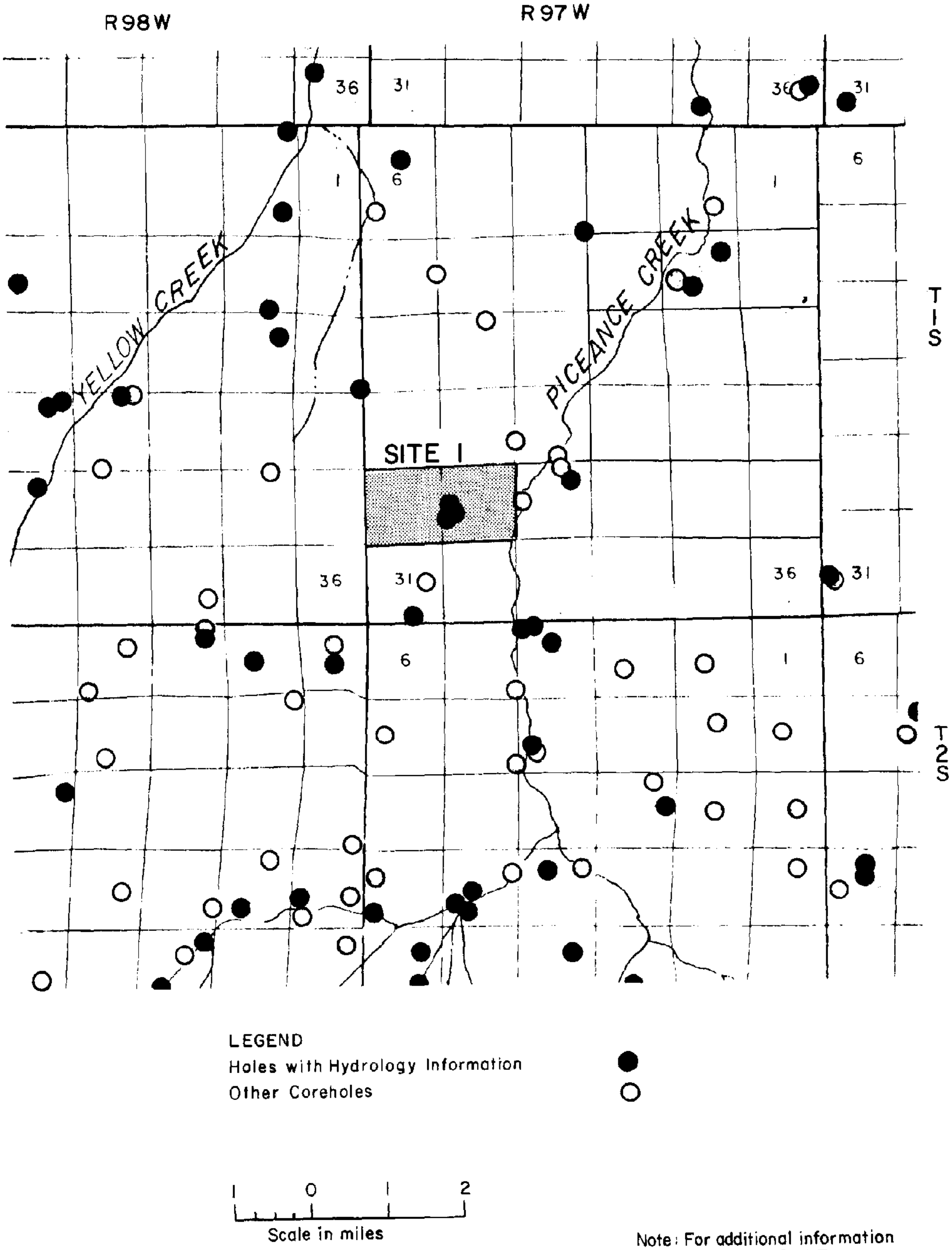
Four holes have been drilled in the near vicinity of the proposed site, as shown in Figure 4-4. Additionally, two existing holes are located approximately three miles either side of the site in a northerly and southerly direction. From these holes, all but one of which were cored, a reasonably detailed geological picture has been generated. This geology is shown in Figure 4-5 and is taken from material presented in a report by Golder Associates (1977).

4.2.2 Hydrology of Site 1

Of the drill holes mentioned above, a variety of hydrologic data was obtained (Weeks, 1976; Golder Associates, 1977):

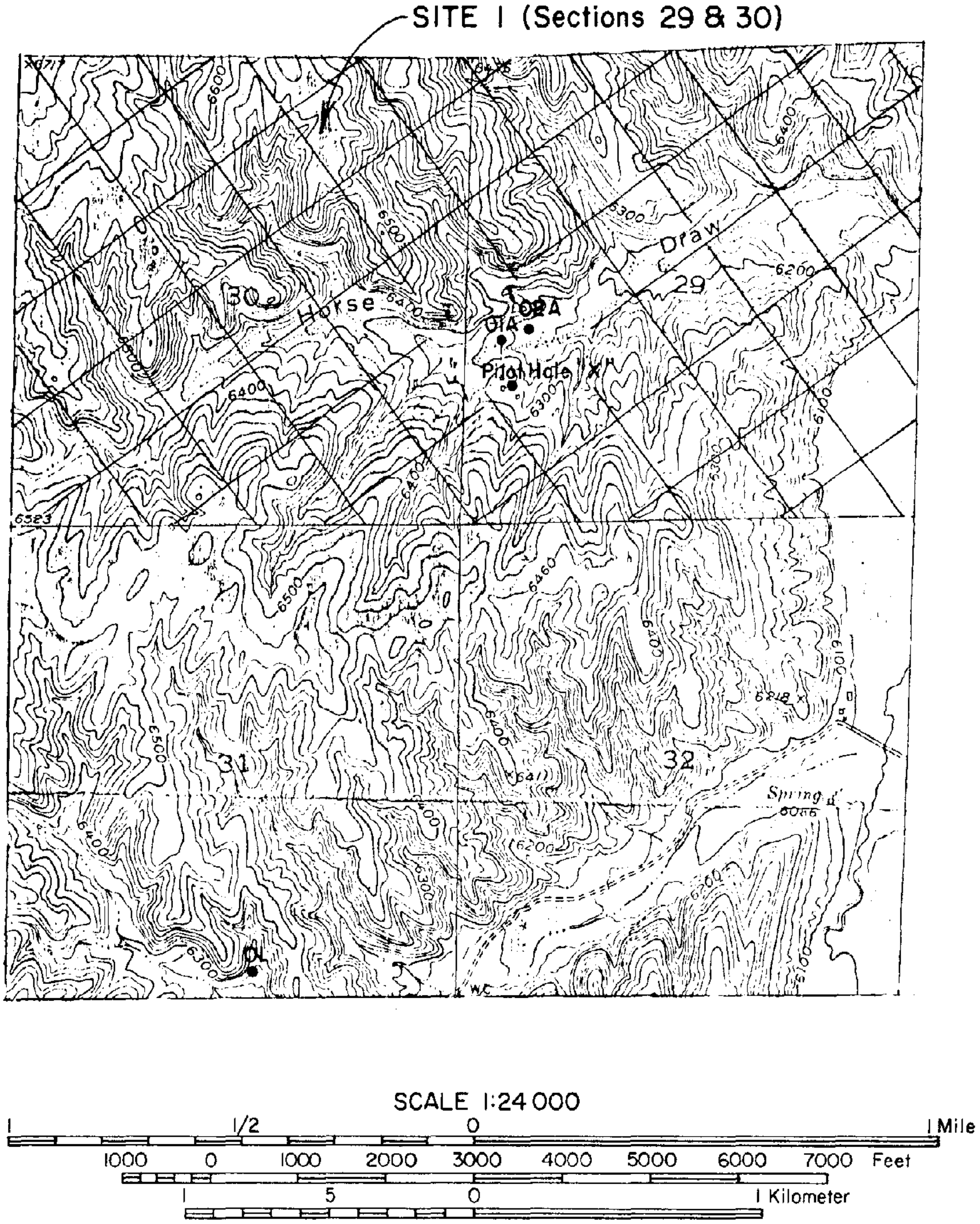
a. Information Taken During Drilling. All holes except Pilot Hole "X" were drilled using the air-mist technique, and data on water flow rate, temperature, and conductivity were taken as a function of hole depth. This information relates to some extent to hydrology. Additionally, a series of informal pump tests were conducted when the holes reached various specified depths, and the results of the tests have been analyzed to produce average permeability values. Both of the above sets of

Figure 4-3 SITE I LOCATION AND DRILL HOLE INTENSITY


R98W
R97W
36
31
1
6
36
31
1
6
YELLOW CREEK
PICEANCE CREEK
SITE I
36
31
36
31
6
1
6
T
1
S
T
2
S
LEGEND
Holes with Hydrology Information ●
Other Coreholes ○
1 0 1 2
Scale in miles

Note: For additional information
See APPENDIX F

Figure 4-4 LOCATION OF COREHOLES IN VICINITY OF SITE I


SITE I (Sections 29 & 30)
6600
6500
6400
6300
6200
6100
6460
6523
6218
6411
6066
Horse
Draw
Spring
30
29
31
32
ORA
OIA
Pilot Hole "X"
SCALE 1:24 000
1 1/2 0 1 Mile
1000 0 1000 2000 3000 4000 5000 6000 7000 Feet
1 5 0 1 Kilometer

Contour Interval 20 Feet
Datum is Mean Sea Level
(PART OF T1S, R97W, 6th P.M.)

Base Map: USGS topographic map (Square S Ranch, Colorado quadrangle)

Figure 4-5 GEOHYDROLOGY MODEL OF SITE I

Geol. Unit		Feature Description	Elevation (Above M.S.L.)	Permeability		Drainable Porosity	Specific Storage $(ft.^{-1})$
				Horizontal (ft./day)	Vertical (ft./day)		
Uinta Formation		Ground Surface	6225				
		Water Table	6100				
		Uinta Sandstone		0.89	▦ 0.03	▧ 0.10	3×10^{-7}
			5500				
GREEN RIVER FORMATION	Parachute Creek Member	Upper Parachute Cr. Member		5.71	▦ 0.03	▦ 0.01	3×10^{-7}
		A Groove	5350				
		Mahogany Marker	5300	▧ 1.74	0.009	▦ 0.01	▧ 3×10^{-7}
		B Groove	5150				
				0.53	▦ 0.003	▦ 0.025	▧ 3×10^{-7}
		Horizon X	4850				
			4450	▧ 0.003	▦ 0.0003	▦ 0.01	▦ 3×10^{-7}
		R-4 Zone					
			4200				
	Garden Gulch Member	Blue Marker	3925				
		Orange Marker	3750	▧ Assumed Functionally Impervious			

NOTES:

1. Geology based on USBM 01-A and USBM 02-A.
2. Hydrology data primarily from USBM 01-A, USBM 02-A, and USBM pilot hole "X" testing.
3. All elevations rounded to nearest 25 feet.
4. Not to scale.
5. Quality of information for the purposes of this study:
   - □ "Based on acceptable test data"
   - ▧ "Estimated or based on poor data"
   - ▦ "Experiential guess"
6. Available data indicates that this model is not valid at points 3 to 4 miles distance from Horse Draw. It should be used only with great caution, and with a complete understanding of the data upon which it is based.
7. Horizon X is defined in section 4.5.1.

information are regarded as being of second-order accuracy, providing indications of hydrologic conditions rather than hard numerical data.

b. Pumping Tests. After coring was performed in holes USBM 01-A and USBM 02-A, two pump tests were performed, with pumping in USBM 02-A and observation in two completed intervals of USBM 01-A. The intervals tested were from the water table to the Mahogany Zone in the first test, and from the Mahogany Zone to the saline zone in the second. Some information about the vertical permeability of the Mahogany Zone was also obtained. (Golder Associates, 1977)

The results of the testing, augmented with some experiential knowledge of the conditions encountered in oil shale, have been used to prepare the hydrological model of Site 1 shown as Figure 4-5.

It is necessary to emphasize that the testing which has been performed is not, in general, particularly appropriate for the purposes of mine inflow analysis, particularly for underground mines where subsidence is limited. Accordingly, many of the important parameters have been estimated. The degree of confidence for each parameter is indicated on the figure.

The testing in this location has produced one of the few values of vertical permeability for the Mahogany Zone, and this value (0.0098 ft/day) is similar to the value developed by Weeks, et al. (1974)--0.0014 ft/day. The parameters which are based on experiential values have been estimated from data obtained at other locations in the Basin, or in other similar rock geohydrologic systems.

In summary, the Site 1 hydrology can be characterized as being made up of a 1,400-foot thick, highly permeable oil shale and sandstone zone overlying a 900-foot thick, relatively impermeable zone of saline minerals and oil shale. Beneath this zone the Garden Gulch Member of the Green River Formation is considered to be functionally impervious.

4.3 SITE 2 MODEL

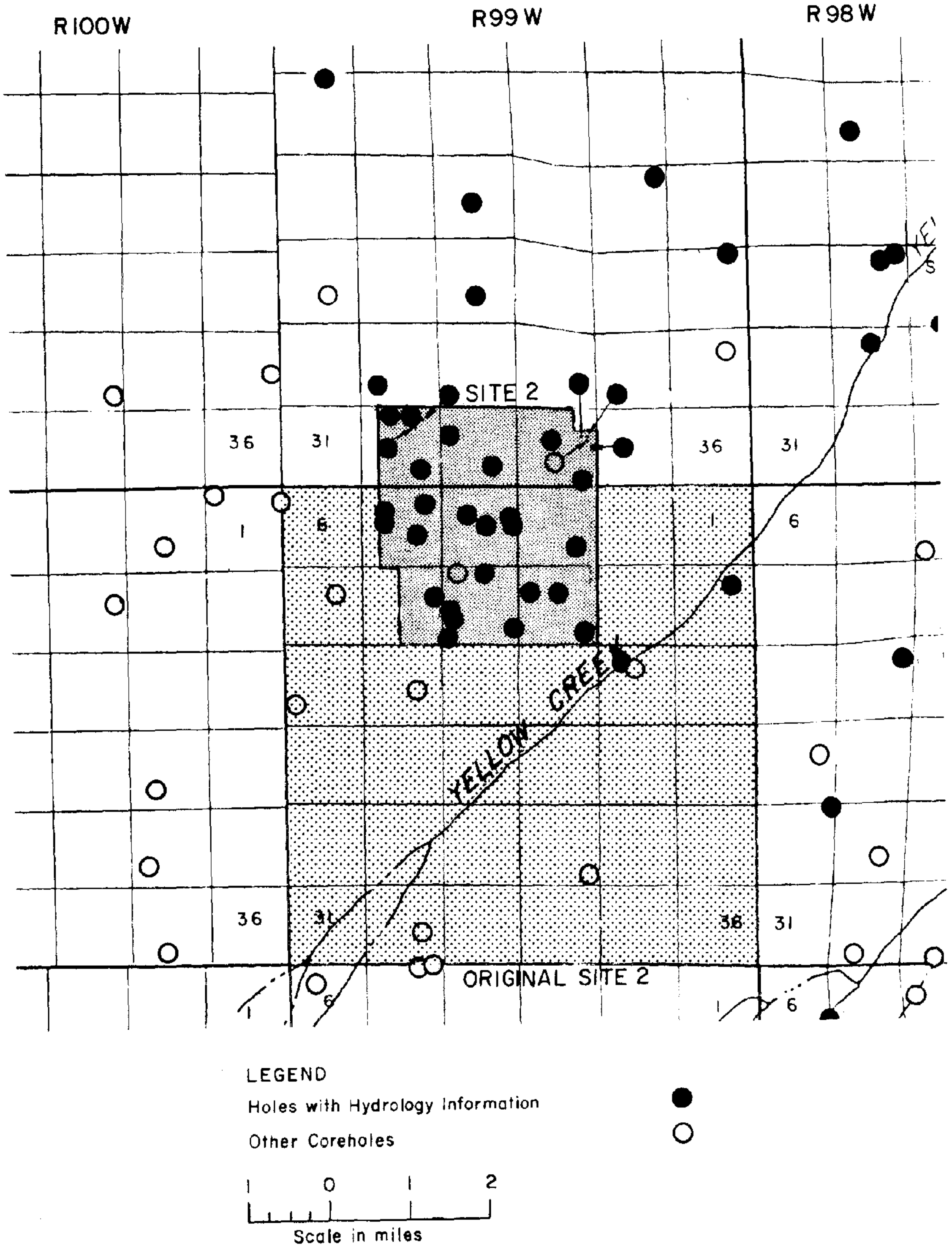
The contract called for selection of Site 2 within T2S, R99W, 6th PM. Figure 4-6 shows this location and Federal Tract C-a, together with drill hole intensity in the area. The available data dictated that the only rational Site 2 location was within C-a Tract, and accordingly the location shown was selected.

4.3.1 Geology of Site 2

Site 2 geology has been extensively evaluated as part of the Tract C-a lease studies. The Quarterly Progress Reports of the Rio Blanco Oil Shale Project (RBOSP) and the DDP prepared by that group set out the geology in great detail. This geological sequence has been coalesced into a single typical section, with geology based generally on corehole CE-705. The sequence is presented in Figure 4-7. While there is some variation of the geologic column to the west of the Tract, this sequence is quite typical.

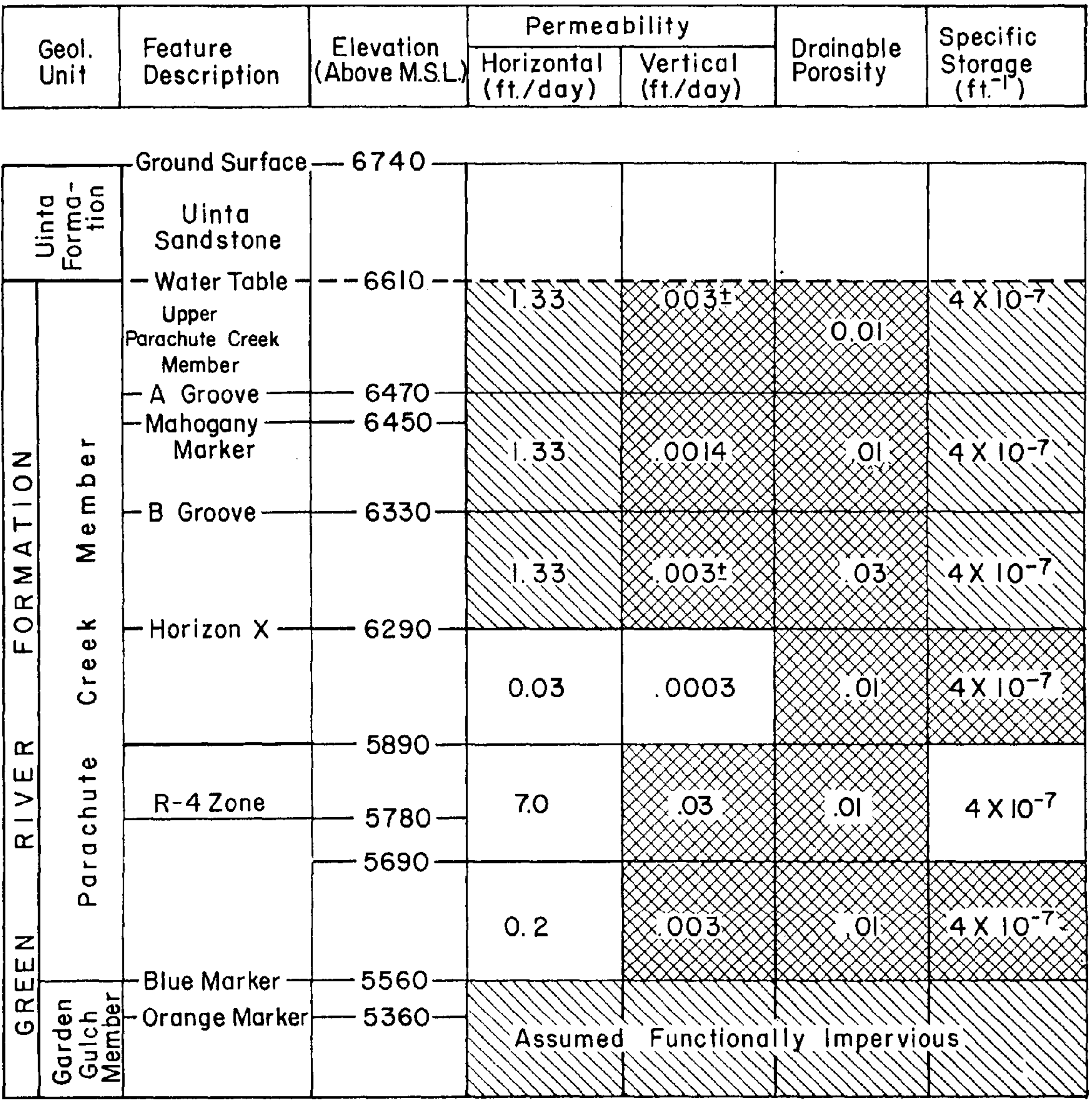
A reported feature of the C-a Tract is the faulting which crosses the Tract. The C-a DDP reports quite extensive faulting, especially in the southern half of the Site (Figure 4-8). However, based on other data presented in the DDP it seems unlikely that this faulting has disturbed material beneath the Mahogany Zone, and there is certainly strong hydrologic evidence to suggest that it does not extend below the bottom of the

Figure 4-6 SITE 2 LOCATION AND DRILL HOLE INTENSITY


R100W
R99W
R98W
T1S
T2S
36
31
1
6
36
31
1
6
36
31
36
31
1
6
SITE 2
YELLOW CREEK
ORIGINAL SITE 2
LEGEND
Holes with Hydrology Information ●
Other Coreholes ○
1 0 1 2
Scale in miles

Note: For additional information See APPENDIX F

Figure 4-7 GEOHYDROLOGY MODEL OF SITE 2

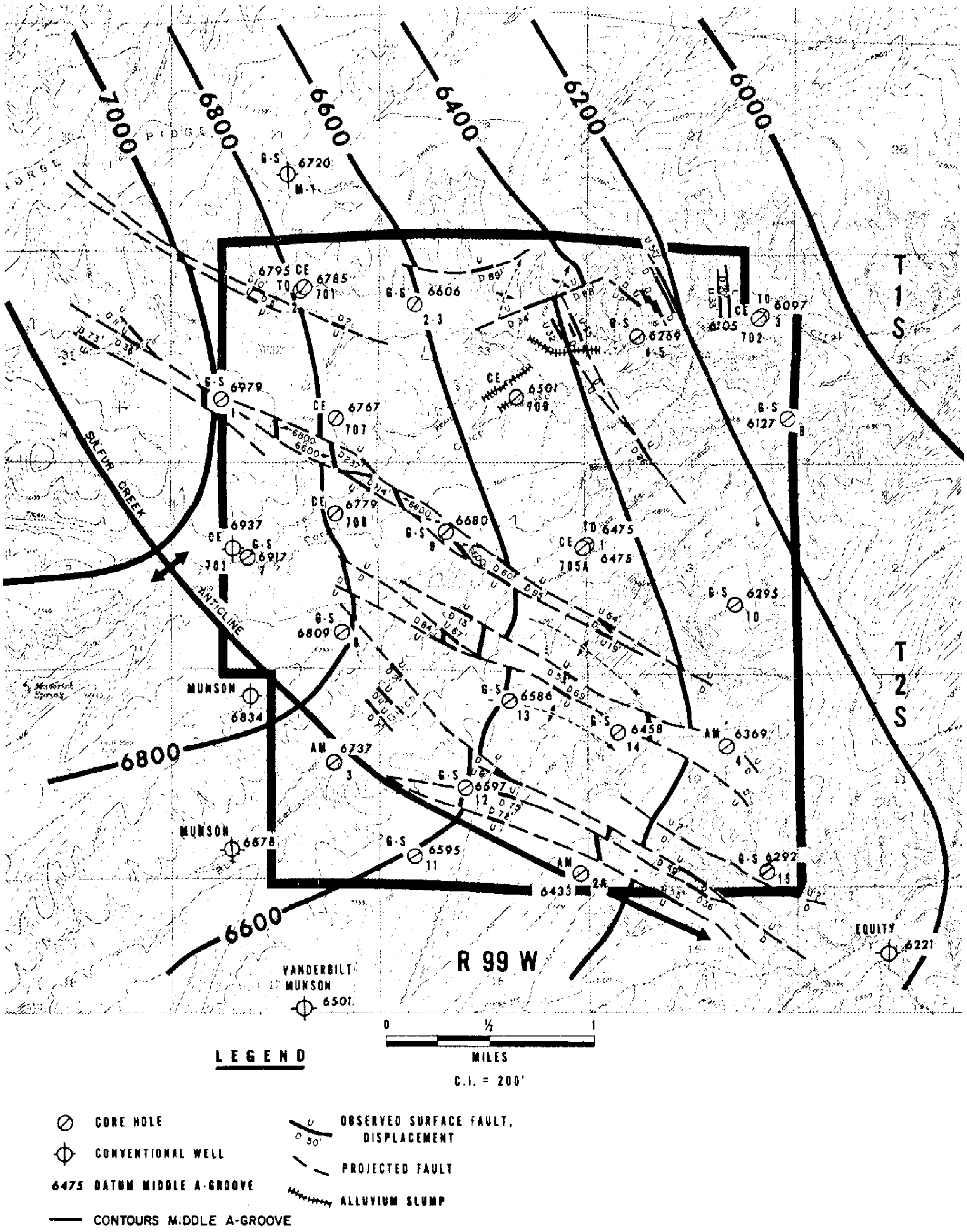


Geol. Unit		Feature Description	Elevation (Above M.S.L.)	Permeability Horizontal (ft./day)	Permeability Vertical (ft./day)	Drainable Porosity	Specific Storage ($ft.^{-1}$)
Uinta Formation		Ground Surface	6740				
		Uinta Sandstone					
GREEN RIVER FORMATION	Parachute Creek Member	Water Table	6610				
		Upper Parachute Creek Member		1.33	.003±	0.01	4×10^{-7}
		A Groove	6470				
		Mahogany Marker	6450	1.33	.0014	.01	4×10^{-7}
		B Groove	6330	1.33	.003±	.03	4×10^{-7}
		Horizon X	6290	0.03	.0003	.01	4×10^{-7}
			5890				
		R-4 Zone	5780	7.0	.03	.01	4×10^{-7}
			5690	0.2	.003	.01	4×10^{-7}
	Garden Gulch Member	Blue Marker	5560				
		Orange Marker	5360	Assumed Functionally Impervious			

NOTES:

1. Based on Cameron Engineers CE 705.
2. All elevations rounded to nearest 10 feet.
3. Not to scale.
4. Quality of information for the purposes of this study:
   - ☐ "Based on acceptable test data"
   - ▧ "Estimated or based on poor data"
   - ▩ "Experiential guess"
5. Horizon X is defined in section 4.5.1.

Figure 4-8 FAULTING ON TRACT C-a


7000
6800
6600
6400
6200
6000
T 1 S
T 2 S
R 99 W
SULFUR CREEK
ANTICLINE
G-S 6720 M-1
6795 CE TD 6785 701
G-S 6606 2-3
G-S 6269 4-5
TD 6097 CE 702
G-S 6979 1
CE 6767 707
CE 6501 709
G-S 6127 8
CE 6779 708
G-S 6680 9
TD 6475 CE 705A
6937 CE 703 G-S 6917 7
G-S 6295 10
G-S 6809 6
MUNSON 6834
G-S 6586 13
G-S 6458 14
AM 6369 4
AM 6737 3
G-S 6597 12
MUNSON 6678
G-S 6595 11
AM 6433 2A
G-S 6292 15
EQUITY 6221
VANDERBILT MUNSON 6501
0 ½ 1
MILES
C.I. = 200'
LEGEND
CORE HOLE
CONVENTIONAL WELL
6475 DATUM MIDDLE A-GROOVE
CONTOURS MIDDLE A-GROOVE
OBSERVED SURFACE FAULT, DISPLACEMENT
PROJECTED FAULT
ALLUVIUM SLUMP

Source: Rio Blanco Oil Shale Project, 1976, p.3-3-52 leached zone. Throws on faults are reported to be in the range of five to 200 feet at ground surface, with the majority of faults showing throws of less than 50 feet.

4.3.2 Geohydrology of Site 2

The geohydrology of C-a Tract has also been very extensively investigated as part of the C-a Tract lease investigation. A total of 13 pumping tests were performed using up to 31 observation completions in wells. Additionally, there is a large amount of second-order data which was obtained during air-mist drilling of the holes on the tract.

This information has been re-analyzed in a somewhat different manner than presented by the C-a Tract leasees, to allow for the very major field transients observed in some of the tests. Based on this re-analysis, the hydrologic section shown in Figure 4-7 has been developed.

The most noticeable feature of the model is the high permeability zone just above the Blue Marker. This is not reported anywhere else in the Basin and has a profound effect on the results obtained for mine inflows at Site 2. As in the hydrologic model for Site 1, much of the parameter table has been estimated. However, the vertical permeability of the material between the base of the leached zone and the lower aquifer zone is based on the very limited leakage observed in lower aquifer testing. In passing, it should be noted that the Mahogany Zone at C-a Tract is penetrated by about 30 holes, most of which hydraulically connect the material above the Mahogany Zone with that immediately below it. Thus, any measured vertical permeability across this feature would be modified by these connections.

It is also important to note a terminological difference between the Weeks, et al. (1974) report and the C-a DDP (1976). In the Weeks, et al. report, the term "upper aquifer" was used to describe a permeable zone of rock from the water table to the Mahogany Zone, and the term "lower aquifer" to describe a permeable zone from the Mahogany Zone to the base of the leached zone, generally around 1,500 feet depth. In the C-a DDP, the term "upper aquifer" was used to describe all the significantly permeable material in the upper Parachute Creek Member, while the term "lower aquifer" was used to describe a highly permeable section of the stratigraphy just above the Blue Marker. It should not be assumed that the Weeks, et al. and C-a Tract "aquifers" necessarily directly link up, as evidence to the contrary exists.

The piezometric pressures vary dramatically across Tract C-a in an east-west direction. On the eastern boundary conditions are hydrostatic, with the upper boundary of the saturated zone at about 6,600 ft. elevation, which is about the elevation (in that location) of the bottom of Coral Gulch and Stake Springs Draw. To the west, the lower aquifer piezometric elevation remains approximately constant, while the upper aquifer elevation rises to somewhat below the elevations of the bottoms of the (dry) gulch beds, which have also risen. The selected piezometric condition for the model is a hydrostatic pressure distribution with depth and a "water table" elevation of 6,610 feet, which happens to equal the elevation of the Uinta Formation/Green River Formation interface in our geologic model.

In summary, then, Site 2 is characterized by a two-aquifer system. The upper aquifer is typically 300 feet thick, of moderate to high permeability but low porosity. The lower aquifer is typically 200 feet thick and has very high permeability. They are separated by a 400-foot thick aquitard of extremely low vertical and horizontal permeability. It is assumed that the Garden Gulch Member is impermeable, although the limited second-order data which exists does not uniformly support this assumption.

4.4 SITE 3 MODEL

The contract called for selection of Site 3 from within T2S, R97W, 6th PM. However, a review of available data showed this township to be devoid of useful hydrologic data (Figure 4-9). Consequently it was decided to move the Site 3 location to the location of Federal Tract C-b, where a considerable amount of information is available.

4.4.1 Geology

Geology is based on the average geologic column across C-b Tract. This is shown in Figure 4-10, and corresponds approximately to the geology at SG 11 and C-b 3.

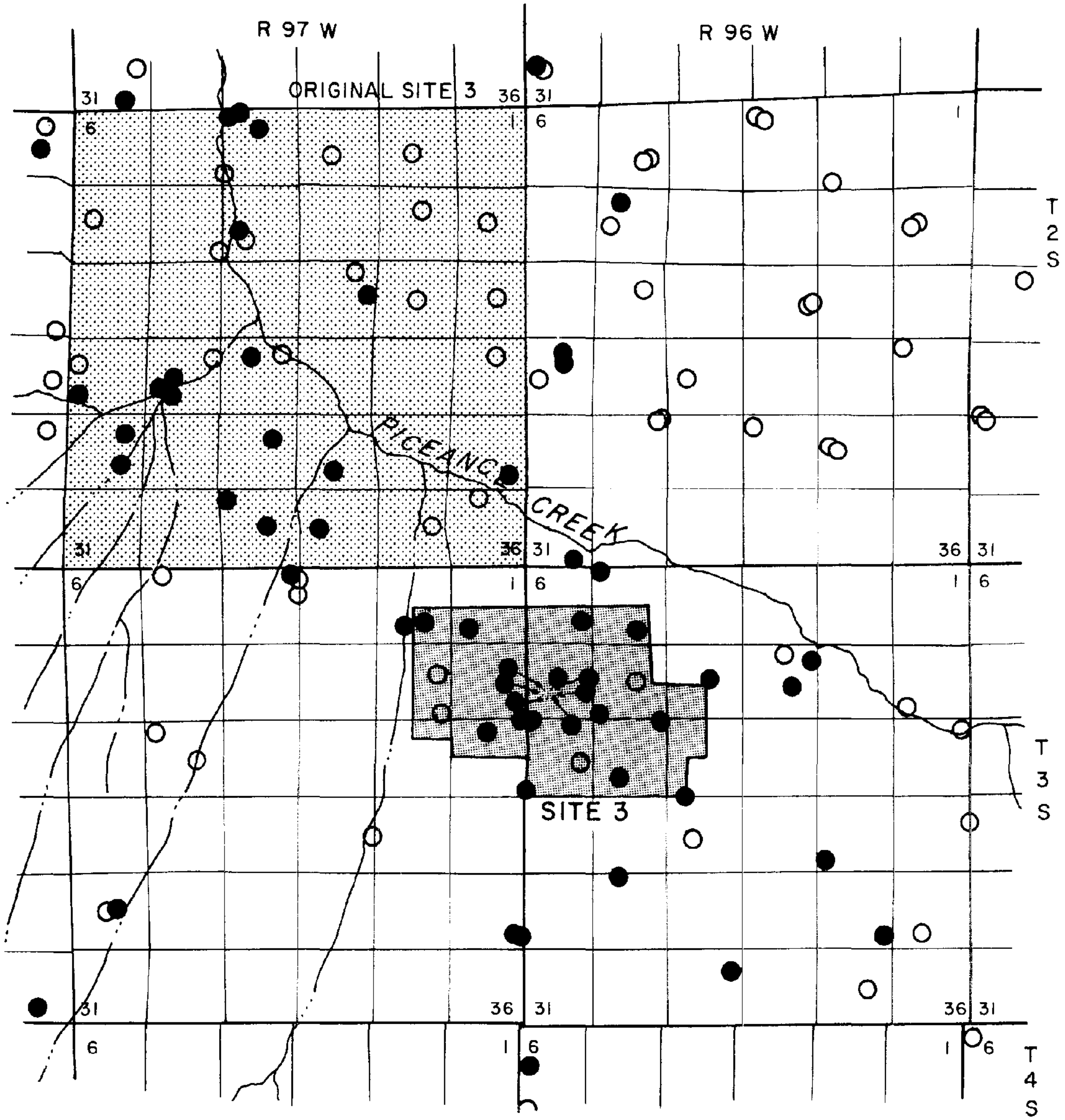
It is worth mentioning that Site 3 lies just on the edge of the saline-rich area of the lower Parachute Creek Member. However, it appears that saline minerals appear in significant quantities over most of the area.

Little if any faulting has been observed on the Site. Joint and fracture intensity decrease markedly at a depth of about 1,500 feet below the surface.

4.4.2 Geohydrology

A significant amount of geohydrologic data is available for Site 3. This was developed before and during the evaluation of C-b Tract, and comprises:

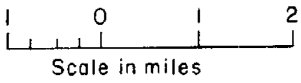
Figure 4-9 SITE 3 LOCATION AND DRILL HOLE INTENSITY


R 97 W
R 96 W
ORIGINAL SITE 3
PICEANCE CREEK
SITE 3
T 2 S
T 3 S
T 4 S
31
6
36
1
31
6
36
1
31
6

LEGEND

Holes with Hydrology Information ●

Other Coreholes ○


1
0
1
2
Scale in miles

Note: For additional information See APPENDIX F

Figure 4-10 GEOHYDROLOGY MODEL OF SITE 3

Geol. Unit		Feature Description	Elevation (Above M.S.L.)	Permeability		Drainable Porosity	Specific Storage (ft^{-1})
				Horizontal (ft./day)	Vertical (ft./day)		
Uinta Formation		Ground Surface	6740				
		Water Table	6410				
		Uinta Sandstone		.093	▧ .03	▦ .10	3×10^{-7}
GREEN RIVER FORMATION	Parachute Creek Member		5820				
				.005	▧ .003	▦ .01	3×10^{-7}
			5720				
		A Groove	5490	.411	▧ .008	▦ .02	3×10^{-7}
		Mahogany Marker	5460				
				.033	.0003	▦ .01	▦ 3×10^{-7}
			5410				
		B Groove	5310	.586	▦ .058	▦ .02	3×10^{-7}
		Horizon X	5260				
				.077	▦ .008	▦ .01	▦ 3×10^{-7}
			4630				
		R-4 Zone					
			4500	.063	▦ .008	▦ .01	▦ 3×10^{-7}
		Blue Marker	4200				
	Garden Gulch Member			▧ Assumed Functionally Impervious			

NOTES:

1. Based on TOSCO Cb-3.
2. All elevations rounded to nearest 10 feet.
3. Not to scale.
4. Quality of information for the purposes of this study:
   - ☐ "Based on acceptable test data"
   - ▧ "Estimated or based on poor data"
   - ▦ "Experiential guess"
5. Horizon X is defined in section 4.5.1.

i. Second-order data obtained during drilling on the Site.
ii. Results of two major pump tests performed on Site.
iii. Results of a thorough evaluation of one corehole (SG 17) using sectioned packer testing over small intervals.
iv. Results of pumping tests over small intervals in SG 1.
v. Piezometric conditions at equilibrium.

Based on this data, the geohydrology model shown in Figure 4-10 has been developed for Site 3. Once more, attention must be drawn to the lack of confidence in many of the parameters which play an important role in mine inflow evaluation.

In summary, it can be seen from the model that the overall permeability of the material above the top of the saline zone is considerably less than at the other two sites, and in fact lower than in most other parts of the Basin.

4.5 BASIN-WIDE MODEL

The geohydrology model used for the Basin-wide evaluations in this contract was required to be relatively simple, so as to allow multiple evaluations. Weeks, et al. (1974) have already presented a three-layer model of Basin hydrology, and after a great deal of consideration we have opted for a single-layer model.

The difference between a multilayer model and a single-layer model lies in the model's ability to provide an analogue of vertical flow. In the case of a single-layer model, there is assumed to be adequate vertical connection over the areas involved to allow needed vertical fluid movement. In the case of multilayered models, the vertical movement is explicitly modelled, and the need for the above assumption is eliminated.

The importance of correctly modelling the resistance to vertical flow depends on the scale of the problem. For mine inflow analyses where the vertical flow above and below the mine is a major determinant of the total flow, it is essential to correctly model the vertical flow resistance. On the other hand, in Basin-wide studies the resistance to vertical flow within the 1,500-foot deep permeable region is not very significant, as the enormous areas involved allow enough vertical water flow to prevent major head differences between the upper and lower parts of the aquifer. The single-layer model used for this section of the study completely ignores vertical flow resistance, and therefore could not be used to predict the amount of inflow to a mine. However, in this study we know the net amount of water which each mine will remove from the aquifer, and the single-layer model is capable of accurately predicting the Basin-wide effect of this removal.

The above argument does not apply to the resistance to vertical flow in the layer isolating the prolific lower aquifer at Site 2. This resistance is apparently so great as to effectively isolate that lower aquifer (whose extent is unknown) from the main aquifer system.

The decision to use a single-layer model was not made without some reluctance. One of our objectives when we started on this project was to develop a believable multilayer model of the entire Piceance Basin. To this end a five-layer model was developed and calibration against observed data was attempted. It soon became clear that the available data were entirely inadequate to define the multitude of parameters required for such a model. While the five-layer model could be adjusted to match the available data reasonably well, equally good results could be achieved with a two-layer or even a single-layer model.

For these reasons we feel that a single-layer model will suffice for the present evaluation. It is interesting to note that the multilayer Weeks, et al. (1974) model showed very little difference in the heads in the two layers, resulting from mining at C-a or C-b Tract, indicating that a multilayer model may be unnecessary in any case. Further, the steady state results of the single-layer model for the Weeks, et al. model are functionally identical.

The locations where a single-layer model will not accurately predict Basin piezometric conditions are in the recharge and discharge areas, where significant vertical head gradients could be expected. The values obtained by the model will approximate average heads over the entire section.

Required input data for the model comprises:

i. Elevations of the base of the permeable layer
ii. Average material permeability (at each location) and horizontal anisotropy
iii. Average material specific storage (at each location)
iv. Average material specific yield (at each location)
v. Elevations of creek beds
vi. Location and intensity of recharge
vii. Nature of external boundaries

The bulk of this information was drawn from the primary testing performed in the Basin, in the five localities mentioned above. This was backed up in areas where information was lacking by secondary information.

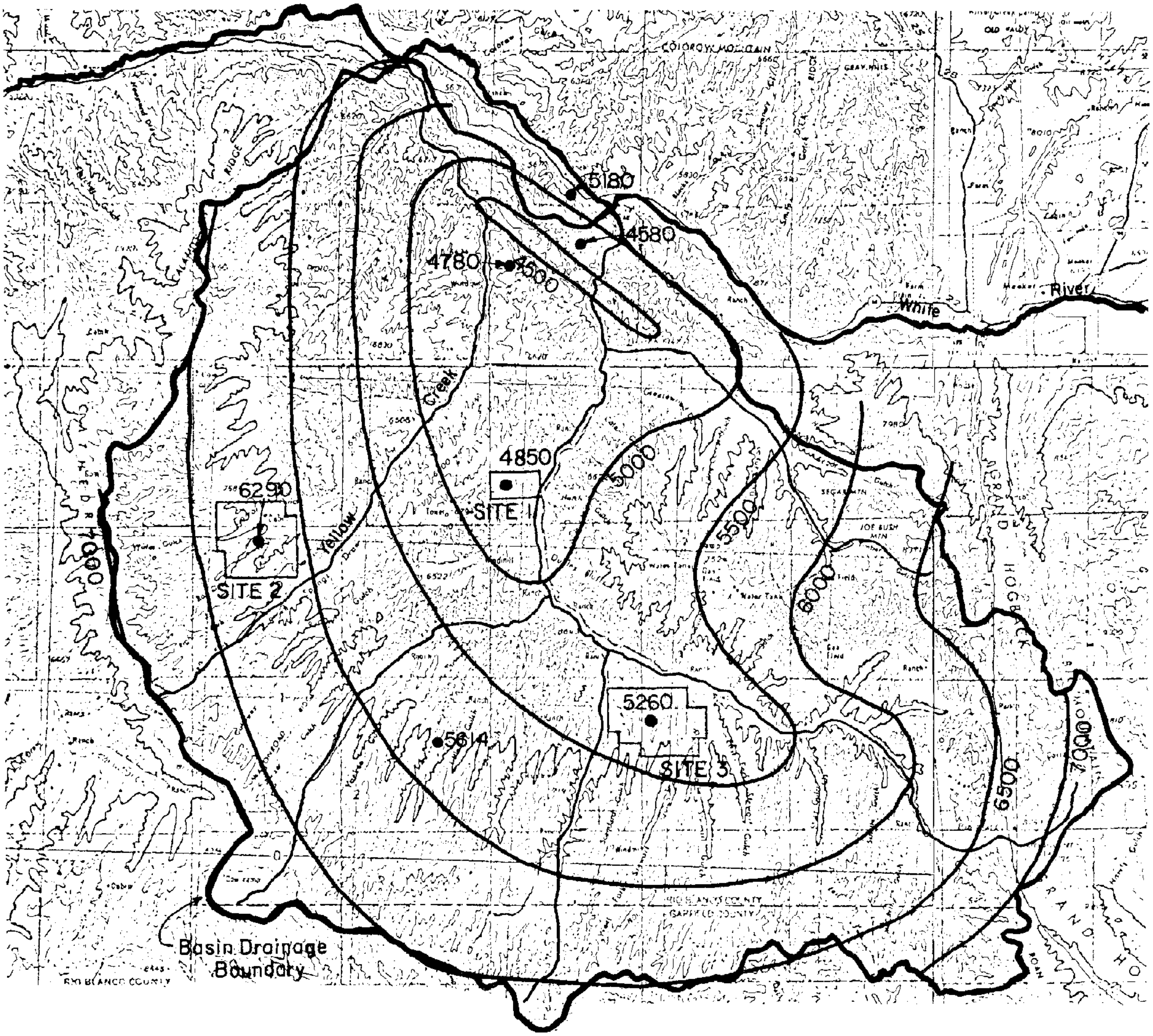
4.5.1 Base of the Permeable Layer (Horizon X)

"Horizon X" is defined as the plane which defines the base of material in the Piceance Basin which is both significantly permeable, and contains circulating groundwater. Testing all over the Basin indicates that rocks at greater depth than 1,500 feet are not significantly permeable. Further, tests in some permeable zones at depth strongly suggest that they are not significantly connected to the circulating groundwater system.

This horizon has proven very difficult to identify in some locations, but is generally easily defined. It can be evaluated by reference to geophysical testing, spot permeability testing, flow encountered during drilling and temperature and velocity profiles in holes. Particularly, resistivity logs were central to the evaluation. In general the resistivity of the deeper saline rock sequences is very high if they contain no connected water passages. However, if there are significant connected water passages in the rock itself, then the high conductivity of the solution filling these passages will decrease the apparent rock resistivity markedly. Thus, high resistivity measurements in this area are prima facie evidence of very low hydraulic conductivities.

The results of the available data have been contoured and are presented on Figure 4-11. Note that the data in the northeastern section of the Basin are largely lacking. Fortunately

Figure 4-11 ELEVATION PLAN OF HORIZON "X"


5180
4580
4780
4500
4850
SITE 1
5000
5500
6000
6290
SITE 2
7000
5260
SITE 3
5614
6500
7000
White
River
Yellow
Creek
Basin Drainage
Boundary
RIO BLANCO COUNTY
GARFIELD COUNTY

● 6290 Data points with elevation of Horizon X (feet)

——— Contours of elevation of Horizon X (feet)

Note: Values for Site 1, 2, and 3 are averages.

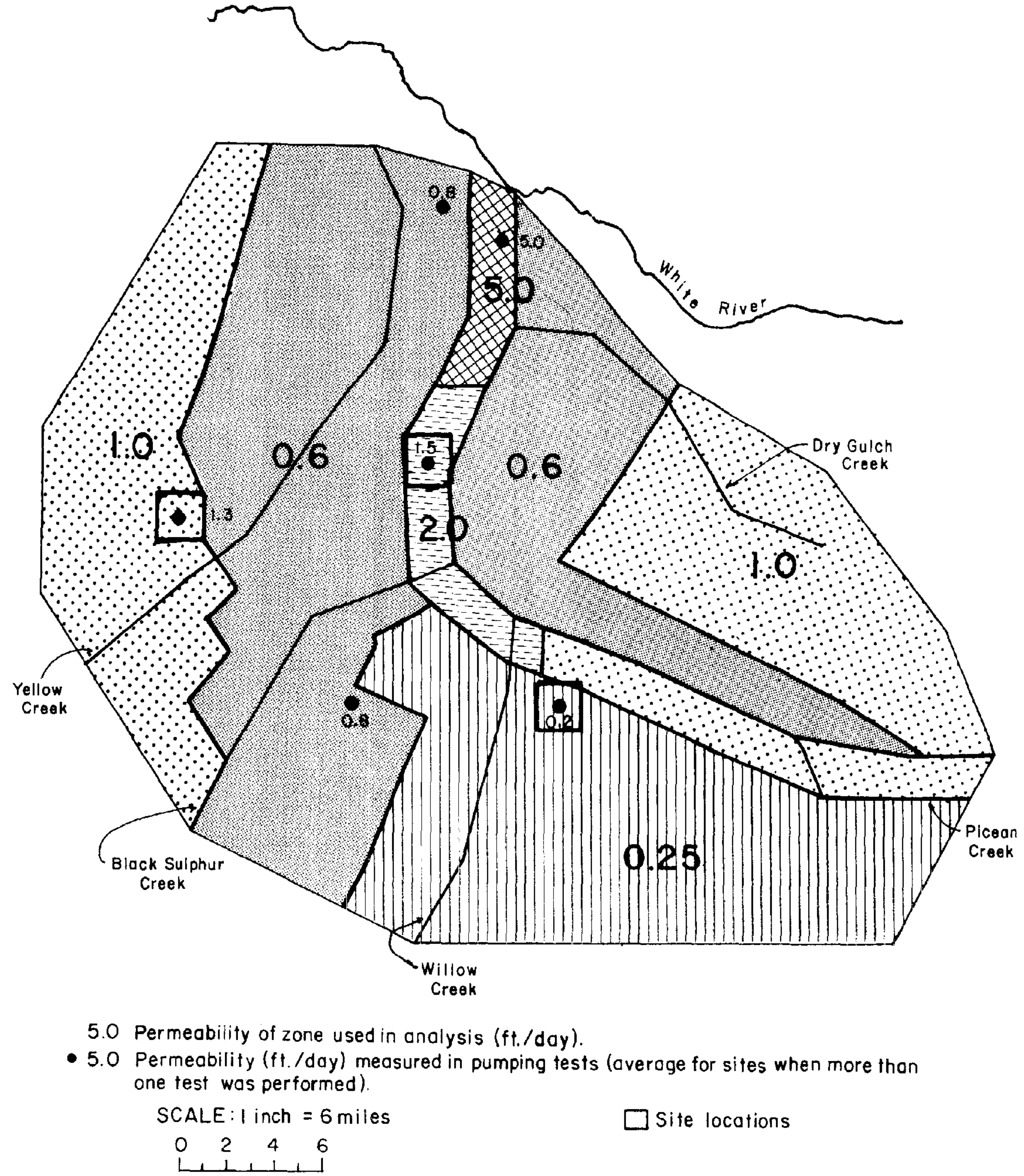
this is not critical, as this portion of the Basin has little impact on the western and southern sections, where the three sites are located.

It should be cautioned that this plan is based on relatively crude information. It should not be used for purposes other than Basin-wide modelling. This is particularly true in the area around C-a Tract. After a detailed review of all test data collected at C-a Tract we have concluded that the highly prolific "lower aquifer" of the C-a DDP (not to be confused with the "lower aquifer" in the Weeks, et al. (1974) report) is not significantly connected to the upper aquifer. This is a critical evaluation, as it renders C-a Tract a very groundwater-poor location. This finding is based on the high degree of confinement of the lower aquifer which was observed in the pumping tests, plus the extraordinary transient changes which have occurred in the lower aquifer since drilling began in the area. Finally, the head gradient in the lower aquifer is so flat as to imply that little if any recharge to that aquifer occurs. This finding should, of course, be reviewed at other locations around the Basin periphery, but at present no data exists to perform that evaluation.

4.5.2 Average Material Permeability

The average material permeability (horizontal) has been evaluated at a number of points around the Basin and has been cast into zones as shown in Figure 4-12. It would appear that there is a highly pervious zone running along Piceance Creek, although we hesitate to describe it necessarily as a fault zone. Data in the highlands to the northeast is entirely lacking, so we have assumed that the horizontal permeability of the material in this area is the same as for the highlands to the west.

Figure 4-12 HORIZONTAL PERMEABILITY ZONES USED IN THE BASIN-WIDE MODEL


White River
0.8
5.0
5.0
1.0
0.6
1.5
0.6
Dry Gulch Creek
1.3
2.0
1.0
Yellow Creek
0.8
0.2
Picean Creek
Black Sulphur Creek
0.25
Willow Creek

5.0 Permeability of zone used in analysis (ft./day).

● 5.0 Permeability (ft./day) measured in pumping tests (average for sites when more than one test was performed).

SCALE: 1 inch = 6 miles

0 2 4 6

☐ Site locations

Several tests in the Basin have exhibited significant anisotropy in horizontal permeability. This anisotropy is aligned with the regional joint fabric, at about N70°W, and has been suggested as being as high as 20:1 (C-b Shale Oil Project, 1976). However, the anisotropy apparently dies out beneath the Mahogany Zone and has been ignored in this study. The appropriateness of this decision was supported by calibration runs of the model.

It must be stated that the permeability data for the model is very sparse. However, for general evaluations it is likely adequate.

4.5.3 Average Material Specific Storage

The specific storage of the rock in all cases where data is available is remarkably constant, with all values within 20% of $3 \times 10^{-7} ft^{-1}$ (the units can also be expressed as cubic feet of water produced per cubic foot of rock per foot of head change). This value has been used throughout the study.

4.5.4 Average Material Specific Yield

This was a more difficult parameter to determine. The average value in the sandstone may be as high as 20%, and in the marlstone it may be as low (in places) as 0.01%. We feel that an average of 5% overall is realistic for the present study, as mainly the sandstone is being dewatered. Note that this choice has no impact on any steady-state run of the model.

4.5.5 Creek Bed Elevations

These elevations form upper boundary conditions when the creeks are running but do not enter the computation if they dry up due to nearby mine inflows. Data was taken from standard U.S.G.S. topographic plans.

4.5.6 Location and Intensity of Recharge

The data presented in Weeks, et al. (1974) was used. This was presented as Figure 3-10. It should be noted that subsequent studies on C-b Tract strongly suggest that considerable infiltration (in excess of 1" per year) occurs at this location. We have ignored this in the present study, but it seems likely that the infiltrations determined by Weeks' group may be somewhat too low.

4.5.7 Nature of External Boundaries

All external boundaries were assumed impervious. The only entry of water to the system was via recharge, and the only exit was via Yellow and Piceance Creeks. The location of the no-flow boundary was arbitrarily chosen to coincide with the Basin drainage boundary, as this is close to the physical limit of the Basin rocks on three sides. On the southern edge of the Basin (as modelled), the rock sequence continues uninterrupted to the Roan Cliffs. Deeply incised streams provide boundaries for drainage. While it is conceivable that impacts of groundwater removal in the northern section of the Basin would be felt in the southern part of the Basin, it was clear that these effects would be minimal for the sites chosen for this study.

CHAPTER 5
WATER SUPPLY TO THE SITES

The physical availability and quality of water that could be used to supply oil shale development is outlined in this chapter. Various methods and costs of supplying water to the three sites specified in the contract are presented.

5.1 SURFACE WATER SUPPLY

5.1.1 IN-BASIN SUPPLY

As set out in Section 3.2 above, the combined average annual flow of the Piceance and Yellow Creeks is 18,610 acre-feet per year (11,560 gallons per minute). It is conceivable that this water could be used to supply a prototype oil shale industry, but we have in general chosen to ignore this potential supply, for the following reasons:

a. The supply is most irregular on a monthly basis.

b. The quality of the water is quite low (1,000 - 4,000 mg/l total dissolved solids).

c. The water is heavily appropriated, and it is doubtful that it can be made available without protracted legal battles.

d. The flow in the creeks will almost certainly be reduced by nearby mine development, and hence it cannot be regarded as reliable.

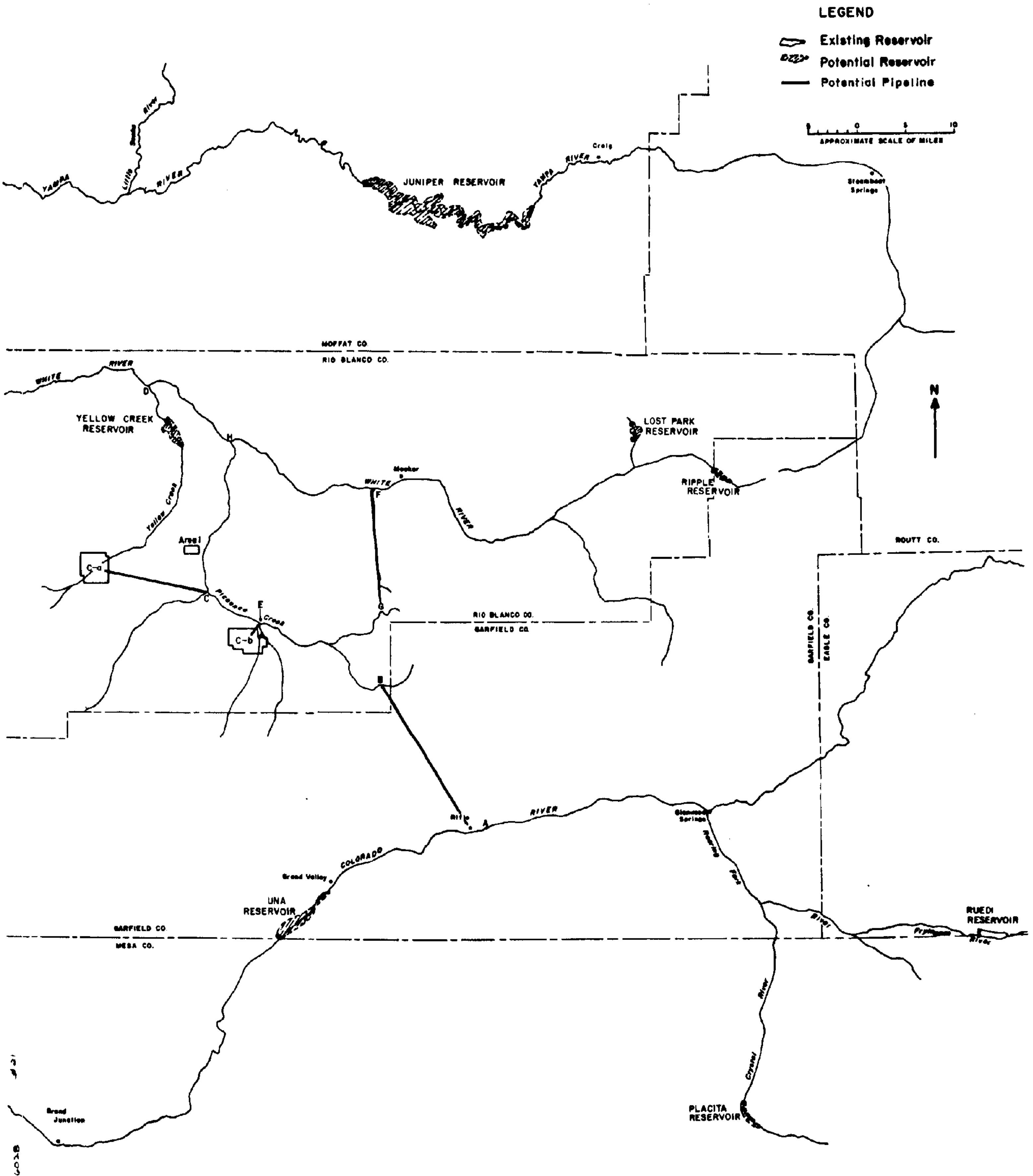
e. Environmental considerations (primarily relating to salinity and minimum flow rates) will almost certainly seriously restrict allowable diversion of water for consumptive use.

It is perhaps ironic that the consumptive use of all of the water exiting the Basin would substantially reduce the salinity of the Colorado River.

5.1.2 EXTRA-BASIN SUPPLY

Various alternative plans for supplying surface water for oil shale development in the Piceance Creek Basin were summarized by the U.S. Bureau of Reclamation (September 1974). Figure 5-1 shows the location of the alternative sources that were presented as being the most desirable from a physical feasibility, cost, and environmental standpoint. The letters on the figure relate to points that will be discussed in the text (i.e. pipeline diversion points and termini, etc.). As a basis for comparisons of the alternative plans, the above report estimated the annual costs of each plan, including the annual equivalent of the construction cost and interest during construction as well as the annual operating costs. Costs of construction, including costs of rights-of-way, materials, labor, engineering overhead, and contingencies, were based on January 1974 prices. Interest during construction was taken as a flat 12 percent of the construction cost on the assumption that the costs would be spread on a straight-line basis over a 40-year period at 6 percent interest. Annual operating costs include costs for purchase of water from reservoirs (but not of senior water rights, which are discussed in Section 5.1.2.5), purchase of power for pumping, and operation, maintenance, and replacement costs. The annual cost was given both in terms of a total and per acre-foot of water supplied.

Figure 5-1 ALTERNATIVE SOURCES OF SURFACE WATER SUPPLY FOR OIL SHALE DEVELOPMENT IN THE PICEANCE CREEK BASIN


LEGEND
Existing Reservoir
Potential Reservoir
Potential Pipeline
0
5
10
APPROXIMATE SCALE OF MILES
YAMPA RIVER
Little Snake River
JUNIPER RESERVOIR
YAMPA RIVER
Craig
Steamboat Springs
MOFFAT CO.
RIO BLANCO CO.
WHITE RIVER
D
YELLOW CREEK RESERVOIR
H
Yellow Creek
Area I
C-a
C
Piceance Creek
E
C-b
Meeker
WHITE RIVER
F
G
LOST PARK RESERVOIR
RIPPLE RESERVOIR
ROUTT CO.
RIO BLANCO CO.
GARFIELD CO.
B
GARFIELD CO.
EAGLE CO.
Rifle
A
RIVER
Glenwood Springs
Roaring Fork River
COLORADO
Grand Valley
UNA RESERVOIR
GARFIELD CO.
MESA CO.
RUEDI RESERVOIR
Fryingpan River
Crystal River
PLACITA RESERVOIR
Grand Junction
N

The report presented a wide range of plans, from which we have selected nine separate proposals which are appropriate to the present study. The first three proposals supply water to Site 2 (C-a Tract), proposals 4 and 5 supply water to Site 3 (C-b Tract), and proposals 6 through 9 supply both tracts in joint developments. Each is detailed below.

5.1.2.1 Supply to C-a Tract

Alternative plans for supplying surface water to Tract C-a are outlined in Proposals 1 through 3. They were based on a 300,000 barrel per day oil shale industry requiring 57,000 acre-feet per year of water.

a. Proposal 1 is diversion of direct flows from the Colorado River. It involves utilizing 30,000 acre-feet per year from the existing Ruedi Reservoir on the Fryingpan River 30 miles southeast of Glenwood Springs and pumping an additional 27,000 acre-feet per year. Water would be released from Ruedi Reservoir into the Fryingpan River and thus into the Colorado River, diverted into a pipeline from 4 miles east of Rifle (A) to Piceance Creek (B) (having 3 pumping plants along its length), released into Piceance Creek at B, and rediverted into a pipeline from the mouth of Black Sulphur Creek on Piceance Creek (C) to Tract C-a (having 2 pumping plants along its length). The water would have a dissolved solids concentration of 160 to 930 milligrams per liter, with an average of 500. The annual cost would be $8,558,000 or $150 per acre-foot.

b. Proposal 2 is construction of Yellow Creek Reservoir and diversion of surplus flows from the White River. Surplus flows would be diverted into a pipeline from the mouth of Yellow Creek on the White River (D) to Yellow Creek Reservoir (having one pumping plant along its length). Yellow Creek Reservoir would have a total capacity of 60,000 acre-feet and an active capacity of 30,000 acre-feet, allowing for unusually high sediment inflow. Water would be pipelined from Yellow Creek Reservoir to Tract C-a (having 2 pumping plants along its length). The water would have a dissolved solids concentration of 270 milligrams per liter. The annual cost would be $5,967,000 or $105 per acre-foot.

c. Proposal 3 is construction of Ripple Reservoir on the North Fork of the White River. Ripple Reservoir would have a total capacity of 18,000 acre-feet and an active capacity of 17,000 acre-feet, with negligible sediment inflow. Water would be released from Ripple Reservoir into the White River, and diverted into a pipeline from the mouth of Yellow Creek on the White River (D) to Tract C-a (having 2 pumping plants along its length). The water would have a dissolved solids concentration of 200 to 500 milligrams per liter, with an average of 320. The annual cost would be $5,760,000 or $101 per acre-foot.

5.1.2.2 Supply to C-b Tract

Alternative plans for supplying surface water to Tract C-b are outlined in Proposals 4 and 5. They were based on a 100,000 barrel per day oil shale industry requiring 18,000 acre-feet per year of water.

a. Proposal 4 is diversion of direct flows from the Colorado River. Water would be diverted into and released from a pipeline from Rifle to Piceance Creek at Rio Blanco, and rediverted into a pipeline from the mouth of Stewart Gulch on Piceance Creek (E) to Tract C-b (having 1 pumping plant along its length). The water would have a dissolved solids concentration of 160 to 930 milligrams per liter, with an average of 500. The annual cost would be $2,446,000 or $136 per acre-foot.

b. Proposal 5 is construction of Ripple Reservoir on the North Fork of the White River. Ripple Reservoir would have a total capacity of 9,000 acre-feet and an active capacity of 8,000 acre-feet, with negligible sediment inflow. Water would be released from Ripple Reservoir into the White River, diverted into a pipeline from the mouth of Sheep Creek on the White River (F) to Fourteen Mile Creek tributary to Piceance Creek (G) (having 2 pumping plants along its length), and rediverted into a pipeline from the mouth of Stewart Gulch (E) to Tract C-b. The water would have a dissolved solids concentration of 200 to 500 milligrams per liter, with an average of 320. The annual cost would be $2,026,000 or $113 per acre-foot. An alternative would be to pipeline the water from the mouth of Piceance Creek on the White River (H) to Tract C-b (having 2 pumping plants along its length). The annual cost would be $2,258,000 or $126 per acre-foot.

5.1.2.3 Joint Supply for C-a and C-b Tracts

Alternative plans for supplying surface water for joint development of Tracts C-a and C-b are outlined in Proposals 6 through 9. They were based on a 300,000 barrel per day oil shale industry at Tract C-a requiring 57,000 acre-feet per year of water and a 100,000 barrel per day industry at Tract C-b requiring 18,000 acre-feet per year of water.

a. Proposal 6 is diversion of direct flows from the Colorado River, via Rifle to Piceance Creek at Rio Blanco and thence via Piceance Creek and pipelines to the tracts, as in Proposals 1 & 4. The water would have a dissolved solids concentration of 160 to 930 milligrams per liter, with an average of 500. The annual cost would be $9,765,000 or $130 per acre-foot, with the cost to Tract C-a being $7,840,000 or $138 per acre-foot, and to Tract C-b being $1,925,000 or $107 per acre-foot.

b. Proposal 7 is the multiple-purpose West Divide Project involving construction of Una Reservoir on the Colorado River west of Grand Valley. This would be as a substitute for the originally proposed Placita Reservoir on the Crystal River south of Glenwood Springs. Una Reservoir would have a total capacity of 196,000 acre-feet and an active capacity of 61,000 acre-feet, allowing for high sediment inflow. Water would be released from Una Reservoir to replace that which would be diverted as in Proposal 6. The water would have a dissolved solids concentration of 160 to 930 milligrams per liter, with an average of 500. The annual cost, including those from Proposal 6, would be $13,755,000 or $183 per acre-foot, with the cost to Tract C-a being $10,508,000 or $185 per acre-foot, and to Tract C-b being $3,247,000 or $180 per acre-foot.

c. Proposal 8 is the multiple-purpose Lower Yampa Project involving construction of Juniper Reservoir on the Yampa River 18 miles west of Craig. Juniper Reservoir would have a total capacity 879,000 acre-feet and an active capacity of 181,000. Water would be pipelined from Juniper Reservoir to Fourteen Mile Creek tributary to Piceance Creek (G) (having 3 pumping stations along its length), and rediverted into pipelines like the second one in Proposal 1 (C to Tract C-a) and the second one in Proposal 4 (E to Tract C-b). The water would have a dissolved solids concentration of 150 to 500 milligrams per liter, with an average of 230. The annual cost would be $12,859,000 or $171 per acre-foot, with the cost to Tract C-a being $10,261,900 or $180 per acre-foot, and to Tract C-b being $1,597,100 or $145 per acre-foot.

d. Proposal 9 is the multiple-purpose Yellow Jacket Project involving construction of Ripple Reservoir on the North Fork of the White River and Lost Park Reservoir on Lost Creek, a tributary of the North Fork of the White River. Ripple Reservoir would have a total capacity of 20,000 acre-feet and an active capacity of 17,000 acre-feet; Lost Park Reservoir would have a total capacity of 24,500 acre-feet and an active capacity of 22,000 acre-feet. A feeder canal system could divert water from the Yampa River drainage to Lost Park Reservoir to augment the natural supply. The rest of the project would be like Proposals 3 and 5. The water would have a dissolved solids concentration of 200 to 600 milligrams per liter, with an average of 360. The annual cost would be $7,683,000 or $102 per acre-foot, with the cost to Tract C-a being $5,750,000 or $101 per acre-foot, and to Tract C-b being $1,933,000 or $107 per acre-foot.

5.1.2.4 Water Rights Costs

The cost of water rights in the vicinity of the Piceance Basin is difficult to quantify, for a number of reasons:

a. The value of a water right varies with the demand for water. If an oil shale industry were set up, and if it demanded large quantities of water, this would vastly increase the value of a water right over present costs.

b. The selling price of water rights are not generally recorded, and are thus difficult to discover.

c. The nature of the water right, and of the proposed use after sale, vary so widely that it is enormously difficult to compare or generalize transactions. This is particularly true of conditional rights, and rights of different seniority.

Nevertheless, we have canvassed opinion in both public and private areas as to reasonable prices for water rights, and have concluded that a reasonable cost for planning purposes is \$40 to \$60 per acre-foot per year. Converting this to the same basis as the Bureau of Reclamation study (Section 5.1.2) produces an equivalent annual cost of 12 percent of the capital cost, i.e. \$5 to \$7 per acre-foot per year.

It is questionable whether this "cost" is real in terms of the economics of water supply. The water right, once acquired, is a potentially appreciating asset, and at the end of the project could be sold. Thus it is not unreasonable to ignore the "cost" of the water right, and we have chosen to do so in this study.

5.1.2.5 Impact of Water Diversions on the Colorado River System

The impact on salinity of diversions from the river systems discussed above may be significant, especially if the diversions are large. Based on the Bureau of Reclamation (September 1974) figures, the increase in salinity concentration of the Colorado River at Imperial Dam due to diversion of 1,000 acre-feet per year (620 gallons per minute) of water from the rivers is as shown in Table 5-1.

TABLE 5-1
INCREASE OF SALINITY CONCENTRATION
AT IMPERIAL DAM PER 1,000 AFY OF
WATER DIVERTED FOR OIL SHALE DEVELOPMENT

Source of Water	Increase in Salinity (mg/l per 1,000 AFY)
Colorado River	0.04
White River	0.07
Lower Yampa River	0.07

The potential impact of this increase can be gauged in economic terms by reference to information presented by the U.S. Bureau of Reclamation (January 1974). The total economic cost of increased concentration of salts in the river is given as:

TABLE 5-2

SUMMARY OF ESTIMATED SALINITY IMPACTS ON ALL USERS

(1974 Dollars per mg/l per year)

Agricultural impacts		$108,400
Direct	$ 66,900	
Indirect	41,500	
Municipal impacts		119,500
Low estimate	83,800	
High estimate	285,000	
Industrial impacts		1,500
Total impacts		$229,400
Low estimate	193,700	
High estimate	394,900	
Direct impacts		187,900
Low estimate	152,200	
High estimate	353,400	

SOURCE: U.S. Bureau of Reclamation, January 1974.

Combining this information with the material above allows an evaluation of the salinity costs resulting from diversions for oil shale development:

TABLE 5-3

ESTIMATED COST OF WITHDRAWALS OF WATER FOR OIL SHALE DEVELOPMENT DUE TO COLORADO RIVER SALINITY INCREASES

Source of Water	Salinity Increase (mg/l per 1000 AFY)	Annual Cost (1974 Dollars per AFY)
Colorado River	0.04	$ 9.20
White River	0.07	$16.10
Yampa River	0.07	$16.10

The use to which the above data can be put is not clear in this study. As the costs are indirect, developers will not have to meet them directly. However, they do represent a real social cost of water use, and as such we have decided to include an additional amount per acre-foot per year to water costs to recognize this penalty.

5.1.2.6 Total Extra-Basin Water Supply Costs

In summary, the total cost of water supply to the three sites of the study is expected to be as follows:

ANNUAL COSTS (1974 DOLLARS PER ACRE-FOOT PER YEAR)

Source	Supply	Rights	Salinity	Total
Colorado River	$130	($6)*	$ 9	$139
White River	$105	($6)*	$16	$121
Yampa River	$170	($6)*	$16	$186

* Rights not included in total as costs are potentially recoverable.

Costs of the supply portion of the total are shown for all cases considered in Figure 5-2. Average values shown above ignore the most expensive schemes in each case, and assume that there is no significant economy of scale to be obtained.

The total costs above suggest that water would be drawn from the White River or the Colorado River. A reasonable average cost is $140 per acre-foot (1974 dollars), which allows for some loss of economy due to water requirements lower than those assumed in the Bureau of Reclamation study. This value will be used in the present study.

5.2 GROUNDWATER SUPPLY

As described in Section 3.3 above, the Piceance Basin contains a relatively prolific sequence of rock aquifers. While the quality of the water is not always good, the opportunity to use this resource as a source of water supply rather than constructing dams outside the Basin, obtaining water rights, and pumping the water to the sites, cannot be overlooked. In fact, the detailed development plans of both C-a and C-b Tracts call for groundwater usage as the only significant water source.

This section of the report looks at three aspects of obtaining water by this means:

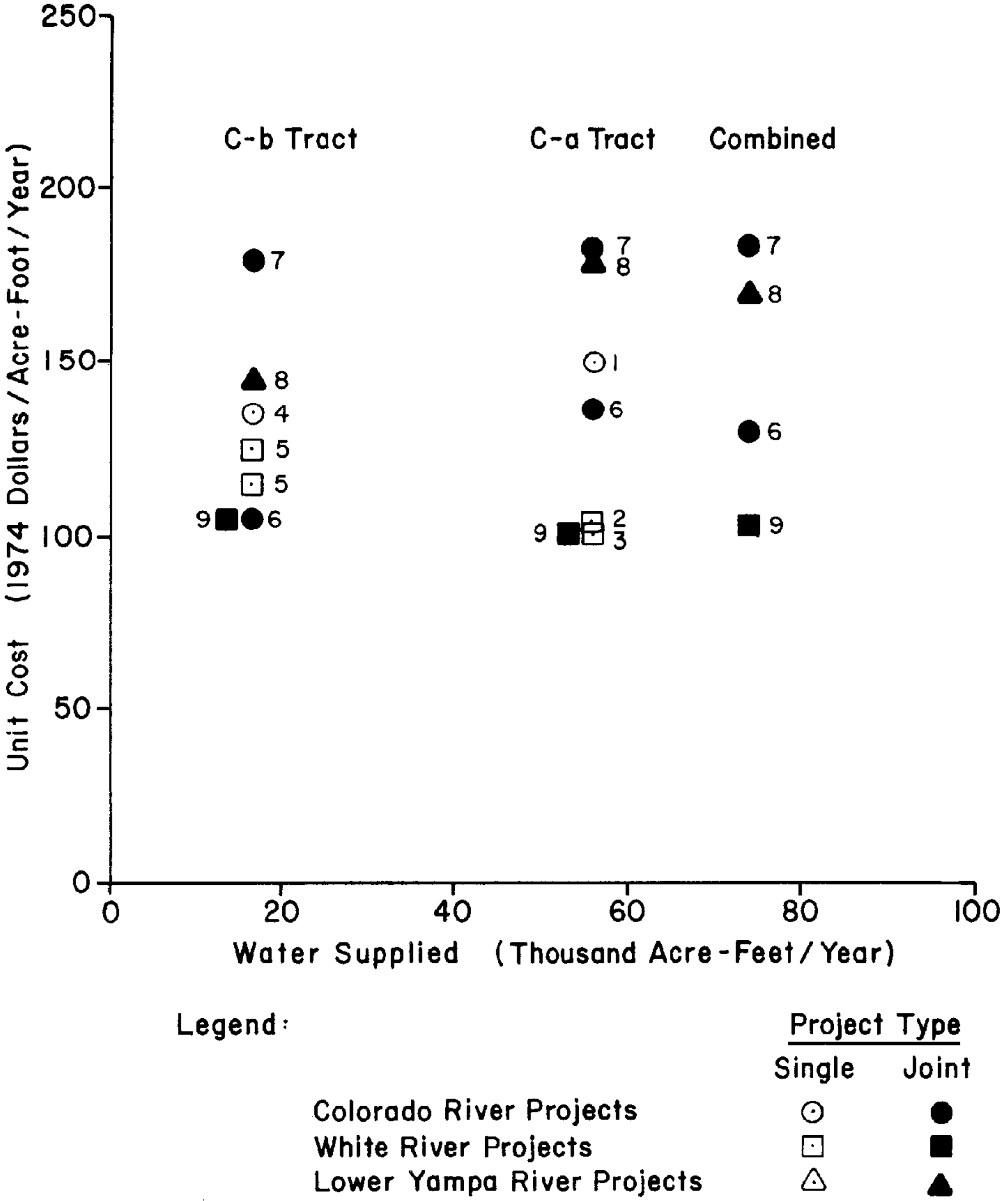
- i. Available quantities of water.
- ii. Cost of obtaining water.
- iii. Legal and environmental considerations.

5.2.1 GROUNDWATER AVAILABILITY AND COST

The normal method of obtaining groundwater is by pumping from wells which are completed in the water bearing deposits. The

Figure 5-2 COST OF SUPPLYING WATER

Source of Data: U.S. Bureau of Reclamation, September 1974



Note: Numbers beside points refer to Proposals: see Text water production of which these wells are capable is determined by the geometry of the well, the spacing between wells, the drawdown in each well, and the geohydrologic characteristics of the strata at and near the well site.

The results of analyses of the flow available from individual wells are presented below. Allowance has been made for the fact that the drawdowns may be large compared with the depth of the aquifer system. The optimum flow available from a single well has been computed by balancing the higher flows available by increasing the drawdown with the higher costs involved in lifting the water a greater distance to the surface. The basic parameters used are:

i. Geohydrology - as given in Chapter 4 for each site.

ii. Well Costs - $100 per foot, including drilling, casing, screens, purchase of pump, installation, and wellhead gear (12" diameter well).

iii. Pipeline Costs - arbitrarily assumed equal to the cost of the well.

iv. Lifting Efficiency - assumed 80% (i.e. 20% overall energy loss due to friction, pump inefficiency, entry and exit losses, etc.).

v. Power Costs - 2.0¢ per kilowatt hour.

vi. Well Life - assumed 10 years.

vii. Interest Rate - assumed 6% pa.

Using these parameters, some useful derived parameters are:

i. Installation Cost = $200 per foot of well.

ii. Lift Costs = 3.08¢ per acre-foot per foot lift.

iii. Depreciated annual cost of the capital expenditure on the well = 13.6¢ per capital dollar per year (for 10 years).

5.2.1.1 Site 1 Groundwater Well Performance

Site 1 is characterized by a relatively high "water table", a prolific aquifer above the Mahogany Zone, and a relatively prolific aquifer between the Mahogany and saline zones. Accordingly, the direct cost of obtaining water from subsurface resources is relatively small. The results of the inflow/drawdown analysis are shown in Figure 5-3. The cost comparison for different flow rates from each well are shown in Figure 5-4. These clearly show that the minimum cost per acre-foot is about $30, and that this applies for an operating flow per well of 2,000-4,000 AFY (1,100-2,700 gpm).

The analysis assumes that there is no interference with other wells or with mine inflow dewatering effects. For the flow rates nominated, and assuming the vertical permeability parameters given above, wells spaced in excess of 1,000 feet apart will interfere to cause about a 30% drop in production. However, as it is expected that wells for water supply purposes could be spread very much more widely than this, this should not have any impact.

If mine inflow is significant from the same strata as are tapped by the wells, it may be assumed that the water withdrawn

Figure 5-3 FLOW/DRAWDOWN RELATION FOR A WELL AT SITE I

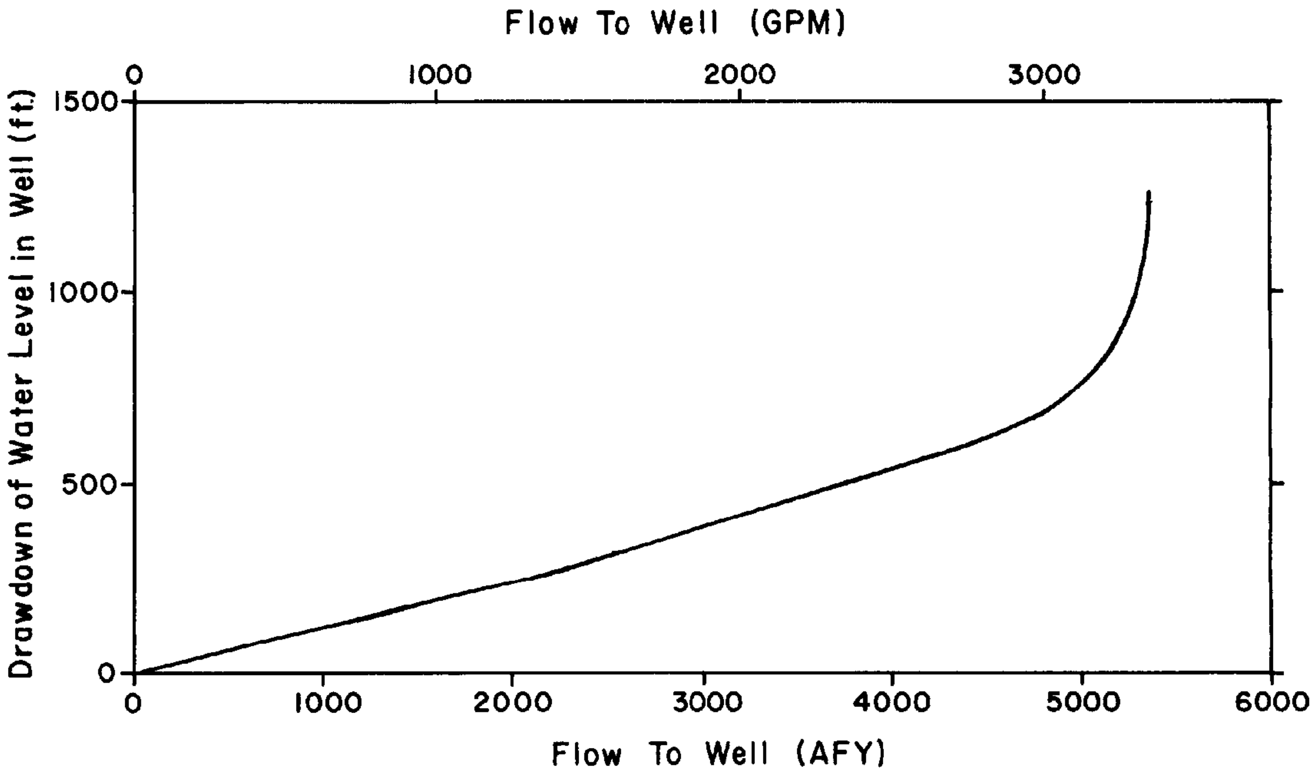
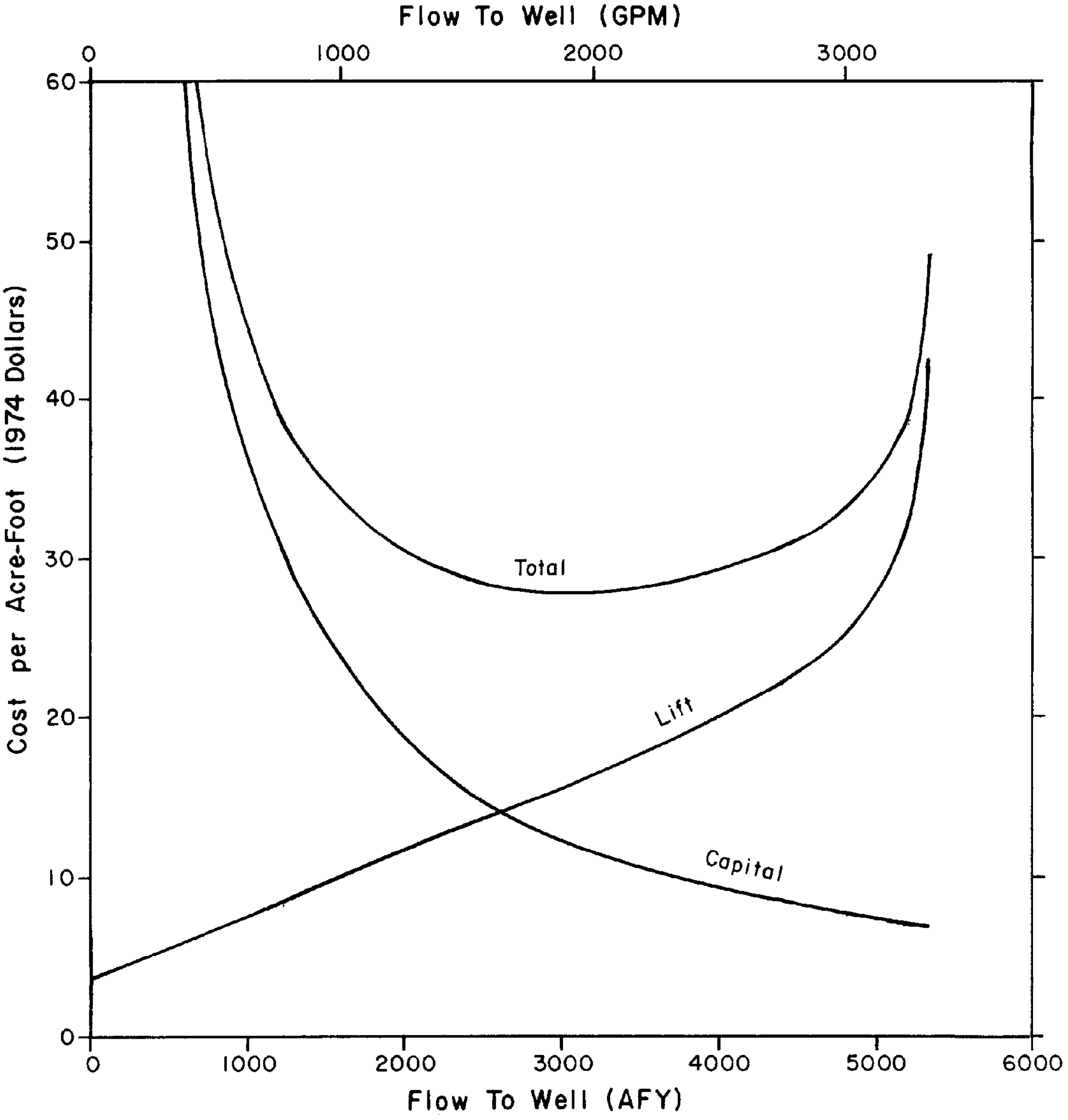


Figure 5-4 UNIT COSTS OF GROUNDWATER AT SITE I



from the wells will have an impact on reducing mine inflow. Each case must, however, be evaluated individually.

In summary, groundwater may be obtained from wells at Site 1, at a cost of approximately $30 per acre-foot, for well flows of between 2,000-4,000 AFY (1,100-2,700 gpm).

5.2.1.2 Site 2 Groundwater Well Performance

Site 2 is characterized by a prolific water-bearing zone just above the Blue Marker (i.e. between 850 and 1,050 feet below surface), and a relatively unproductive zone between the water table and Horizon X. The cost of obtaining groundwater from a well which is drilled to the Blue Marker is accordingly relatively low.

The relationship between drawdown and flow is shown on Figure 5-5, and the relationship between unit cost and flow is shown on Figure 5-6. In summary, wells at Site 2 will produce about 1,500-4,000 AFY (1,000-2,500 gpm) of water at 300-600 foot of drawdown, at a cost of around $30 per acre-foot.

5.2.1.3 Site 3 Groundwater Well Performance

Site 3 is characterized by substantially less permeable rocks than in the previous two cases. Accordingly, water flows are lower and drawdowns and unit costs are higher. The flow/drawdown relation for a well penetrating to Horizon X is shown on Figure 5-7, and it can immediately be seen that even if the well is fully drained, less than 1,000 AFY (600 gpm) can be expected from an average well.

Figure 5-5 FLOW/DRAWDOWN RELATION FOR A WELL AT SITE 2

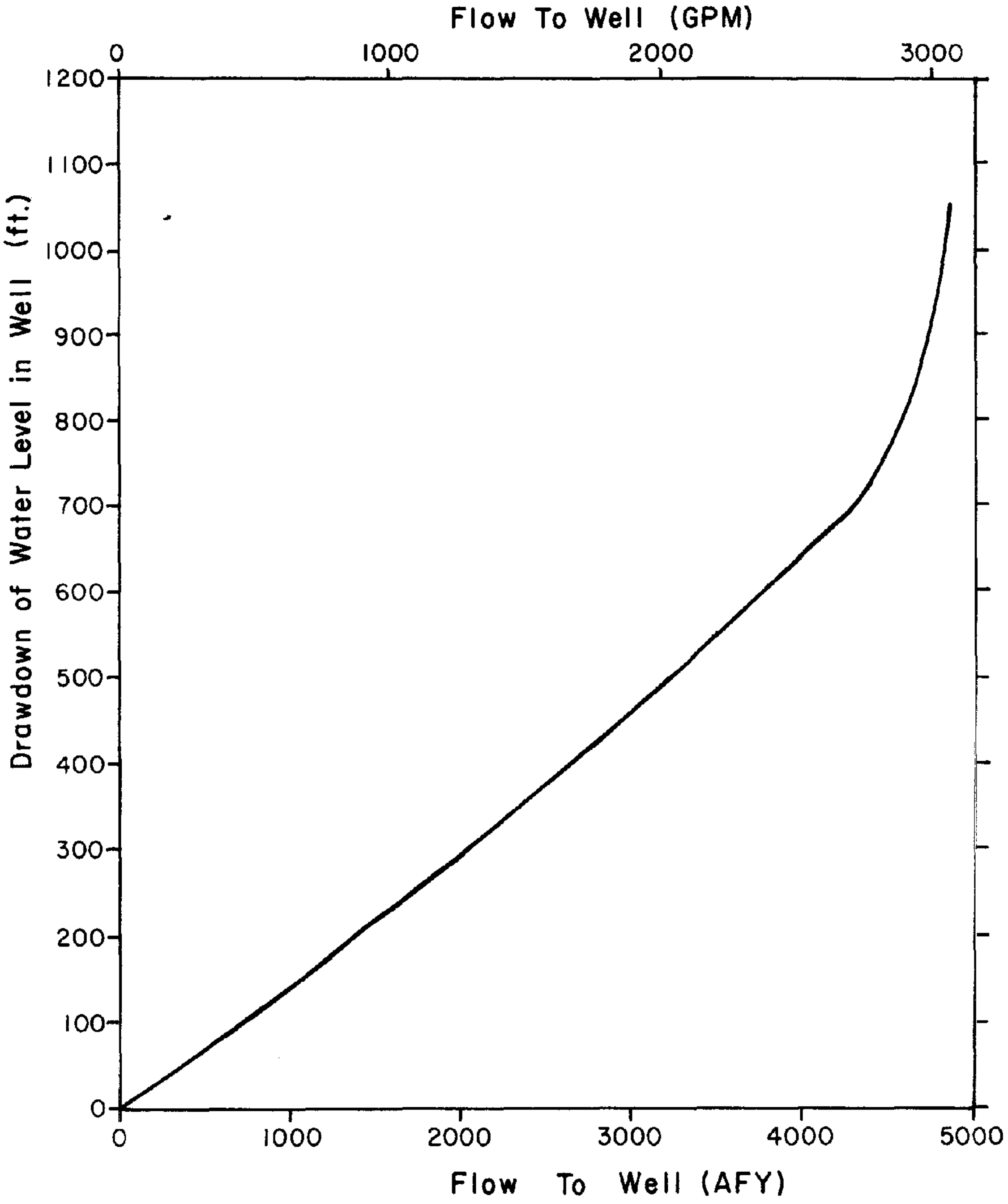


Figure 5-6 UNIT COSTS OF GROUNDWATER AT SITE 2

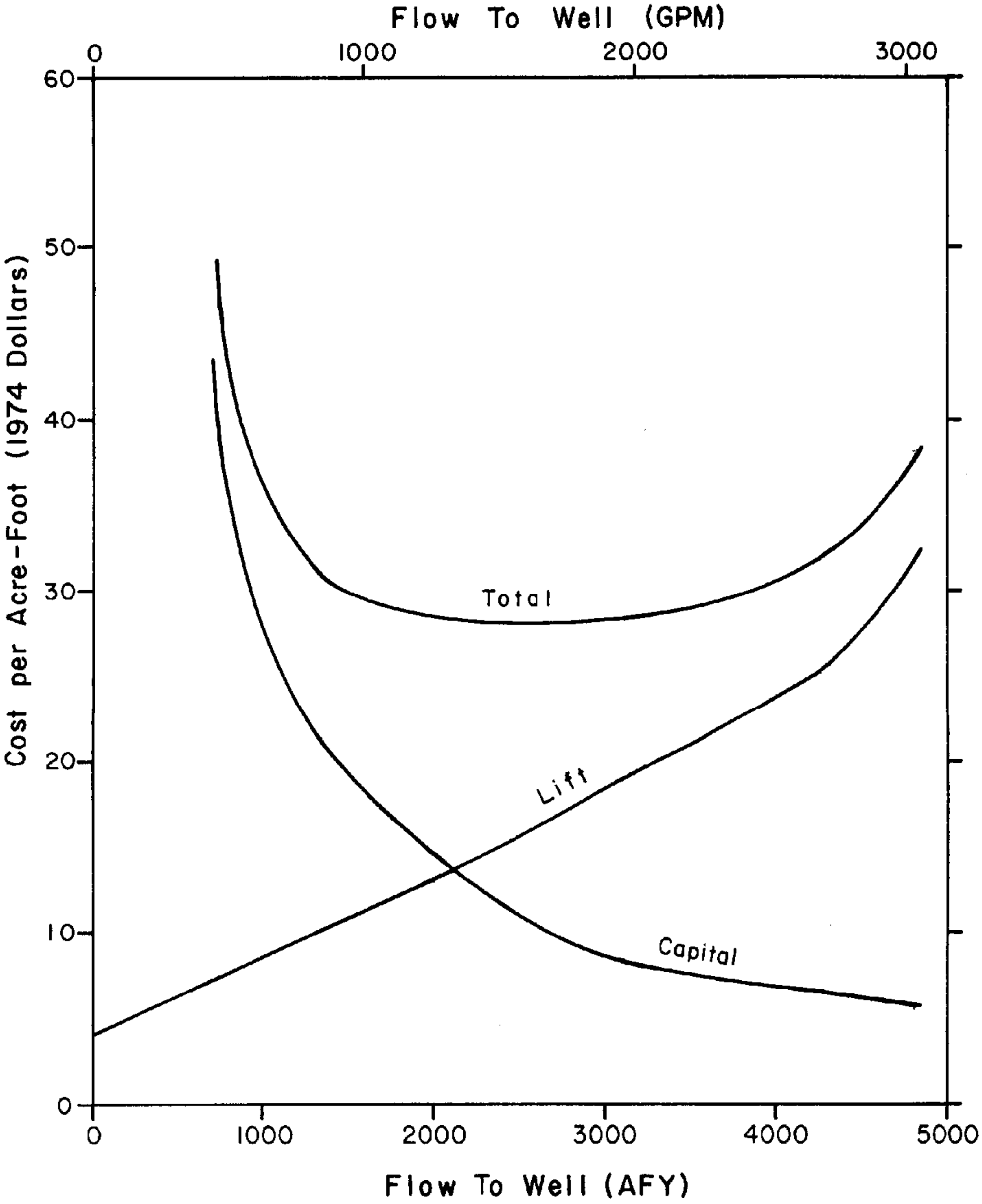
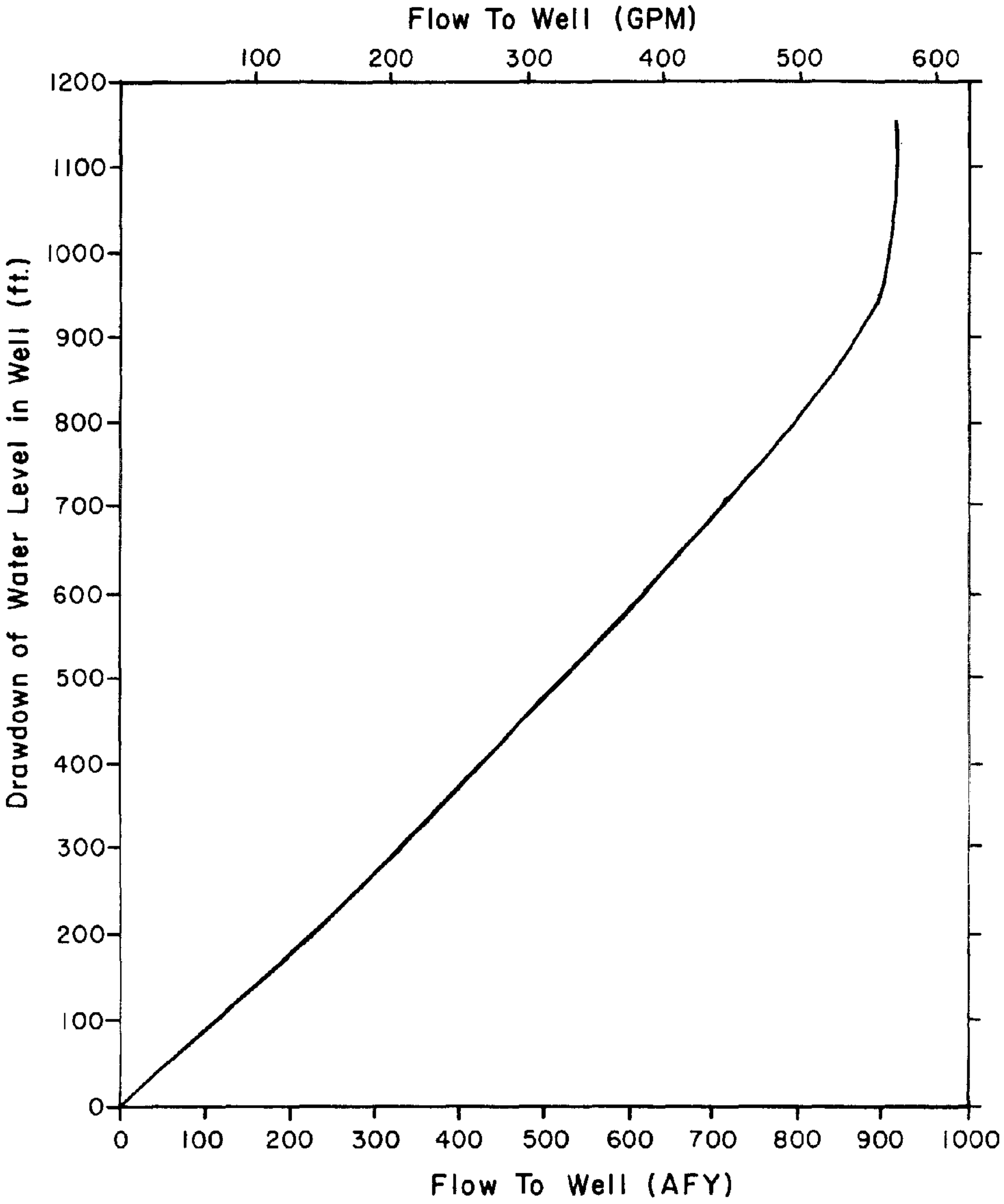


Figure 5-7 FLOW/DRAWDOWN RELATION FOR A WELL AT SITE 3



The cost/flow relationship is shown on Figure 9-8, and this is dominated by the high capital cost of the well per acre-foot of water produced. This suggests that it is prudent to run the well at a very large drawdown and that even if 700-900 AFY (400-550 gpm) can be obtained, the unit cost of water of $90 per acre-foot will result. This is three times more than at Sites 1 and 2.

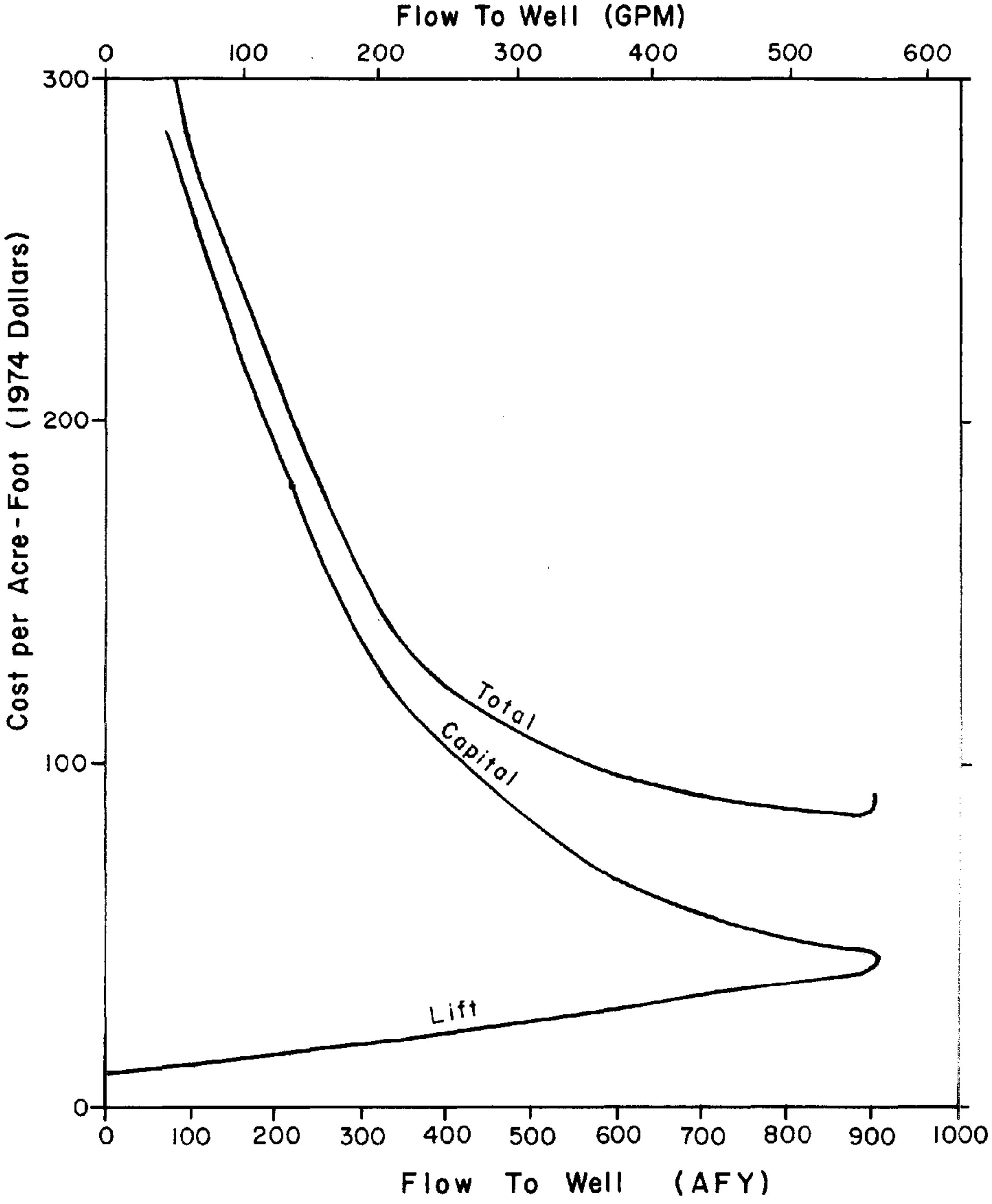
5.2.2. LEGAL AND ENVIRONMENTAL CONSIDERATIONS

As explained in Appendix B, the groundwater of the Piceance Basin is in general the property of the state of Colorado, and is subject to the same appropriation procedure as surface water. Thus it will be necessary for any user to obtain a water right before using this water. While this in itself is not difficult, the problem which will be created will relate to injuries to other actual and potential users.

The removal of water from the rock aquifers of the Basin has a very widespread impact on the pressure of water in the aquifers. Thus, removal of water at one locality will significantly increase the pumping head, and hence the costs, of removing water from wells at adjacent locations. Additionally, the total flow obtainable from wells nearby will be reduced as a result of the operations of prior installations.

Not only does the likelihood of injury to other actual and potential groundwater users exist, but the interception and consumptive use of groundwater flow by wells will also reduce flows in the perennial streams of the Basin. Although the relationship between streamflow and deep groundwater is not yet fully understood, analysis suggests that a significant proportion of the stream baseflow originates from the deep

Figure 5-8 UNIT COSTS OF GROUNDWATER AT SITE 3



aquifers in the marlstone of the Parachute Creek Member, rather than from the more perched aquifers of the Uinta sandstone (Weeks, et al., 1974).

In order to determine questions of water ownership, damage to other users, and optimum utilization of the groundwater resource, it will probably be necessary to utilize a model of the hydrologic system which operates in the Basin, combined with a comprehensive network of observation piezometers in the major water-bearing units in the Basin. By simulating the development of water pressure declines under withdrawals at various locations, the incremental impact of each usage, at a given surface or subsurface location, may be evaluated. Compensations can then be determined on a rational basis. This approach, which differs from that used in most other areas, will allow beneficial use of a highly interconnected water supply, which might otherwise not be available because of legal and ownership disputes.

Groundwater in the Basin comes from recharge or from storage. Weeks, et al. (1974) conclude that the Basin contains 2.5 million to 25 million acre-feet of available water, and that it receives a recharge of 24,100 acre-feet per year by way of surface water infiltration. Clearly, total usage of groundwater in excess of this latter figure will constitute mining of the groundwater resource, which is, however, reversible upon cessation of the withdrawal.

CHAPTER 6
WATER DISPOSAL AND TREATMENT

The disposal of water and the treatment of water to use or discharge standards are matters of central importance in the water-deficient study area. Water quality is usually sufficiently low to require treatment before it is suitable for any use. This chapter describes the quality requirements for various use and discharge categories, some methods and costs of treating water to those standards, and methods of disposal.

6.1 WATER DISPOSAL

Based on the results of our investigations, it seems likely that there will be a significant excess of available water over water requirements for most of the mining/retorting complexes. In this context, water is "disposed of" if the amount used in any phase is greater than the reasonable minimum necessary for any part of the shale oil recovery system. It is important to make this distinction because of the capability to dispose of water in spent shale piles in excess of the quantity needed to make the spent shale transportable and compactable.

This section evaluates means of disposing of water. It is assumed in this section that water is a valuable resource in the study area, and thus water recycling, reinjection, and treatment are all assumed to be important resource optimization tools.

Because water is such a limited resource in Colorado, there is a substantial body of regulatory and legal restraint relating to water quality. These primarily relate to the quality of effluent discharge to surface streams and subsurface aquifers. A detailed discussion of these appear in Appendix B, and summaries appear in the appropriate sections below.

6.1.1 Direct Discharge to Streams

Discharge to surface streams is regulated by the Colorado Department of Health using standards approved by the Environmental Protection Agency. Broadly, these provide that discharges to streams from industrial activities shall meet all toxicity requirements for drinking water, and conditions laid down by the Department of Health. The total dissolved solids contained in effluent waters must not exceed the receiving water concentrations under the anti-degradation clause in the regulations. Finally, the salinity should be such that it does not burden the Colorado River system, which potentially limits discharge dissolved solids concentrations to about 700 mg/l. Table 6-1 summarizes the discharge standards which it would appear prudent to achieve.

There are no known specific regulations relating to the quantity of water which can be discharged to any stream. However, there will certainly be constraints imposed by environmental considerations. Particularly the minimization of erosion and minimization of the impact of increased flows on channel morphology, both for environmental and bridge and dam safety reasons will pose some restrictions. However, it is unlikely that objection can be raised if the disposal rate does not exceed the previous average streamflow.

TABLE 6-1
WATER QUALITY GUIDELINES FOR DISCHARGES TO STREAMS WITHIN PICEANCE BASIN

General Guidelines		Toxic Materials Guidelines	
Standard	Requirements	Contaminant	Maximum Level Allowable (mg/l)
Settleable Solids	Free From	Arsenic	.05
Floating Solids	Free From	Barium	1.0
Taste, Odor, Color	Free From	Cadmium	.010
Toxic Materials	Free From	Chromium	.05
Oil and Grease	Cause a film or other discoloration	Lead	.05
Radioactive Material	Drinking Water Standards	Mercury	.002
Fecal Coliform Bacteria	Geometric Mean of <1000/100ml from five samples in 30-day period	Nitrate (as N)	10.0
Turbidity	No increase of more than 10 J.T.U.	Selenium	.01
Dissolved Oxygen	5 mg/l minimum	Silver	.05
pH	6.0 - 9.0	Fluoride	1.4 - 2.4
Temperature	Maximum 90°F Maximum Change: Streams - 5°F Lakes - 3°F		
Fecal Strepotococcus	----		

SOURCE:
Colorado Department of Health,
Water Quality Control Commission,
Water Quality Standards and Stream Classification, 1974, p. 11.

SOURCE:
Environmental Protection Agency,
National Interim Primary
Drinking Water Regulations,
Federal Register, July 9, 1976.

6.1.2 Disposal in Spent Shale Piles

Spent shale can be compacted satisfactorily with moisture contents which may range from dry (Paraho) to 23% (TOSCO II). For the purposes of dust control during transport and disposal, it is expected that a minimum moisture content of 8% will be required. Assuming that the practical maximum water content is 20%, this leaves a range of 12% by weight of the spent shale which can be used as a "reservoir" for disposal of foul water. For a 50,000 TPD operation, 85% by weight of the ore (42,500 TPD) appears as spent shale, providing a potential water disposal rate of 5,100 TPD or 1,370 AFY (850 gpm) above that needed for dust control. This water could be of any quality, provided it could be shown that the water will stay in the shale pile, and providing a way to add it to the spent shale can be found which does not involve spraying. As discussed in Chapter 10, it is presently expected that the low permeability of the spent shale pile, combined with high evapotranspiration rates, will ensure that leaching through the piles will be negligible.

A significant problem with disposal in this way is that it wastes two potentially reclaimable products - dissolved salts (mainly bicarbonates) and water. As technology is now available for the treatment of wastewater in the volume and of the type expected, this matter may become increasingly relevant to oil shale processing.

6.1.3 Evaporative Disposal

In the Piceance Basin evaporative disposal of foul water is a possible means of disposal. Annual evaporation in the Basin averages about 45 inches per year (Wymore, 1974), but takes place primarily in the months April to October. Precipitation averages 16 inches per year, so net evaporation is 29 inches. Based on this rate, an evaporation pond could dispose of 2.4 AFY (1.5 gpm) per acre of pond. It is clear that rather large ponds would be required for even modest disposal rates. However, this might be a feasible disposal method for very saline waters, for example those originating from a reverse osmosis plant or from retort stripping. Because of the pervious nature of the near-surface rock materials, it would be necessary to line or seal any long term evaporation pond to prevent seepage.

Based on a dam placed in a typical gulch in the Basin and on a 100-acre size (to produce disposal of 240 AFY - 150 gpm), the total cost of construction of a lined, earth-embankment type retaining pond would be in the order of $1,200,000 (1974 Dollars), assuming a 50-foot high embankment at the center of the gulch. Assuming a 10-year life and a 6% capitalization rate, this produces an annual cost of $163,000, or $690/AF of water evaporated. The value is not very sensitive to size.

6.1.4 Well Injection

The regulations relating to discharge to aquifers are not particularly well defined. However, in analogy with disposal to streams, it seems likely that subsurface emplacement of water will be allowed only providing that the quality of the water injected is in all respects equal to or better than that in the receiving aquifer, and that it does not disrupt the receiving environment. This follows from an application of the anti-degradation concept to subsurface water injection.

Two special considerations are worthy of note in the Piceance Basin context. First, it is conceivable that operators might wish to inject low quality water into the low quality aquifers at depth. However, due to their relatively low permeability and porosity this might result in these aquifers becoming overpressured, and thus enhance leakage of foul water to better quality aquifers above. It is likely that permits for this kind of injection will not be obtainable.

Secondly, a likely scenario is that an operator will wish to reinject dewatering or mine inflow water back into the same aquifer from which it came. The dual benefit from this would be the recharging of water pressures back towards their pre-mining levels, and the disposal of unusable water. It would seem highly unlikely that an application to install such a system could be refused by a responsible regulatory body.

The costs of well-injection disposal vary with site and water quality. However, assuming that the hydrogeological models presented in Chapter 4 relate also to the injection sites, and that injection is carried out between the present "water table" and the top of the leached zone, under an injection head of 400 feet, then for wells spread 1,000 feet or more apart the injection rate which can be sustained on Sites 1 and 2 is in excess of 800 AFY (500 gpm) per well. Due to the lower permeability of Site 3, a rate of only about 320 AFY (200 gpm) per well can be sustained at that site. Cost of wells and casing is about $100 per foot, and the pipe network to take water to the wells possibly equals the well cost, producing a cost of about $200,000 per well. If it is assumed that the wells would last 5 years, then the cost per year would be $48,000 at a 6% discount rate, and the cost per acre-foot of disposal per year would be $60 for Sites 1 & 2 and $150 for Site 3.

Disposal wells are difficult to keep in working order due to clogging and corrosion. Accordingly, they have in the past been used relatively sparingly for large volume disposal. Unaccounted costs in the above computation include maintenance and pumping costs to transfer the water to the well.

6.1.5 In-Mine Disposal

The other subsurface disposal technique involves storage in mine backfill material. Based on our computations in Chapter 10, and on the study of backfilling techniques by Cleveland-Cliffs Iron Company (1977), the transporting of the shale requires slurrying to a consistency which is 60% water by weight. Once placed in the mine, 65% - 75% of the water drains off. This leaves a residue of 30% by weight water in the final backfill. Based on a 50,000 TPD mining rate, producing 42,500 TPD of spent shale, of which 40% (or 17,000 TPD) is estimated could be stowed underground by this method, then this would absorb a maximum of 2,300 AFY (1,400 gpm) of waste water. Direct additional costs would be small, as the spent shale has to be disposed of in some way.

However, there are two major environmental problems with this approach. First, the 60% of material which could not be stored below ground would have to be stored above ground, much of it as slimes underflow from cycloning the slurry in order to improve in-mine backfill drainage. This would create a massive environmental problem. Second, the injection of a slurry of spent shale and water into the midst of the aquifer system in which the mine is located would certainly create major potential for leaching of the spent shale and transport of the leachate into the aquifers. For these reasons we do not consider this technique of water/spent shale disposal as very attractive.

6.2 WATER TREATMENT

The quality of water which is available to shale oil industries is, in general, low. The input water quality requirements for the industry vary from potable to unrestricted. As a result, there is a considerable demand for water supplies which are of higher quality than that of the supply, so that water treatment will be required. This section evaluates the need for treatment, and the likely unit cost of treatment, so that these parameters can be used in the system integration phase (Chapter 11).

6.2.1 QUALITY OF AVAILABLE WATER

There are three primary external sources of water for a shale oil industry: groundwater, extra-basin surface water, and water stripped from the oil produced by retorting.

i. Groundwater. As discussed in Section 3.3.5, the quality of groundwater is believed to vary dramatically across the Basin, and with depth in any location. However, for the three sites selected, the quality of groundwater only varies from 1,000-3,000 mg/l, with an expected flow-weighted mean of about 1,500 mg/l. Because the computations in the remainder of this chapter are relatively insensitive to precisely what value is taken for this salt concentration, the value of 1,500 mg/l will be used.

It transpires that the only specific ion which appears in too great a concentration to satisfy present drinking water standards is fluorine. It will be assumed that, on average, fluorine is present in the groundwater at 5 mg/l concentration, which is equivalent to the water from between the base of the Mahogany Zone and Horizon X.

ii. Extra-Basin Surface Water. The quality of water from outside the Basin depends upon the source of supply. As detailed in Chapter 5, the major likely sources are the Colorado and White Rivers.

Colorado River water at Rifle has an average salinity of 500 mg/l, varying from 160 to 930 mg/l. No dissolved ion exceeds the toxicity level maxima for drinking water, although there are seasonal turbidity highs beyond drinking water standards.

White River water would be diverted from either the vicinity of Buford, upstream of Meeker, or from the vicinity of the junction of the mouth of the Piceance Creek and White River. The quality depends upon whether it is pumped directly to the use point, or allowed to flow down Piceance Creek to the use point. The former method delivers water at about 270 mg/l, while the latter delivers water at about 320 mg/l. Toxicity requirements for dissolved ions would probably not be exceeded in either case.

For the purposes of this study an average total dissolved solids for imported surface water of 350 mg/l will be assumed.

iii. Stripped Foul Water. This water is highly saline (up to 40,000 mg/l dissolved solids) and also contains significant quantities of organic pollutants. An average of 25,000 mg/l of total dissolved solids will be assumed for this water over the entire project, and an average of 40 mg/l of fluoride ion concentration will also be assumed.

6.2.2 TREATMENT

6.2.2.1 Reverse Osmosis

Most potential developers of oil shale industries in recent years have looked to reverse osmosis as a treatment method for removing dissolved solids from water. In this method the feed solution and the product solution are separated by a membrane, and the pressure on the feed side is elevated to a level sufficient to force relatively pure water back through the membrane against the normal osmotic pressure. Hence the name "reverse osmosis" which has been applied to the system.

The ability of this method to improve the quality of water is quite dramatic. For non-hydrocarbons, the rejection percentage (concentration in feed minus concentration in product water, as a ratio of the concentration in the feed water) is between 90 and 99%. Table 6-2 shows typical rejections.

Costs of reverse osmosis systems have been presented by Fenix and Scisson (1976) and Water Purification Associates (1975). For the purposes of this report, it is convenient to break these costs down into a pre-treatment phase and a reverse osmosis phase, as pre-treatment is a major part of the cost. This information is presented in Table 6-3.

TABLE 6-2
TYPICAL REJECTIONS* BY REVERSE OSMOSIS MEMBRANES

Species	Rejection (%)
Ca^{2+}	99
Mg^{2+}	99
Na^{+}	94-96
Ni^{2+}	98
Cr^{6+}	95-97
Copper	>99.5
Cl^{-}	94-95
F^{-}	∿ 90
Cyanide	∿ 90 (pH dependent)
H_3BO_3	30
Sugars	99.9
Formaldehyde	25
Phenol	0-60 (pH dependent)
Benzyl alcohol	0

$$* \quad \text{Rejection} = \frac{\text{(conc. at membrane - conc. of product)}}{\text{concentration at membrane}}$$

SOURCE: Water Purification Associates, 1975, p.76.

TABLE 6-3

COST BREAKDOWN FOR REVERSE OSMOSIS SYSTEMS

(Costs in 1974 Dollars Per Acre-Foot)

Treatment	Feed Water Quality 2,000 mg/l Capital	 Operating	 Total	 30,000 mg/l Capital	 Operating	 Total
Pre-treatment	98	18	116	163	27	190
Reverse Osmosis	29	80	109	59	216	275
TOTAL	127	98	225	222	243	465

DATA SOURCE: Fenix and Scisson, 1976, p.113.

NOTE:
1. Data on original table for a flow rate of 2,400 AFY. For simplicity it is assumed that any economies of scale are small.
2. Data assumes that the product:concentrate ratio is 3:1, and that treatment is on a single pass basis.
3. Capital costs depreciated at 6% over a 10 year life.

The reverse osmosis technique produces significant quantities of concentrate flow (25% of the original inflow rate for non-recycled flows). Thus second stage treatments by this technique are often attractive to produce high concentration effluent. Such treatment does not, of course, require any further pre-treatment.

The cost data given in Table 6-3 have been generalized to cover the expected range of dissolved solids for this study. Figure 6-1 shows the relation between TDS and cost for pre-treatment, while 6-2 shows the same relation for reverse osmosis alone.

6.2.2.2 Method of Analyzing Treatment Costs

There are a very large number of possible water purification systems which would be appropriate for an oil shale industry.

Figure 6-1 PRETREATMENT COSTS FOR REVERSE OSMOSIS

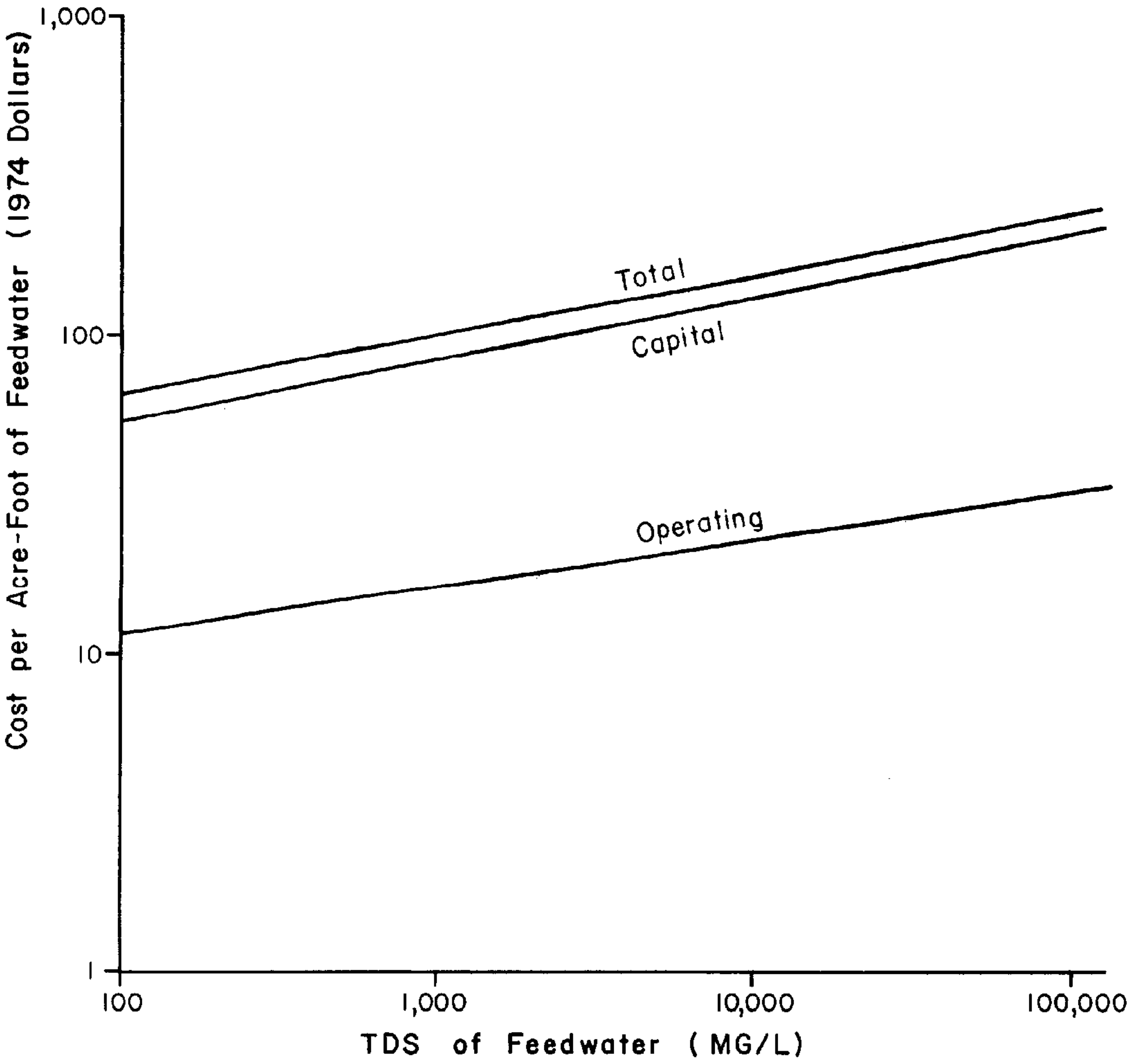
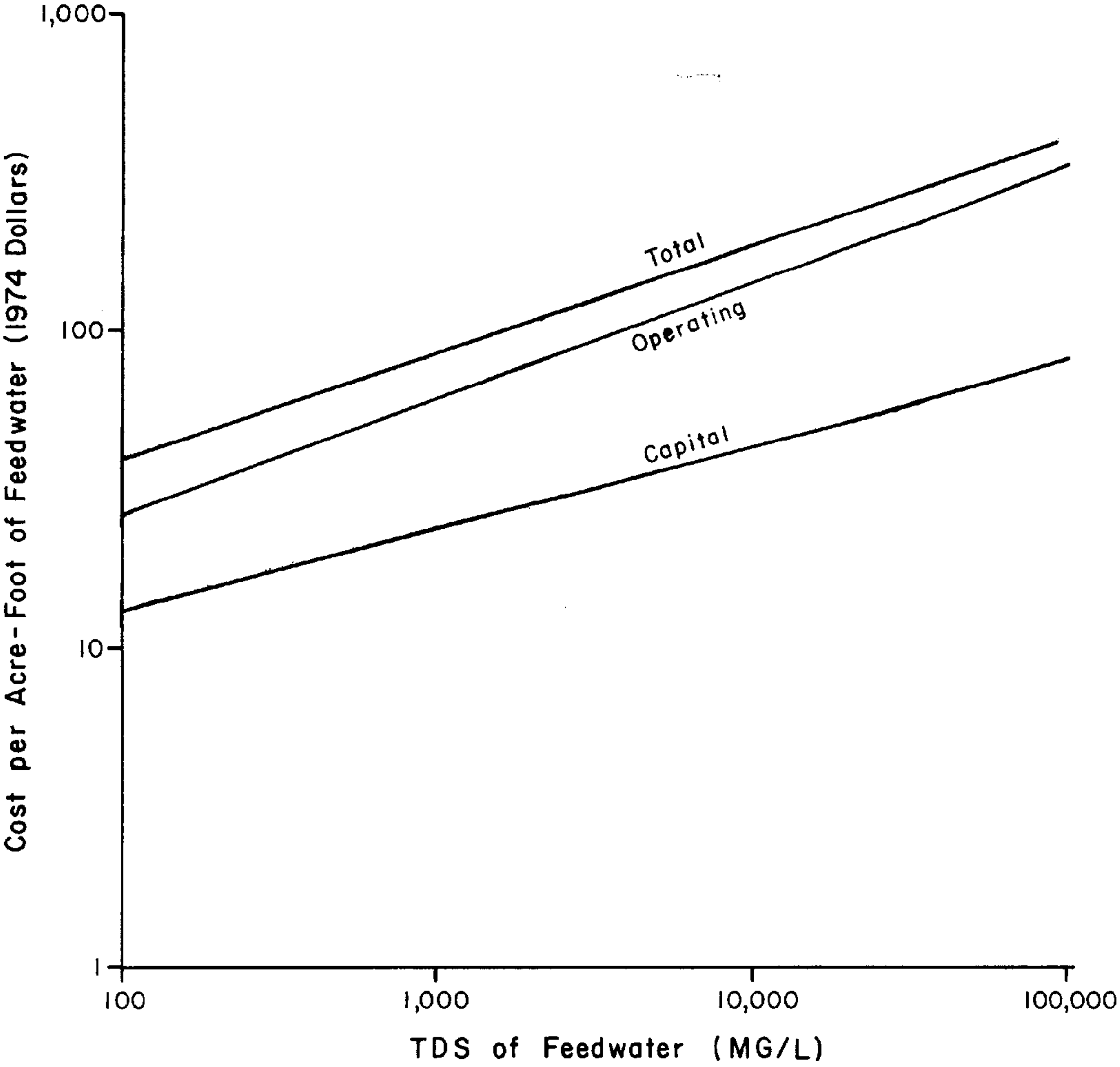


Figure 6-2 REVERSE OSMOSIS COSTS (EXCLUDING PRETREATMENT)



For the purposes of evaluating the costs in this project, it is only necessary that the chosen system produces costs which are realistic and can be compared with those used to evaluate the cost of external water supply.

We have analyzed each water treatment system in either a bypass or recycle mode, and have used second stage purification only where it is essential to meet quality criteria.

i. Bypass Mode. This mode is shown in Figure 6-3. It utilizes reverse osmosis of only part of the pretreated stream, and the product is a blend of low TDS filtrate and unpurified feed water. Although the bypass water could in some instances be un-pre-treated, we have assumed that turbidity and organic content requirements make full pre-treatment necessary. Bypass mode treatment is generally cheaper than recycle when the product quality requirements are not vastly different from the input quality. The method produces relatively large volumes of concentrate, which may pose severe disposal problems in some cases.

ii. Recycle Mode. This mode is shown in Figure 6-4. The quantity of concentrates recycled is set equal to that necessary to produce the desired product concentration in one osmosis module. This has the effect of elevating the concentration of the waste stream, thus reducing the concentrate disposal problem. An additional effect is that the quantity of feed water needed to produce one unit of product water is reduced in this method, as the waste stream is smaller than in the bypass method. In fact, the method is actually cheaper in cases

Figure 6-3 BYPASS PURIFICATION SYSTEM

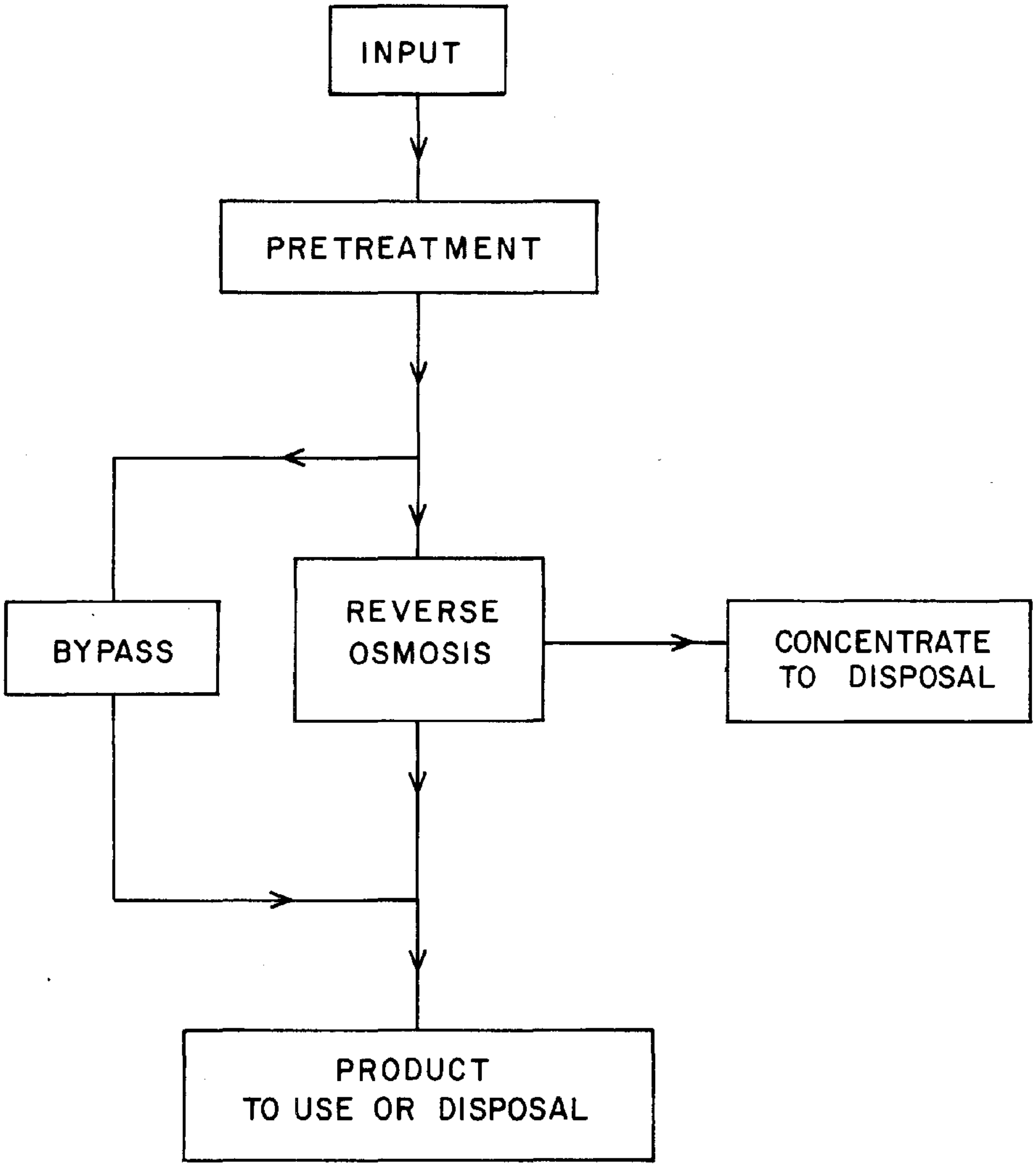
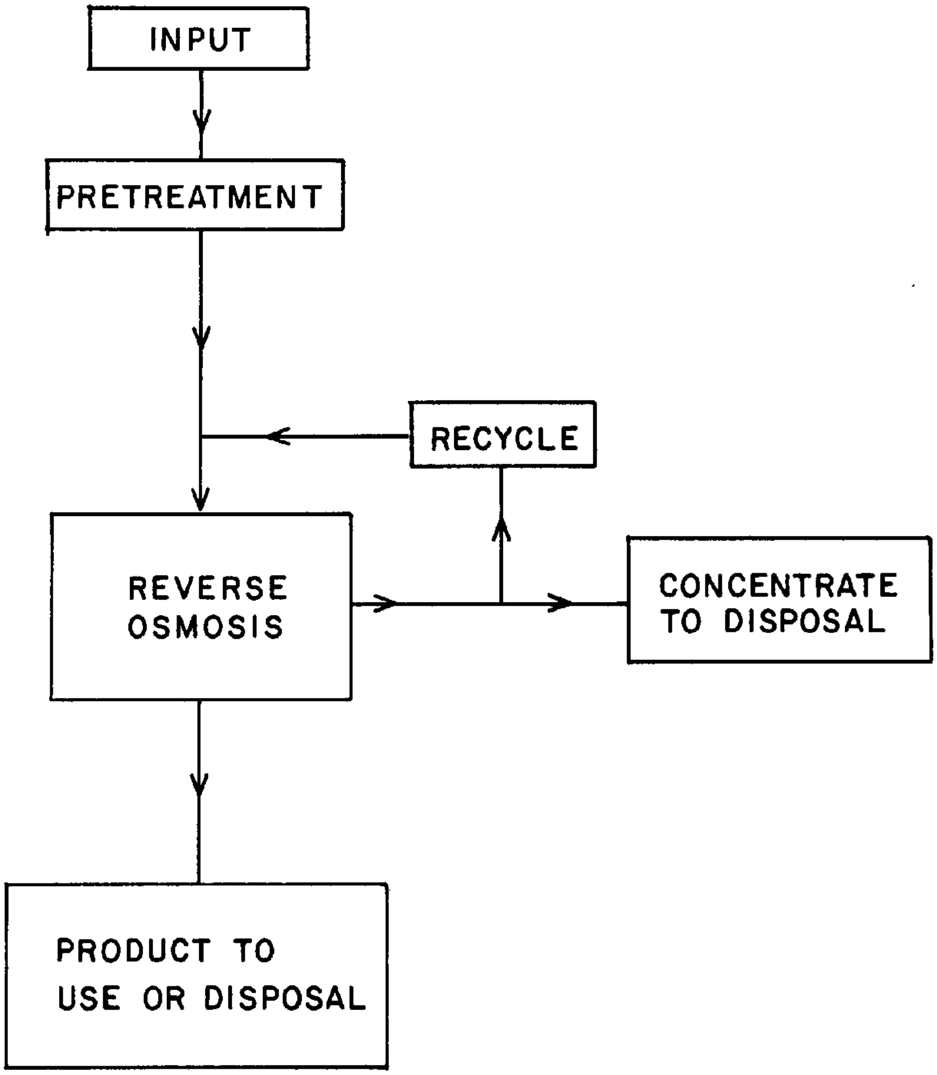

INPUT
PRETREATMENT
BYPASS
REVERSE OSMOSIS
CONCENTRATE TO DISPOSAL
PRODUCT TO USE OR DISPOSAL

Figure 6-4 RECYCLE PURIFICATION SYSTEM


INPUT
PRETREATMENT
RECYCLE
REVERSE OSMOSIS
CONCENTRATE TO DISPOSAL
PRODUCT TO USE OR DISPOSAL

where the difference between the input and product qualitites is large. It has been used below only where the unit cost is lower than for the bypass method.

iii. Two Stage Purification. If the maximum concentration reduction available in a single pass of the reverse osmosis units is inadequate for requirements (as it usually is in foul water applications), a second stage of purification is necessary. The first stage is a normal, full reverse osmosis, followed by either a bypass or recycle second stage. As with the single stage systems, the arrangement shown in Figure 6-5 is only one of many which is possible for this task. Analysis results used in this section show the less expensive of the two systems for the particular case presented.

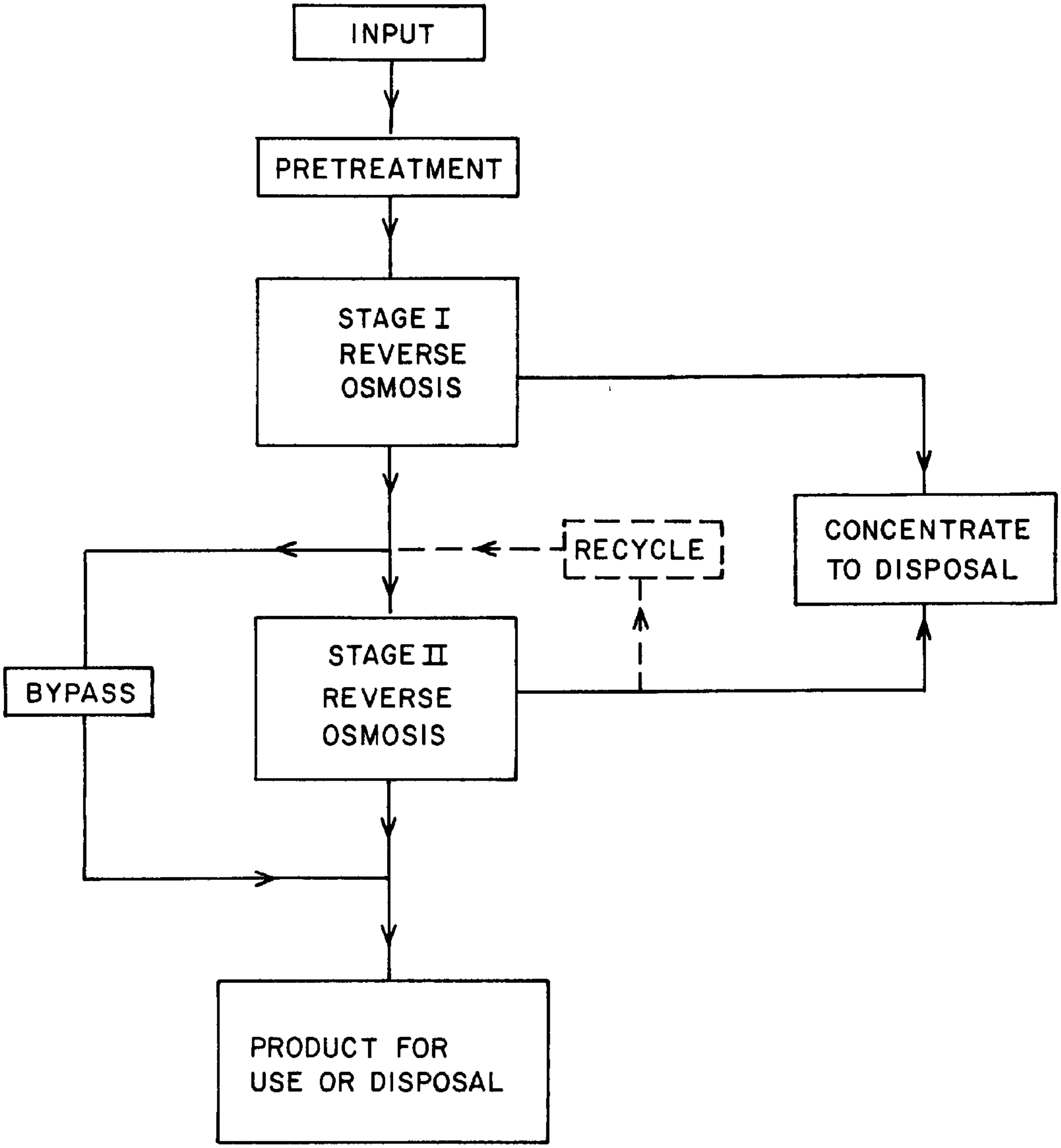
6.2.3 REQUIRED WATER TREATMENTS FOR AN OIL SHALE INDUSTRY

There are several levels of quality of water which are necessary for a shale oil industry.

6.2.3.1 Boiler Feed Water

Make-up water for boiler feed must be of a high quality, with little or no hardness, in order to prevent fouling of boiler pipes. The characteristics of boiler feed water have been given in the U-a/U-b DDP as having a total dissolved solids level of 50-100 mg/l and a total hardness of less than 5 mg/l equivalent $CaCO_3$. No hydrocarbon content is allowed.

Figure 6-5 TWO STAGE PURIFICATION SYSTEM


INPUT
PRETREATMENT
STAGE I REVERSE OSMOSIS
CONCENTRATE TO DISPOSAL
RECYCLE
BYPASS
STAGE II REVERSE OSMOSIS
PRODUCT FOR USE OR DISPOSAL

Note: Either bypass or recycle (shown dotted) can be used in the system.

The costs of obtaining boiler feed water from each major water source are presented in Table 6-4. In this table it is assumed that the concentrate from the reverse osmosis plant is used for spent shale wetting. In reviewing the costs it should be noted that the cost of boiler feed from river water does not include the cost of obtaining or transporting the water.

6.2.3.2 Service Water

There is a considerable need for clean, relatively low-solids water for servicing the retorting, mining, and spent shale sections of the industry. The primary criteria governing the quality of this water are that it should have low turbidity, and low total dissolved solids, primarily because it is used extensively in spray nozzles which are clogged by both these agencies. The U-a/U-b DDP specifies 400-800 mg/l of total dissolved solids as an acceptable range, with 20-50 mg/l suspended solids, but no hydrocarbons allowed.

As with boiler feed water, there is no strict necessity to precondition all of the service water, whether it is going to be purified or not. However, we have assumed that this will be performed, in order to ensure that all figures in this section are comparable. Also, the U-a/U-b DDP (which has by far the most comprehensive water management plan of all the DDP's) shows conditioning of all water except washdown or blowdown water.

The cost of treatment of water to the service water specification is presented in Table 6-5. Again, the basis is 1 acre-foot of filtrate with 750 mg/l of TDS. We have included river water, although all the treatment it will need is filtration. It is doubtful that the cost shown is realistic for simple

TABLE 6-4
DETAILS OF COSTS OF BOILER FEED WATER PURIFICATION

	Groundwater		River Water		Foul Water	
	Volume (Ac.Ft.)	TDS (mg/l)	Volume (Ac.Ft.)	TDS (mg/l)	Volume (Ac.Ft.)	TDS (mg/l)
Inflow Water	1.226	1,500	1.034	350	1.571	25,000
Treatment						
Precondition	1.226	1,500	1.034	1,500	1.571	25,000
R-O Stage I	1.333	2,000	1.333	2,000	1.571	25,000
R-O Stage II	--	--	--	--	1.333	2,000
Outflow Water						
Concentrate	0.226	7,700	0.034	7,700	0.570	68,600
Filtrate***	1.000	100	1.000	100	1.000	100
Costs (1974 Dollars)	Rate*	Cost**	Rate	Cost	Rate	Cost
Precondition	$110	$135	$ 73	$ 75	$185	$291
R-O Stage I	$109	$145	$109	$145	$255	$401
R-O Stage II	--	--	--	--	$109	$145
TOTAL	$228	$280	$213	$220	$532	$836

* Rate = Cost, per acre-foot of feed water to the process step.

** Cost = Cost per acre-foot of final product (not necessarily of the step product).

*** Basis of table is production of 1 acre-foot of filtrate at 100 mg/l total dissolved solids.

TABLE 6-5

DETAILS OF COSTS OF SERVICE WATER PURIFICATION

	Groundwater		River Water		Foul Water	
	Volume (Ac.Ft.)	TDS (mg/l)	Volume (Ac.Ft.)	TDS (mg/l)	Volume (Ac.Ft.)	TDS (mg/l)
Inflow Water	1.158	1,500	1.000	350	1.521	25,000
Treatment						
Precondition	1.158	1,500	1.000	350	1.521	25,000
R-O Stage I	0.631	1,500	--	--	1.521	25,000
R-O Stage II	--	--	--	--	0.561	1,250
Outflow Water						
Filtrate	1.000	750	1.000	750	1.000	750
Concentrate	.158	5,775	--	--	.521	71,600
Costs (1976 Dollars)	Rate*	Cost**	Rate	Cost	Rate	Cost
Precondition	$110	$127	$ 83	$ 83	$185	$281
R-O State I	$ 98	$ 62	--	--	$255	$388
R-O Stage II	--	--	--	--	$ 92	$ 52
TOTAL	$163	$189	$ 83	$ 83	$474	$721

* Rate = Cost, per acre-foot of feed water to the process step.

** Cost = Cost per acre-foot of final product.

filtration, but it maintains the desired relativity with the other costs. Note that the cost of obtaining river water is not included.

6.2.3.3 Water Disposal

The quality of water which can be disposed of to the surface streams in Colorado and in the Colorado River Basin is strictly controlled. As discussed in Section 6.1.1, it would appear that present regulations limit discharges to 750 mg/l of TDS, no hydrocarbon material, little turbidity, and toxicity at or below drinking water standards. This latter requirement is important, as it happens that the groundwater and foul water encountered by the industry is rich in fluoride, and the costs of upgrading the water to discharge standards are largely the costs of reducing fluoride concentrations. For average ambient temperatures in the Basin, the allowable fluoride concentration is 1.5 mg/l.

The application of these standards to discharges to subsurface aquifers which can be reasonably expected to be tributary to surface streams is likely. As a result, we have considered that all discharges, both surface and subsurface, must meet these standards, with the single exception of mine inflow from an aquifer which is re-injected to the same aquifer (Section 6.1.4).

Table 6-6 shows the treatment which is necessary in order to be able to discharge water to the environment. Both groundwater (mine inflow) disposal, and foul water disposal treatments are controlled by fluoride concentrations, and in both cases a recycle final stage is used. Costs are based on an acre-foot of filtrate, although they might more appropriately have been based on an acre-foot of inflow. The cost per unit inflow appears in the "totals" row of the "Rate" column.

TABLE 6-6

DETAILS OF PURIFICATION COSTS FOR WATER DISPOSAL SYSTEMS

	Groundwater			Foul Water		
	Volume (Ac.Ft.)	Fluoride (mg/l)	TDS (mg/l)	Volume (Ac.Ft.)	Fluoride (mg/l)	TDS (mg/l)
Inflow Water	1.069	5	2,500	1.399	40	25,000
Treatment						
Precondition	1.069	5	2,500	1.399	40	25,000
R-O Stage I	1.333	15	8,500	1.399	40	25,000
R-O Stage II	--	--	--	1.333	15	5,500
Outflow Water						
Filtrate	1.000	1.5	423	1.000	1.5	275
Concentrate	0.069	55.5	32,600	0.399	137	87,000
Costs	Flow	Rate*	Cost**	Flow	Rate	Cost
Precondition	1.069	$120	$128	1.399	$185	$259
R-O Stage I	1.333	$178	$237	1.399	$255	$357
R-O Stage II	--	--	--	1.333	$153	$204
TOTAL	1.069	$342	$365	1.399	$586	$820

* Rate = Cost, per acre-foot of feed water to the process step.

** Cost = Cost per acre-foot of final filtrate.

CHAPTER 7
CONVENTIONAL MINING SYSTEMS

7.1 APPROACH

The contract calls for evaluation of a total of five different conventional mining systems to obtain raw shale for surface retorting, namely:

i. Room & Pillar Mining (Sites 1, 2 & 3)
ii. Chamber & Pillar Mining (Site 1)
iii. Sublevel Stoping (Site 1)
iv. Block Caving (Site 1)
v. Open Pit Mining (Site 2)

This section of the report presents a very brief summary of the mining technology assumed in the study. Much of the material is taken from:

i. A Technical and Economic Study of Candidate Underground Mining Systems for Deep, Thick Oil Shale Deposits, Cameron Engineers, 1975 and 1976.

ii. Technical and Economic Study of an Integrated Single Pass Mining System for Open Pit Mining of Deep Oil Shale Deposits, Phase II Report, Banks, et al., 1976.

iii. Detailed Development Plan, Tract C-a, Rio Blanco Oil Shale Project, 1976.

iv. C-b Shale Oil Project, Detailed Development Plan and Related Materials, Ashland Oil, Inc., and Shell Oil Co., 1976.

The emphasis is strongly upon the variables which relate to water management. Firstly, in-mine water usage is a small but significant component of water demand for an integrated shale oil industry. We have identified the use for each system. Secondly, a much more significant component of water management is the quantity of groundwater which flows into the mine. The quantity of this inflow is dependent on the hydrology of the rock sequence in which the mine is placed (which is determined in Chapters 3 and 4 above), and upon the geometry and degree of disturbance of the proposed mine (which is presented in this Chapter). In general, the two critical mining questions which must be evaluated to obtain mine inflow are:

i. What is the size of the mine in plan at any time in its development?

ii. Which strata are removed or significantly disturbed by mining?

With the answers to these two questions, and reasonably detailed hydrologic information on the mine locations, it is possible to compute the likely mine inflow. This step is taken in Chapter 8.

In order to cover the possible ranges of mine inflow, we have chosen to present three sets of conditions for mining, namely:

i. Single pass extraction in or centered upon the Mahogany Zone.

ii. Single pass extraction in or centered upon the R-4 Zone.

iii. Multiple pass extraction to maximize resource recovery, extracting the greatest possible amount of material from the entire Parachute Creek Member.

A third variable in the analysis is the degree of surface subsidence. If no subsidence occurs, the mine roof materials remain intact, and inflows are minimized. If full subsidence is allowed, resource recovery is usually enhanced but inflow to the mines is increased due to disturbance of the mine roof materials. In order to cover this range of conditions, we have elected to consider the two extremes, namely:

i. No subsidence mining.
ii. Full subsidence mining.

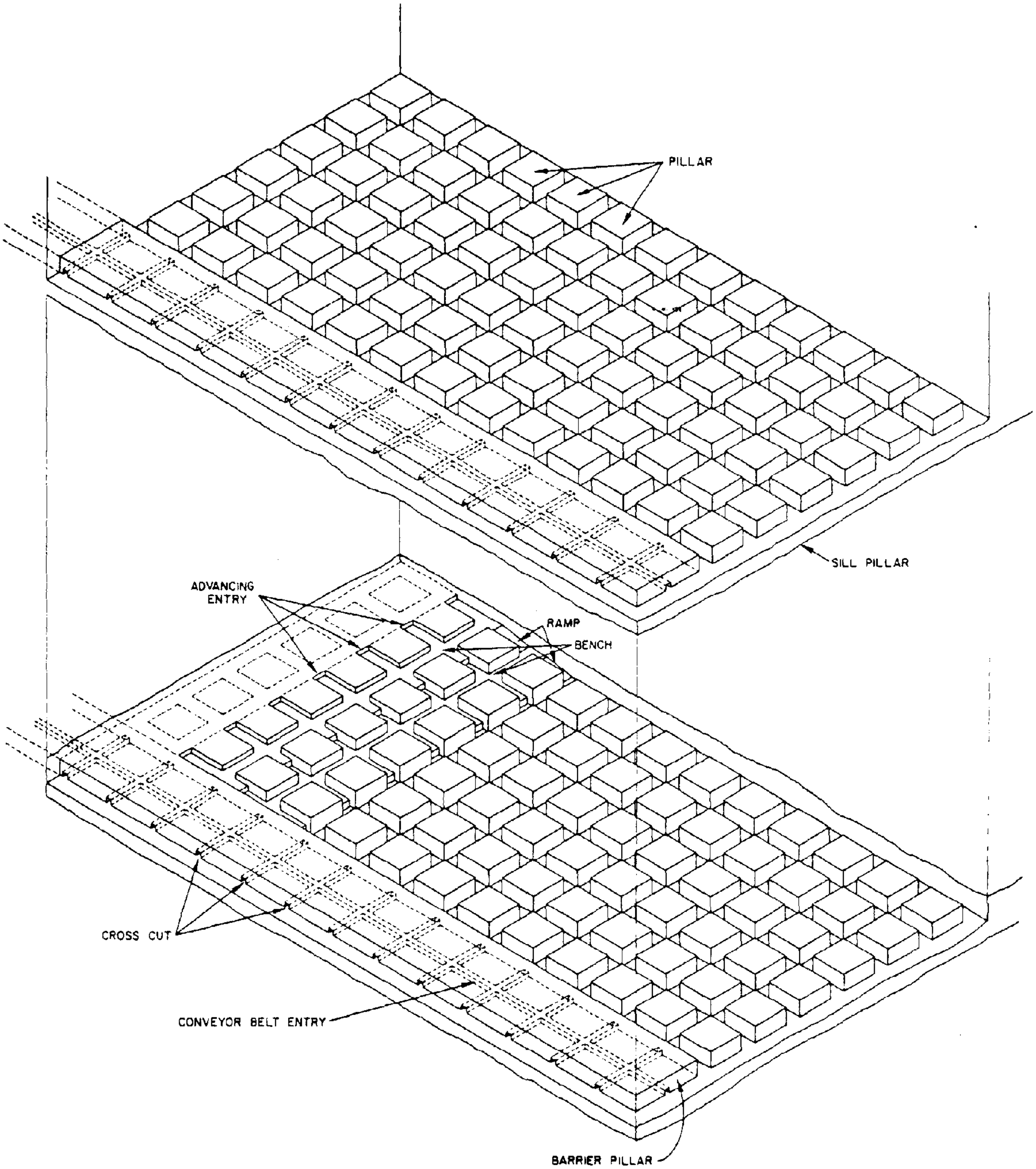
7.2 ROOM AND PILLAR MINING

7.2.1 Outline of Method

For the purposes of this report the method is assumed to be the advance entry and pillar mining concept presented by Cameron Engineers (1975). In this method, multiple headings on evenly spaced centers are advanced in one direction. Crosscuts are driven perpendicular to the headings resulting in square pillars between headings and crosscuts. (Cameron Engineers, 1975, p.4-69). Figure 7-1 shows the layout of a typical multi-level mine.

The typical sequence of operations is as follows. A crosscut or heading is driven using a hydraulic jumbo to drill the entire round in one setup. While the round is being drilled the roof is rock bolted. The round is then charged with ANFO. After blasting, the round is mucked using LHD's (load-haul-dump machines) which dump into portable impact

Figure 7-1 ISOMETRIC VIEW, ROOM & PILLAR MINE


PILLAR
SILL PILLAR
ADVANCING ENTRY
RAMP
BENCH
CROSS CUT
CONVEYOR BELT ENTRY
BARRIER PILLAR

Source: Cameron Engineers, 1976, p.79

crushers. The crushers feed onto 36" wide conveyor belts that converge to a single 60" wide main line conveyor belt.

7.2.2 Water Usage

Water usage within a room and pillar mine has been estimated by Cameron Engineers (1975). After adjusting the values to be appropriate for a 50,000 TPD mine and adding an appropriate amount for general dust suppression in ore handling, expected usage is shown in Table 7-1.

TABLE 7-1

WATER USAGE IN A 50,000 TPD ROOM & PILLAR MINE

	Rate of Usage	
Use	AFY	GPM
Ore Handling	162	100
Drilling	106	66
Bolting	43	27
Crushing	11	7
Miscellaneous	8	5
TOTAL	330	205

It is expected that the use of water will be approximately linear with mining rate.

7.2.3 Mine Inflow Parameters

The relevant parameters for mine inflow computation are the development height, the overall height disturbed by mining, and the rate of expansion of the mine area. These parameters are to some extent a function of location and depth of mining. However, only limited information is publicly available to evaluate the pillar strengths in the various zones of the three sites involved in this study. Table 7-2 shows the values of the various parameters which have been used in this study.

TABLE 7-2

MINE VARIABLES AFFECTING INFLOW - 50,000 TPD ROOM AND PILLAR MINE

Variable	Site 1 (a)	Site 2 (b)	Site 3 (c)
Heights			
Room Height (ft.)	100'	60'	78'
Sill Height (ft.)	40'	40' (f)	40' (f)
Overall Resource Recovery (%) (d)	37%	30%	26%
Mine Expansion Rate (square mile/year) for a 50,000 TPD mine (e)	0.182	0.315	0.303

NOTES:

(a) Data from Cameron Engineers (1975). Recoveries computed from layouts.

(b) Data from Rio Blanco Oil Shale Project (1976).

(c) Data from C-b Shale Oil Project (1976).

(d) Resource recovery here defined as quantity of rock removed by mining as a percentage of original rock in place over the interval between mine floor and the top of the sill pillar. "Overall" resource recovery is for an infinite mining sequence. Shaft pillars are assumed to account for 18% of the total mine area, based on one 2,500 x 2,000 ft. shaft pillar every square mile. Barrier pillars are included.

(e) Mine expansion rate assumes a mine expanding at a rate determined by the height & resource recovery. A 50,000 TPD operation is assumed; area expansion rate is linear with mine production. A unit weight of oil shale of 138.5 lb./ft.^{3} is assumed.

(f) Sill pillar heights assumed.

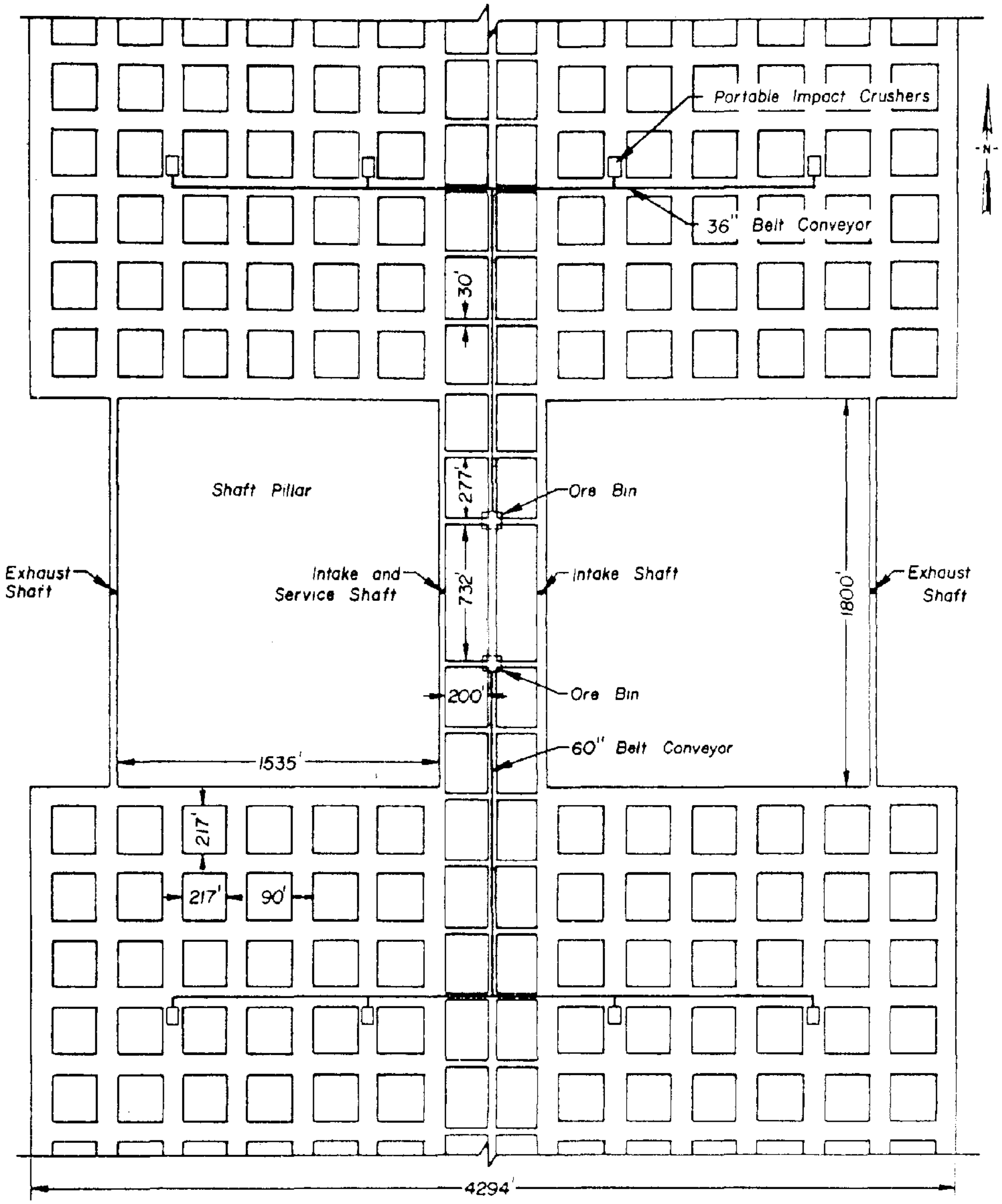
It is assumed that these values are valid for an excavation at any depth in each of the three sites. The rationale behind this assertion is that the values in the table have been derived for the Mahogany Zone area, and the competence of the rock in the Parachute Creek Member generally improves with depth. Thus the assumption is that the increase in overburden stress is balanced by the increase in rock quality and strength. In any event, little data or analysis has been produced for mine design in the deeper oil shale horizons.

Resource recoveries are computed on the basis of excavated height plus sill pillar height because it is this height of material (at least) which is alienated by the mining activity. This approach also allows "stacking" of multiple level developments using the same resource recovery rate per level, which is computationally attractive. Resource recoveries quoted by Cameron Engineers (1975) and others have not been used, as the basis of their computation is usually not clear. For example, for Site 1 the Cameron Engineers report states that "...Overall resource recovery, assuming a 40-foot sill pillar, is approximately 45%..." (p. 4-69). Using the geometry presented in Figure 11-2, it is clear that the resource recoveries are 50% in the actual mining panel, 45% if the central conveyor belt entry pillar is allowed for, and perhaps 37% if the shaft pillar shown is considered. If an external barrier pillar of (say) 400 feet were allowed between each development complex, then the recovery rate would drop to 34%.

7.2.4 Partial Pillar Recovery

The Cameron Report (1975) discusses the possibility of pillar robbing in the retreat phase of room and pillar mining. This could be carried out if subsidence were allowed. The report states that "...resource recovery...is approximately 45% with pillars left, or 55 to 60% with partial pillar recovery.".

Figure 7-2 PLAN VIEW, ROOM & PILLAR MINE


Portable Impact Crushers
36" Belt Conveyor
N
30'
Shaft Pillar
277'
Ore Bin
Exhaust Shaft
Intake and Service Shaft
732'
Intake Shaft
1800'
Exhaust Shaft
Ore Bin
200'
60" Belt Conveyor
1535'
217'
217'
90'
4294'

Source: Cameron Engineers, 1976, p 80.

These are clearly recoveries without consideration of the shaft pillar, and the maximum overall resource recovery likely at Site 1 is therefore about 50% including allowance for a shaft pillar. This is an approximate one-third greater recovery. Applying this factor to all the results of Table 7-2 gives:

TABLE 7-3

MINE VARIABLES AFFECTING INFLOW -
50,000 TPD ROOM & PILLAR MINE WITH PILLAR ROBBING

Variable	Site 1	Site 2	Site 3
Overall Resource Recovery	50%	40%	35%
Mine Expansion Rate (square mile/yr.)	0.135	0.196	0.193

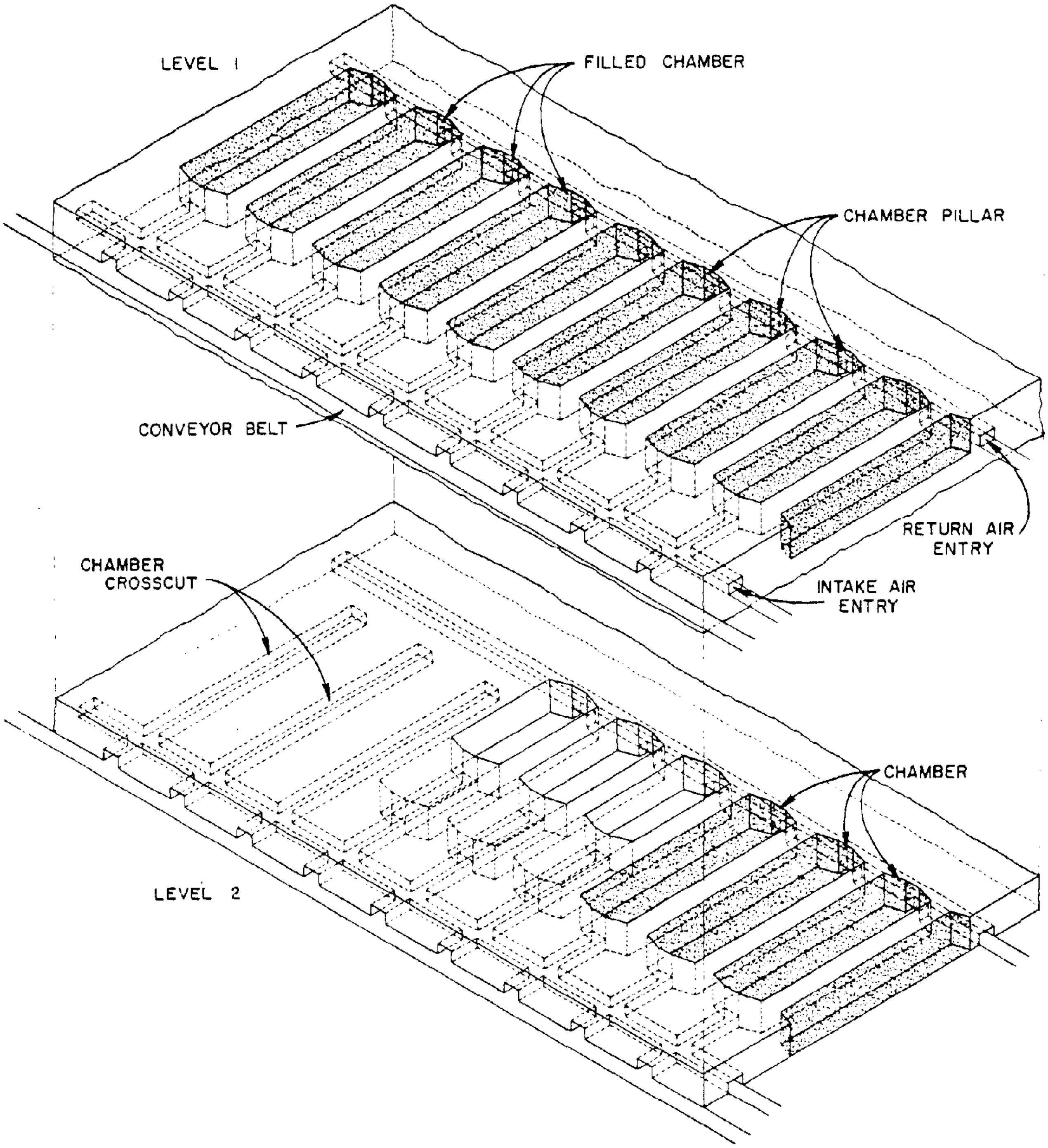
7.3 CHAMBER AND PILLAR MINING

7.3.1 Outline of Method

Chamber and pillar mining is a modification of room and pillar mining in which crosscuts, driven perpendicular to main entries, are enlarged into chambers (Cameron Engineers, 1974, p.4-91). In the design presented by Cameron Engineers, chambers are initially driven 20 feet high and 30 feet wide. They are enlarged to 100 feet wide by 60 feet high. An isometric view of the system is shown in Figure 7-3, and a plan view is shown in Figure 7-4.

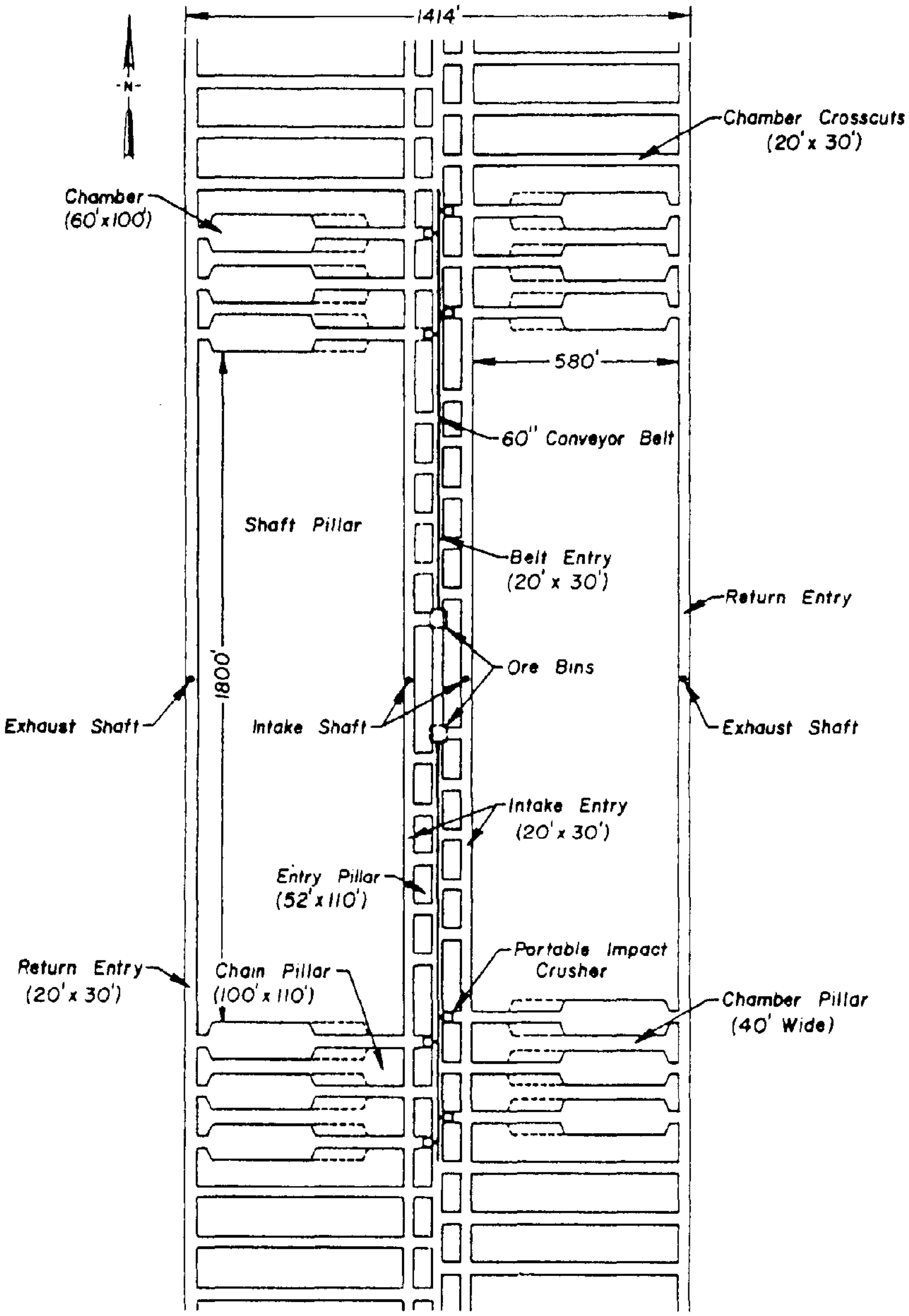
The mining sequence involves fan drilling of the entire chamber, followed by blasting, and then mucking using LHD's. The LHD's dump the broken muck into portable impact crushers, which feed directly onto the central conveyor belt. The ore is then transferred to the shaft and to the surface.

Figure 7-3 ISOMETRIC VIEW, CHAMBER & PILLAR MINE


LEVEL 1
FILLED CHAMBER
CHAMBER PILLAR
CONVEYOR BELT
RETURN AIR ENTRY
INTAKE AIR ENTRY
CHAMBER CROSSCUT
CHAMBER
LEVEL 2

Source: Cameron Engineers, 1976, p.81.

Figure 7-4 PLAN VIEW, CHAMBER & PILLAR MINE


1414'
N
Chamber Crosscuts (20' x 30')
Chamber (60'x100')
580'
60" Conveyor Belt
Shaft Pillar
Belt Entry (20' x 30')
Return Entry
Ore Bins
1800'
Exhaust Shaft
Intake Shaft
Exhaust Shaft
Intake Entry (20' x 30')
Entry Pillar (52' x 110')
Portable Impact Crusher
Return Entry (20' x 30')
Chain Pillar (100' x 110')
Chamber Pillar (40' Wide)

Source: Cameron Engineers, 1976, p.83

7.3.2 Water Usage

Water usage for chamber and pillar mining has been estimated by Cameron Engineers (1975). After adjusting to a 50,000 TPD mine operation and adding an appropriate amount for general dust suppression during ore handling, expected usage is shown in Table 7-4.

TABLE 7-4
WATER USAGE IN A
50,000 TPD CHAMBER & PILLAR MINE

	Rate of Usage	
Use	AFY	GPM
Ore Handling	162	100
Drilling	53	33
Bolting	31	19
Conveying	6	4
Crushing	5	3
Miscellaneous	6	4
TOTAL	263	163

It is expected that the rate of usage of water will be approximately linear with mine production rate.

7.3.3 Mine Inflow Parameters

The mine inflow parameters which will be used in Chapter 8 to compute inflow are as shown in Table 7-5. Only Site 1 parameters are given, as the contract specifies that this method should only be considered for Site 1.

TABLE 7-5
MINE VARIABLES AFFECTING INFLOW
50,000 TPD CHAMBER & PILLAR MINE

Variable	Site 1 Value	Comment
Room Height	60 ft.	Cameron Engineers
Sill Height	40 ft.	Assumed
Resource Recovery		
in panel	31%	Includes sill pillar
overall	26%	Includes shaft pillar
Mine Expansion Rate	0.364 sq.mi./yr.	Based on room plus sill height & overall resource recovery

The comments about depth effects and resource recovery made in Section 7.2.3 are also, in general, valid for this section.

7.3.4 Spent Shale Backfilling Considerations

This method of mining has been specifically designed to allow effective backfilling of the mine by hydraulic placement of spent shale. The water management aspects of this method of spent shale disposal are discussed in Chapter 10 of this report. The spent shale backfill does not have any significant impact upon mine inflow parameters as such, as it is not a factor in mine size or expansion rate in this case. Water requirements associated with the backfill system (apart from slurry water) are assumed negligible. In the case of dry backfill handling (pneumatic), it is assumed that the water content of the backfill will have been adjusted to allow handling in the mine. Dust control in-mine is assumed to be by non-water methods, e.g. bag filters (Cleveland-Cliffs Iron Co., 1977).

7.4 SUBLEVEL STOPING

7.4.1 Outline of Method

The sublevel stoping method presented by Cameron Engineers (1975) involves the drilling and breakage of rock in a stope, withdrawing the broken rock through a lower draw point using front end loaders (FEL's). Railroad haulage is used to transfer the ore to the shaft, prior to transfer to the surface.

If the stope is to be backfilled with spent shale, the extraction ceases at this point, the stope is bulkheaded and spent shale slurry pumped in (Figure 7-5). If full subsidence sublevel stoping is used, however, the crown pillar and one rib pillar are blasted into the open stope and withdrawn through the draw point (Figure 7-6).

7.4.2 Water Usage

Water usage for sublevel stoping has been derived from figures given by Cameron Engineers (1975), and is essentially the same for both techniques, providing the water requirements for hydraulic transport of spent shale is not included (see Chapter 10). The usage is presented in Table 7-6.

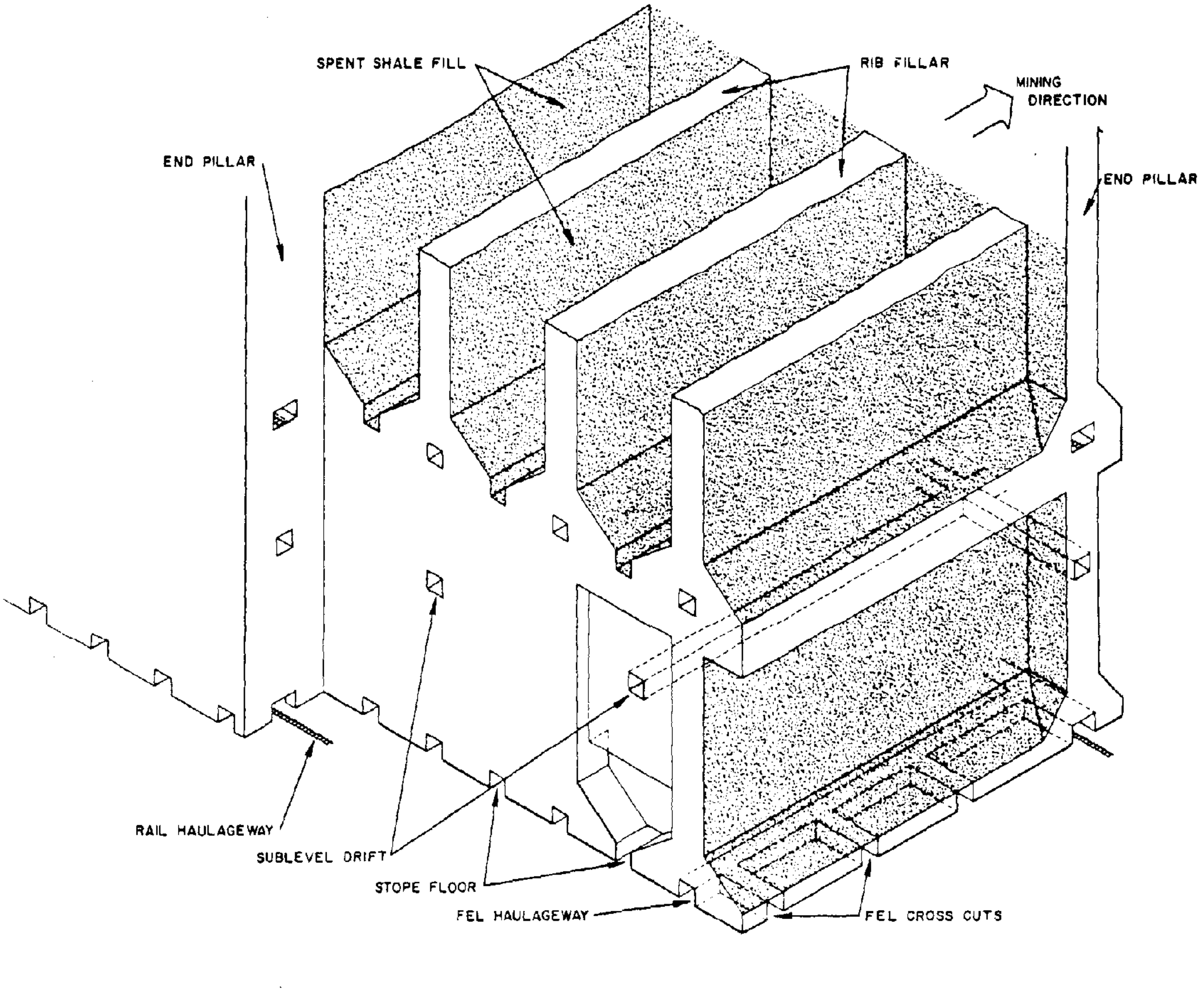
TABLE 7-6

WATER USAGE IN A 50,000 TPD

SUBLEVEL STOPING MINE

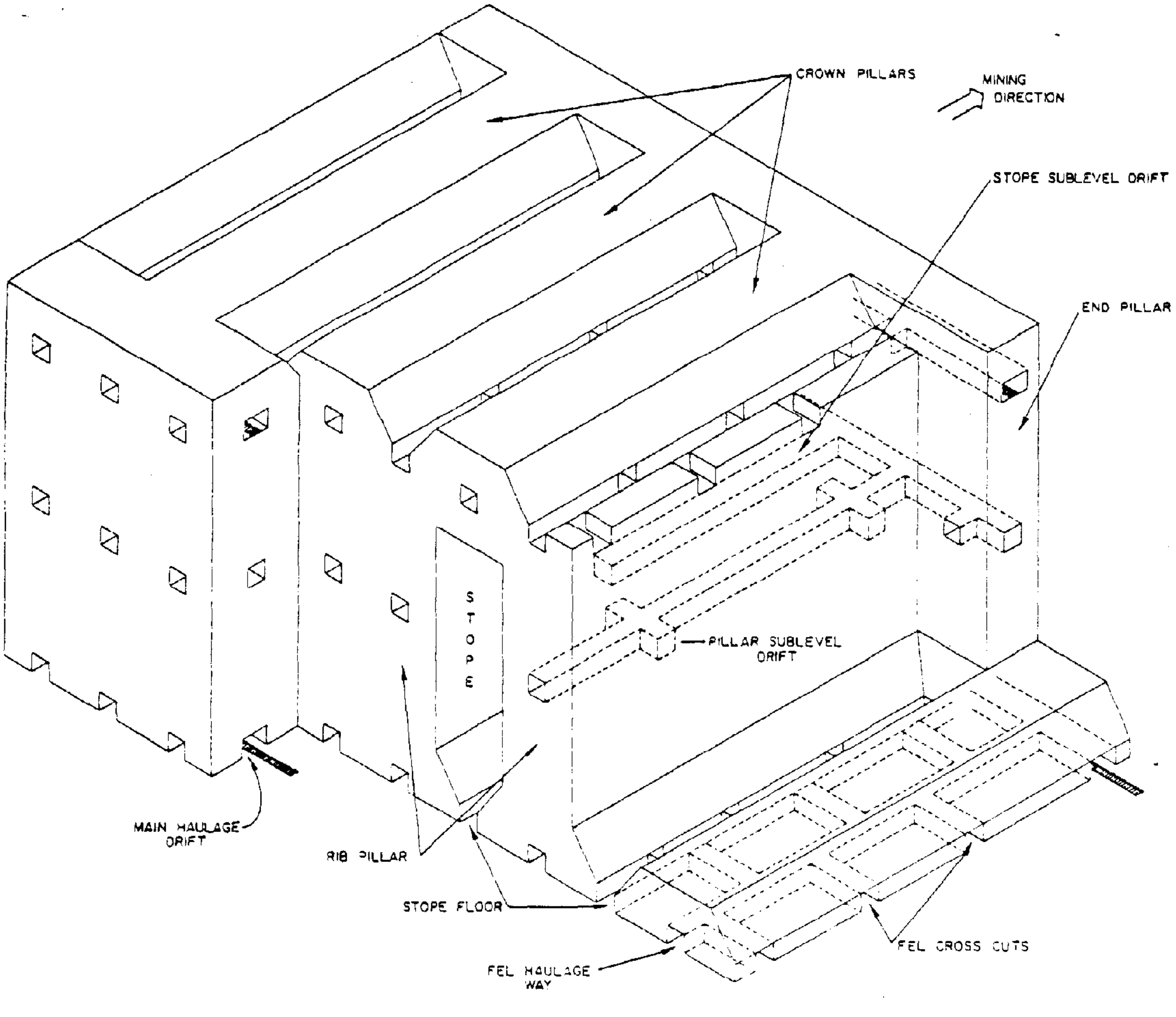
	Rate of Usage	
Use	AFY	GPM
Ore Handling	162	100
Drilling	106	66
Bolting	43	27
Crushing	11	7
Miscellaneous	8	5
TOTAL	330	205

Figure 7-5 ISOMETRIC VIEW, SUBLEVEL STOPING MINE WITH SPENT SHALE BACKFILL


SPENT SHALE FILL
RIB PILLAR
MINING DIRECTION
END PILLAR
END PILLAR
RAIL HAULAGEWAY
SUBLEVEL DRIFT
STOPE FLOOR
FEL HAULAGEWAY
FEL CROSS CUTS

Source: Cameron Engineers, 1976, p. 76.

Figure 7-6 ISOMETRIC VIEW, SUBLEVEL STOPING MINE WITH FULL SUBSIDENCE


CROWN PILLARS
MINING DIRECTION
STOPE SUBLEVEL DRIFT
END PILLAR
S T O P E
PILLAR SUBLEVEL DRIFT
MAIN HAULAGE DRIFT
RIB PILLAR
STOPE FLOOR
FEL HAULAGE WAY
FEL CROSS CUTS

Source: Cameron Engineers, 1976, p. 72.

7.4.3 Mine Inflow Parameters With Spent Shale Backfill

This is a limited resource recovery, limited subsidence mining method. The crown and rib pillars are left in place, in order to create a cavern for spent shale backfilling. Based on the geometry given in the Cameron report, the parameters for use in mine inflow analysis shown in Table 7-7 have been developed. These should be read in conjunction with the discussion in Section 7.2.3.

TABLE 7-7
MINE VARIABLES AFFECTING INFLOW -
50,000 TPD SUBLEVEL STOPING MINE
WITH SPENT SHALE BACKFILL

Variable	Site 1 Value	Comment
Room Height	280 ft.	Lower 60 feet in the form of a funnel
Sill Height	50 ft.	
Resource Recovery		
in panel	48%	Includes end pillars
overall	40%	Includes shaft pillars
Mine Expansion Rate	0.074 sq.mi./yr.	

7.4.4 Mine Inflow Parameters With Full Subsidence

In full subsidence sublevel stope mining, everything except the shaft pillar and the base of the rib pillar in the lowest mining level are removed. Although there would probably be a significant amount of waste ore (of too low grade to classify as ore), for the purposes of this study an in-panel recovery rate of 95% average is assumed. Based on the material in the Cameron Engineers report, the mine inflow parameters are as shown in Table 7-8. This table should be read in conjunction with the discussion in Section 7.2.3.

TABLE 7-8
MINE VARIABLES AFFECTING INFLOW - 50,000 TPD SUBLEVEL STOPE MINING WITH FULL SUBSIDENCE

Variable	Site 1 Value	Comment
Room Height	280 ft.	Initial opening
Sill Height	40 ft.	Removed during mining sequence
Resource Recovery		
in panel	95%	Estimated
overall	78%	Including shaft pillar
Mine Expansion Rate	0.038 sq.mi./yr	

7.5 BLOCK CAVING

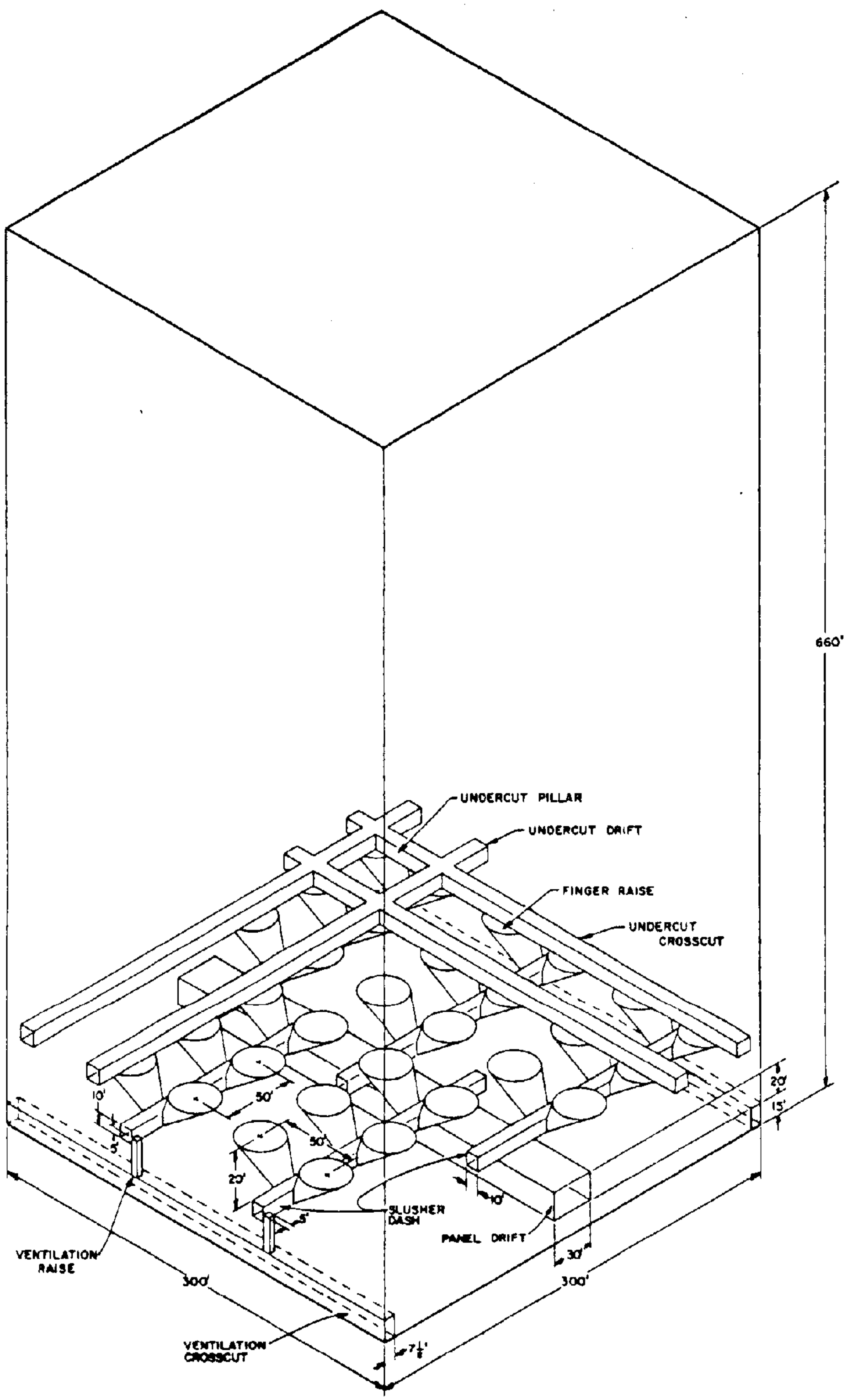
7.5.1 Outline of Method

Block caving involves drawing material from the base of a resource block, which causes the material above to break up and move toward the draw point by blocky flow. The mining method presented by Cameron Engineers considers caving of individual 300-foot square and 615-foot high blocks of material, using an undercut level for initiating the cave. The system is shown in Figure 7-7. The development height is 65 feet at the bottom of the block, and the caving block is thus 550 feet high. The ore is dumped by slushers or LHD's directly into rail trolleys, transported to the shaft station, given primary crushing, and hoisted to surface. Mining is retreat in nature, and totally disturbs all the material above the development panel.

7.5.2 Water Usage

Water usage has been estimated by scaling the figures presented by Cameron Engineers (1975), and individual use rates are given in Table 7-9.

Figure 7-7 ISOMETRIC VIEW WITHIN A PANEL, BLOCK CAVING MINE


UNDERCUT PILLAR
UNDERCUT DRIFT
FINGER RAISE
UNDERCUT CROSSCUT
660'
20'
15'
10'
50'
5'
50'
20'
SLUSHER DASH
10'
5'
PANEL DRIFT
30'
300'
300'
VENTILATION RAISE
VENTILATION CROSSCUT
7½'

Source: Cameron Engineers, 1976, p. 86.

TABLE 7-9

WATER USAGE IN A 50,000 TPD BLOCK CAVING OPERATION

Use	Rate of Usage AFY	Rate of Usage GPM
Ore Handling	162	100
Drilling	118	73
Rock Bolting	21	13
Crushing	8	5
Miscellaneous	8	5
TOTAL	317	196

7.5.3 Mine Inflow Parameters

The parameters which are needed for mine inflow evaluation have been developed from the mine plan shown in Figure 7-8, which is taken from Cameron Engineers report (1975, p.4-113). Based on an assumed 95% extraction in the main caving blocks and on an assumed 600-foot wide pillar between development cells (which may be somewhat conservative), we have obtained the parameters shown in Table 7-10.

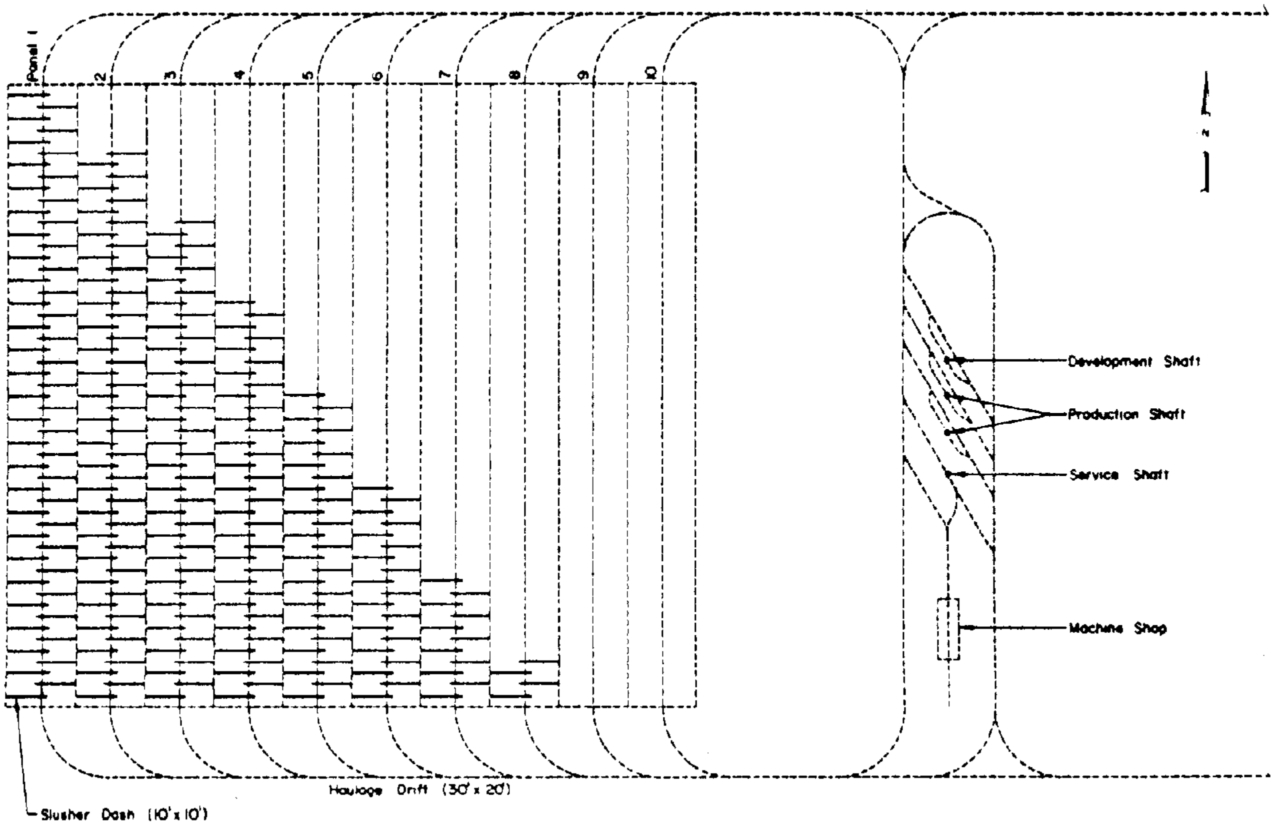
TABLE 7-10

MINE VARIABLES AFFECTING INFLOW:

50,000 TPD BLOCK CAVING OPERATION

Variable	Site 1 Value	Comment
"Room" Height	550 ft.	Material actually caved
Cell Height	615 ft.	For slushers
Resource Recovery		
in individual cell	91%	Assumes development portion lost
overall	51%	Includes shaft pillar
Mine Expansion Rate	0.030 sq.mi./yr.	Single level mining

Figure 7-8 PLAN VIEW OF SLUSHER LEVEL, BLOCK CAVING MINE


Panel 1
2
3
4
5
6
7
8
9
10
Development Shaft
Production Shaft
Service Shaft
Machine Shop
Haulage Drift (30'x 20')
Slusher Drift (10'x 10')

Source: Cameron Engineers, 1976, p. 85

This low value of recovery stems from the relatively large shaft pillar, and the relatively wide barrier pillars left for rail transport around the edge of each cell. It is likely that a commercial operation could improve this ratio over that implied by the Cameron Report by judicious planning, even without increasing haul distances.

The above is for caving using slushers. The values are slightly lower for LHD mucking, but the difference is not significant.

7.6 OPEN PIT MINING

The contract for this project calls for an evaluation of open pit mining only at Site 2. Accordingly, we have leaned heavily on the work of the Rio Blanco Oil Shale Project at C-a Tract in making our mining evaluation. Unlike the underground mining systems, the relevant parameters for this study must relate strongly to the geology of the area.

7.6.1 Outline of Method

Open pit mining is conceptually the simplest form considered in this report. Material is drilled, blasted, excavated (probably using electric shovels), transported (probably using trucks), and primary crushed (probably at the retort site). Other transportation systems, notably conveyors, are feasible, but from a water management standpoint the differences will be insignificant.

7.6.2 Water Usage

Water usage for open pit mining are given in Table 7-11. Data are scaled from the C-a DDP and Banks, et al. (1976). While we are assuming that the water requirement is a function of production, in fact it is more likely to be a function of pit size.

TABLE 7-11
WATER USE IN A 50,000 TPD OPEN PIT MINE

	Rate of Usage	
Use	AFY	GPM
Drilling	29	18
Road Dust	187	116
Crushing	52	32
Miscellaneous	32	20
TOTAL	300	186

NOTE: Breakdown is approximate. All water except miscellaneous is used for dust control.

7.6.3 Mine Inflow Parameters

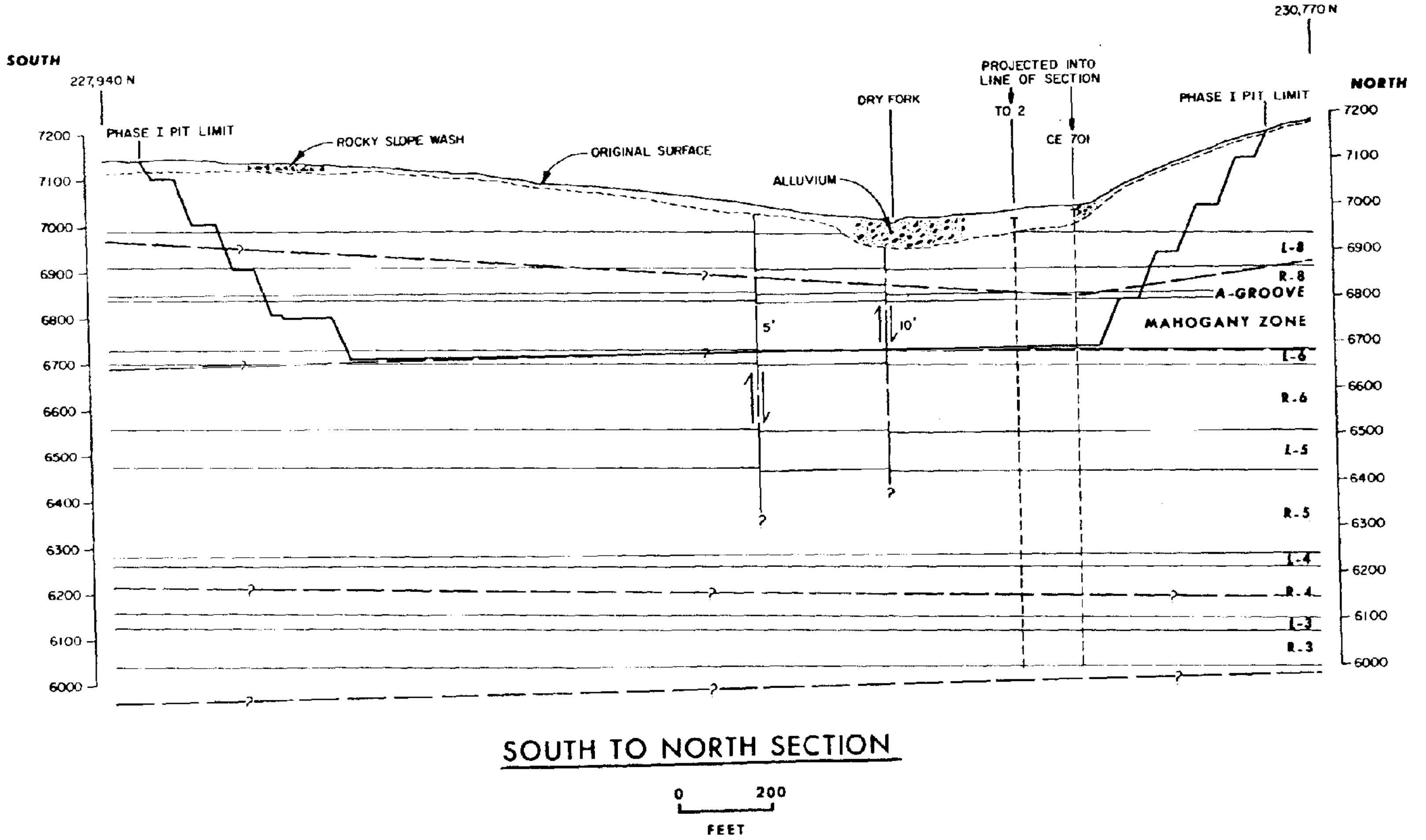
The parameters relating to mine inflow to an open pit are similar to those for a full-subsidence underground mine. Thus rate of mine expansion and mine depth are still the important variables. Two cases are considered:

a. A shallow mine, deep enough to remove the Mahogany Zone to the 'B' groove.

b. A deep mine, removing all the Parachute Creek Member resource (i.e. down to the Blue Marker).

7.6.3.1 Mahogany Zone Mine

The Mahogany Zone mine will look in section like the mine shown in Figure 7-9, taken from the C-a DDP. The average mine depth is 410 feet, and the average cumulative depth of waste plus overburden is 220 feet. For this evaluation, we


SOUTH
227,940 N
PHASE I PIT LIMIT
ROCKY SLOPE WASH
ORIGINAL SURFACE
ALLUVIUM
DRY FORK
PROJECTED INTO LINE OF SECTION
TO 2
CE 701
PHASE I PIT LIMIT
230,770 N
NORTH
5'
10'
L-8
R-8
A-GROOVE
MAHOGANY ZONE
L-6
R-6
L-5
R-5
L-4
R-4
L-3
R-3
7200
7100
7000
6900
6800
6700
6600
6500
6400
6300
6200
6100
6000
SOUTH TO NORTH SECTION
0
200
FEET

NOTE CROSS SECTION 151,370 E SOUTH / NORTH CENTERLINE

After: Rio Blanco Oil Shale Project, 1976 p. 4-3-4

Figure 7-9 CROSS SECTION, SHALLOW OPEN PIT MINE AT SITE 2

are assuming the mine rate is 50,000 tons per day or ore, which necessitates mining 93,200 TPD of total material. Extraction rate is 100%. For simplicity, it has been assumed that the pit is vertical sided, although in practice the slope angles will be much less. However, dewatering of the slopes for stability purposes will unquestionably be performed, so that the water inflow aspects can be well simulated by a ring of vertical wells around the periphery of the mine.

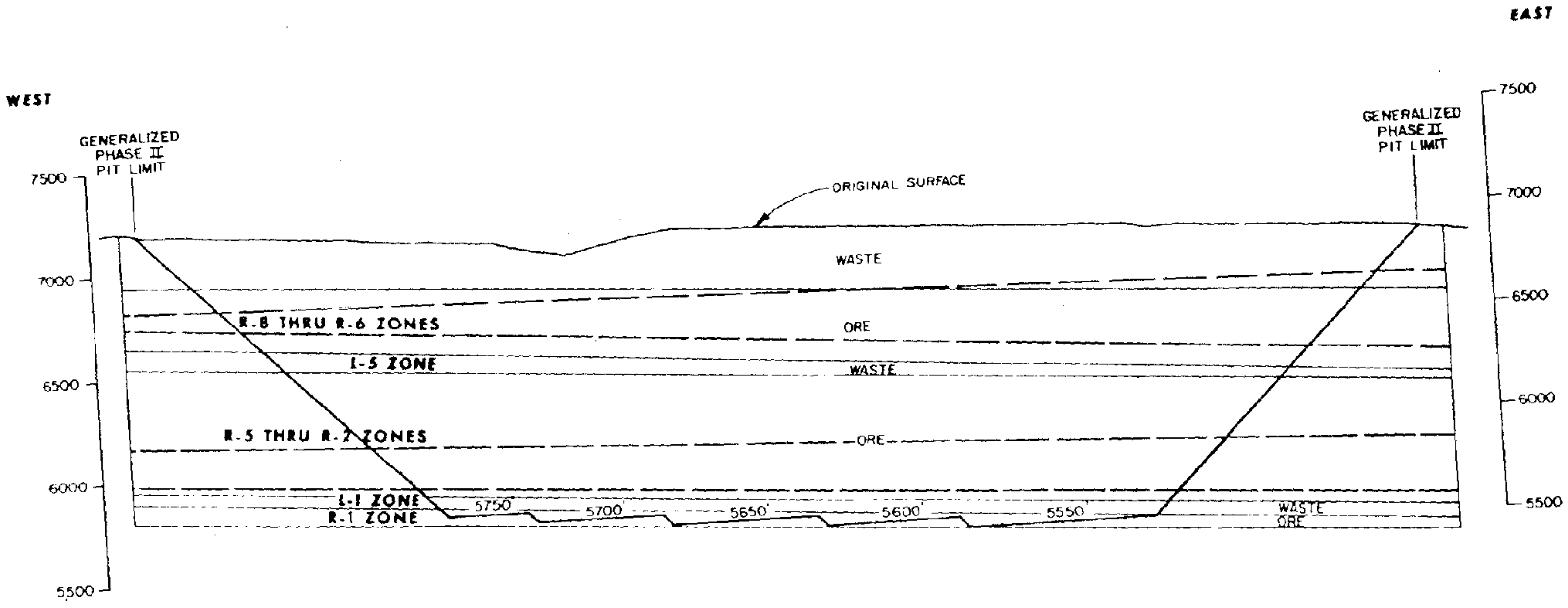
The mine variables effecting inflow to the shallow pit are summarized in Table 7-12.

TABLE 7-12
MINE VARIABLES AFFECTING INFLOW TO A
50,000 TPD (OF ORE) OPEN PIT
MINE - SHALLOW CASE

Variable	Site 2 Value	Comment
Depth	410 ft.	Average
Thickness of Ore	190 ft.	Average
Thickness of Waste	220 ft.	Average
Stripping Ratio	1.16	Waste: Ore
Resource Recovery	100%	Ignores material lost in slopes
Mine Expansion Rate	0.050 sq.mi./yr.	After total depth is reached

7.6.3.2 Mine to Blue Marker

The typical section for this mine is shown in Figure 7-10, also from the C-a DDP. For this mine the average depth is 1,180 feet, of which 400 feet is waste (overburden and unretortable material). For a mining rate of 50,000 TPD of ore, a total mining rate of 75,600 TPD is needed in this case. Resource recovery is 100%. The mine variables affecting inflow for the deep pit are summarized in Table 7-13.


WEST
EAST
GENERALIZED PHASE II PIT LIMIT
GENERALIZED PHASE II PIT LIMIT
ORIGINAL SURFACE
WASTE
R-8 THRU R-6 ZONES
ORE
L-5 ZONE
WASTE
R-5 THRU R-2 ZONES
ORE
L-1 ZONE
R-1 ZONE
5750
5700
5650'
5600'
5550'
WASTE
ORE
7500
7000
6500
6000
5500
7500
7000
6500
6000
5500

WEST TO EAST SECTION

0 500
FEET

NOTE: CROSS SECTION 228,000N
WEST/EAST CENTERLINE

After: Rio Blanco Oil Shale Project, 1976 p. 4-3-7

Figure 7-10 CROSS SECTION, DEEP OPEN PIT MINE AT SITE 2

TABLE 7-13
MINE VARIABLES AFFECTING INFLOW TO A 50,000 TPD (ORE) OPEN PIT MINE - DEEP CASE

Variable	Site 2 Value	Comment
Depth	1,180 ft.	
Thickness of Ore	780 ft.	
Thickness of Waste	400 ft.	
Stripping Ratio	0.51	Waste: Ore
Resource Recovery	100%	Ignores material lost in slopes
Mine Expansion Rate	0.012 sq.mi./yr.	After total depth is reached

7.7 SUMMARY

From a water management point of view, the important aspects of mining are the water usage in mining, and the geometric parameters of the mine which will have a major impact on groundwater inflow.

7.7.1 Water Usage

The water use for the mining systems considered are summarized in Table 7-14.

These flows are exclusive of water requirements for in-mine spent shale placement, which are considered separately in Chapter 10.

TABLE 7-14
SUMMARY OF MINE WATER USAGE FOR 50,000 TPD (ORE) MINES

	Rate of Usage	
Mining Type	AFY	GPM
Room & Pillar	330	205
Chamber & Pillar	263	163
Sublevel Stoping	330	205
Block Caving	317	196
Open Pit	300	186
AVERAGE	308	191

7.7.2 Mine Inflow Parameter Summary

The significant geometric parameters for mine inflow are the vertical height of the mine development and the rate of expansion of the area of the mine. (The location of the mine in the stratigraphic column is also of great significance, as is the degree of disturbance of the material above the mine roof. However, these factors will be considered in the mine inflow section.)

Table 7-15 summarizes the disturbed section height and the rate of mine expansion for all of the cases considered, on a site by site basis.

7.8 ANCILLARY ACTIVITIES

Site development and raw shale delivery are ancillary to an oil shale facility, and water use in these activities is a function of mining rate rather than shale oil production. Thus these activities are related to mining.

TABLE 7-15
SUMMARY OF MINE VARIABLES AFFECTING INFLOW - 50,000 TPD (ORE) MINES

Mine Type	Single Pass Mined Height (ft.)	Thickness Per Pass (ft.)	Single Pass Expansion Rate (mi.^{2}/yr.)
A. SITE 1			
Room & Pillar	100	140	0.182
Room & Pillar with Pillar Robbing	100	140	0.135
Chamber & Pillar	60	100	0.364
Sublevel Stoping with Backfill	280	320	0.074
Sublevel Stoping with Full Subsidence	280+	320	0.038
Block Caving	550+	615	0.030
B. SITE 2			
Room & Pillar	60	100	0.351
Open Pit - shallow case	410	-	0.050
Open Pit - deep case	1,180	-	0.012
C. SITE 3			
Room & Pillar	78	118	0.303

NOTE: (1) "Mined Height" is the approximate thickness of material actually removed by the mining. Where number is followed by "+", this indicates caving is a necessary part of the process.

(2) Expansion rate is for single pass mining. Multiple pass mining rates can be found by dividing the rate by the number of passes.

(3) Maximum number of passes in a given section is found by dividing section thickness by the "Thickness per Pass".

7.8.1 Site Development

Site development of a mine and processing plant sufficient to handle 50,000 tons per day will take place over a time span of two years, before actual production begins. Site development includes earthwork and preproduction mining.

Earthwork is a construction activity involving cutting and filling of the existing land surface contours to produce a finished surface at a prescribed elevation and configuration as required for roads, building foundation footings, dams, and mining machinery access. Water is required for compaction and dust control.

i. Compaction. A 50,000 TPD operation is estimated to require 4.5 million cu. yds. of compacted fill for site preparation. Approximately 1 acre-foot of water is necessary for every 5,000 cubic yards of compacted fill. Assuming a productivity rate of 15,000 cubic yards per day of earthwork for 1 year, the water requirement for compaction is 1,090 acre-feet (675 gallons per minute).

ii. Dust Control. Dust control on access roads and the construction site during the 1-year earthwork period will require an additional 121 acre-feet (75 gallons per minute).

Preproduction mining consists of attaining access to the preferred stratigraphic horizon, exposing a large number of working places, and providing routes for transportation of men, machinery, and materials between the surface and the workings and for ventilation. Water is required for mining, raw shale delivery to stockpiles near the processing plant, and, in the case of open pit mining, overburden and sub-ore disposal. The disposal of raw shale produced during preproduction mining that is not later retorted is dealt with in the section on raw shale disposal. For the first year of preproduction mining 162 acre-feet (100 gallons per minute) of water is required, and 323 acre-feet (200 gallons per minute) for the second year.

The total water requirement for site development is 1,696 acre-feet (1,050 gallons per minute). Averaged out over a 30-year mine life this is 57 acre-feet per year (35 gallons per minute) of water. It can be of any quality. There is no waste water output as all of the water is consumptively used.

7.8.2 Raw Shale Delivery

Raw shale delivery involves handling of the raw shale from the time it leaves the mine site until it enters the retort, and includes secondary crushing, screening, transport of the raw shale between the various facilities, transport of crushing fines to the disposal site, and stockpiling and reclaiming of the shale to be retorted. Water is required for dust control.

In-mine primary crushing serves to make the raw shale into a transportable size, but secondary crushing and screening is necessary to produce crushed raw shale within a specified size range in order for a given retort to function. Transport of the raw shale between the various facilities is done by mechanical means--either conveyor belts or trucks. 134 acre-feet per year (83 gallons per minute) of water is required for crushing, screening, and transport. The quality must be low in total dissolved solids in order to allow spraying. There is no waste water output as all of the water is consumptively used.

Oversize material is recycled back through the crushing and screening steps, but undersize material or crushing fines are transported almost in slurry-like form to the disposal site. This requires 162-242 acre-feet per year (100-150 gallons per minute) of water. It can be of any quality. There is no waste water output as all of the water is consumptively used.

The retort uses a continuous feed system that cannot accept fluctuations normal to mining, so a stockpile of the crushed raw shale acts as a buffer between the mine and the retort. Crushed raw shale is reclaimed from the stockpile as it is needed for the retort. 162 acre-feet per year (100 gallons per minute) of water is required, and it can be of any quality. Waste water output is 80 acre-feet per year (50 gallons per minute), giving a consumptive use of 82 acre-feet per year (50 gallons per minute).

The total water requirement for raw shale delivery is therefore 134 acre-feet per year (83 gallons per minute) of water low in total dissolved solids, and 324-404 acre-feet per year (200-250 gallons per minute) or an average of 364 acre-feet per year (225 gallons per minute) of water of any quality, giving a total of 458-538 acre-feet per year (283-333 gallons per minute) or an average of 498 acre-feet per year (308 gallons per minute) of water. Waste water output is 80 acre-feet per year (50 gallons per minute). Consumptive use is 378-458 acre-feet per year (233-283 gallons per minute) or an average of 418 acre-feet per year (258 gallons per minute) of water.

CHAPTER 8
INFLOW TO CONVENTIONAL MINES

8.1 INTRODUCTION

As mine inflow is expected to provide a significant portion of the water supply in oil shale mine developments in the Piceance Basin, it is clear that the evaluation of inflow is an important part of any water management study. This chapter outlines the methods used in computing mine inflow, and the results obtained when these methods are applied to the three site areas of the study, with the nominated mining scenarios.

The contract called for a significant number of mine inflow analyses. As a result it was decided to develop a technique of hand analysis which would be quick and inexpensive, and specifically tailored to the geohydrology of the Piceance Basin. In addition, numerical simulation check-analyses were run to establish the validity of these inflow assessments.

Mine inflow is controlled by the nature of the materials relatively close to the mine. This is true almost without regard to the quantity of the inflow. In cases where the inflow exceeds the water requirements of the shale oil industry being considered, it is economically and environmentally attractive to re-inject the excess into the formations which it came from (Chapter 6). Thus the net water removed from the Basin system is relatively small for the size of mine being considered in this study, and the overall impact on the Basin is small. Accordingly, the pressure regime remote from the mine is largely unchanged, and the analysis of mine inflow can be largely divorced from questions of Basin-wide geohydrology. The impact on the Basin of the removal of groundwater is considered in detail in Chapter 15.

In the light of this local control of inflow, the specific hydrogeologies of each site are used in performing the inflow computation. In each case the hydrogeology is assumed to be valid over a relatively large area around the mine. A fixed head boundary is assumed at about the edge of the Basin (20 miles away on average), and it is assumed that any re-injection takes place well away from the mine.

8.2 HAND ANALYSIS METHODS

8.2.1 Underground Mine with No Subsidence

This analysis provides minimum inflow for any given mine cavern development. It is assumed that the material properties of the unmined rock remain unchanged by the hydrogeologic and stress changes caused by mining. The analysis technique comprises dividing up the vertical section through the mine into three zones, as shown on Figure 8-1. Zone 1 is the area above the mining horizon, Zone 2 is the area adjacent to the material drained by the mine activity (which may be higher than the actual mine due to roof and floor drainage for stability), and Zone 3 is the material between the mine floor and the top of the first layer of relatively impervious material beneath. Inflow patterns in each zone are shown schematically in Figure 8-1.

8.2.1.1 Zone 1

Flow in zone 1 is relatively complex. Gravity flow to the roof of the mine is augmented by flow from the material in Zone 1 which is outside the mined area. In order to evaluate inflow quantities to the mine from this zone a simple set of parametric studies were performed using Golder Associates' Finite

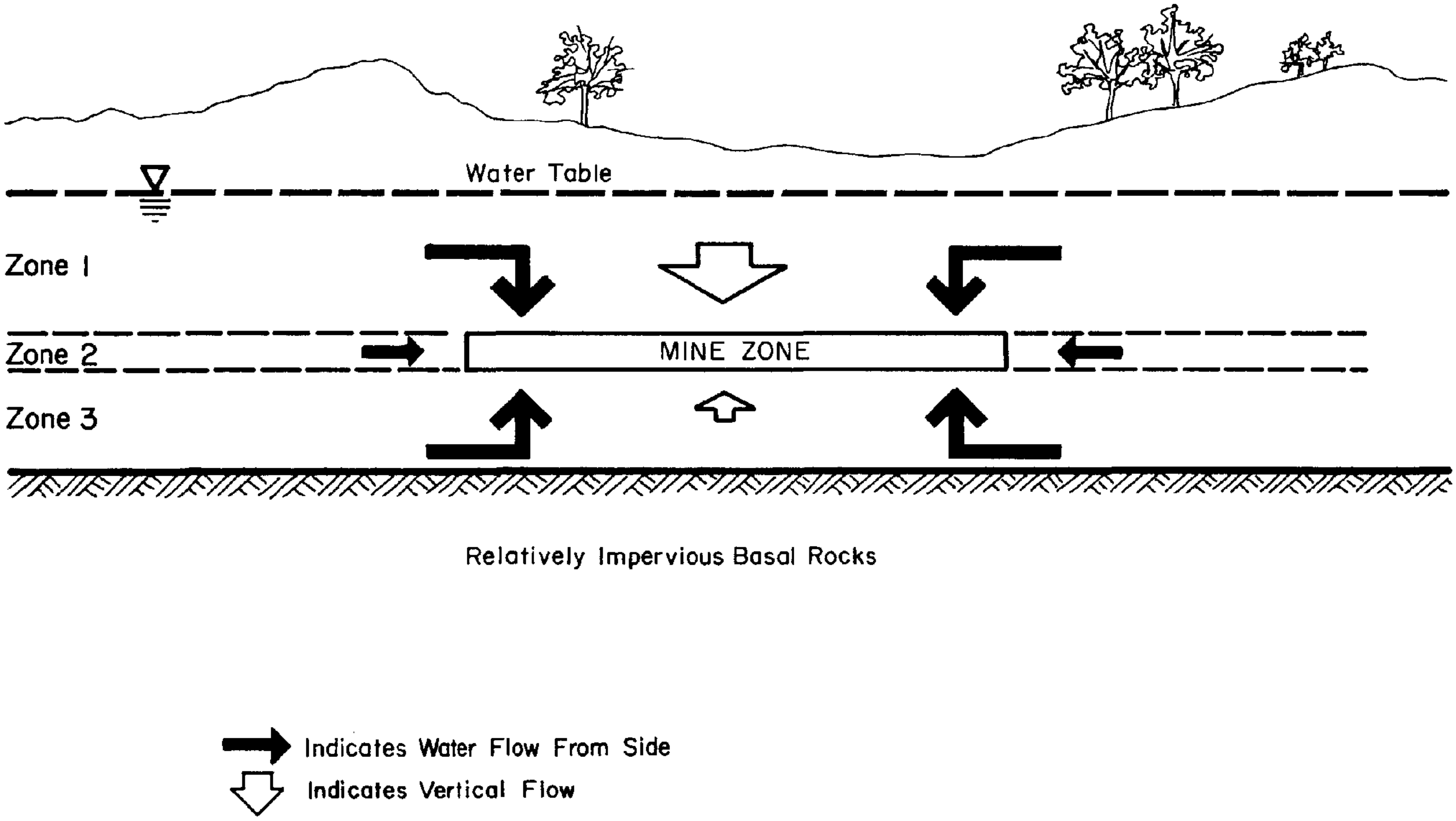

Water Table
Zone 1
Zone 2
Zone 3
MINE ZONE
Relatively Impervious Basal Rocks
Indicates Water Flow From Side
Indicates Vertical Flow

Figure 8-1 SCHEME FOR HAND ANALYSIS of INFLOW to an UNSUBSIDED UNDERGROUND MINE

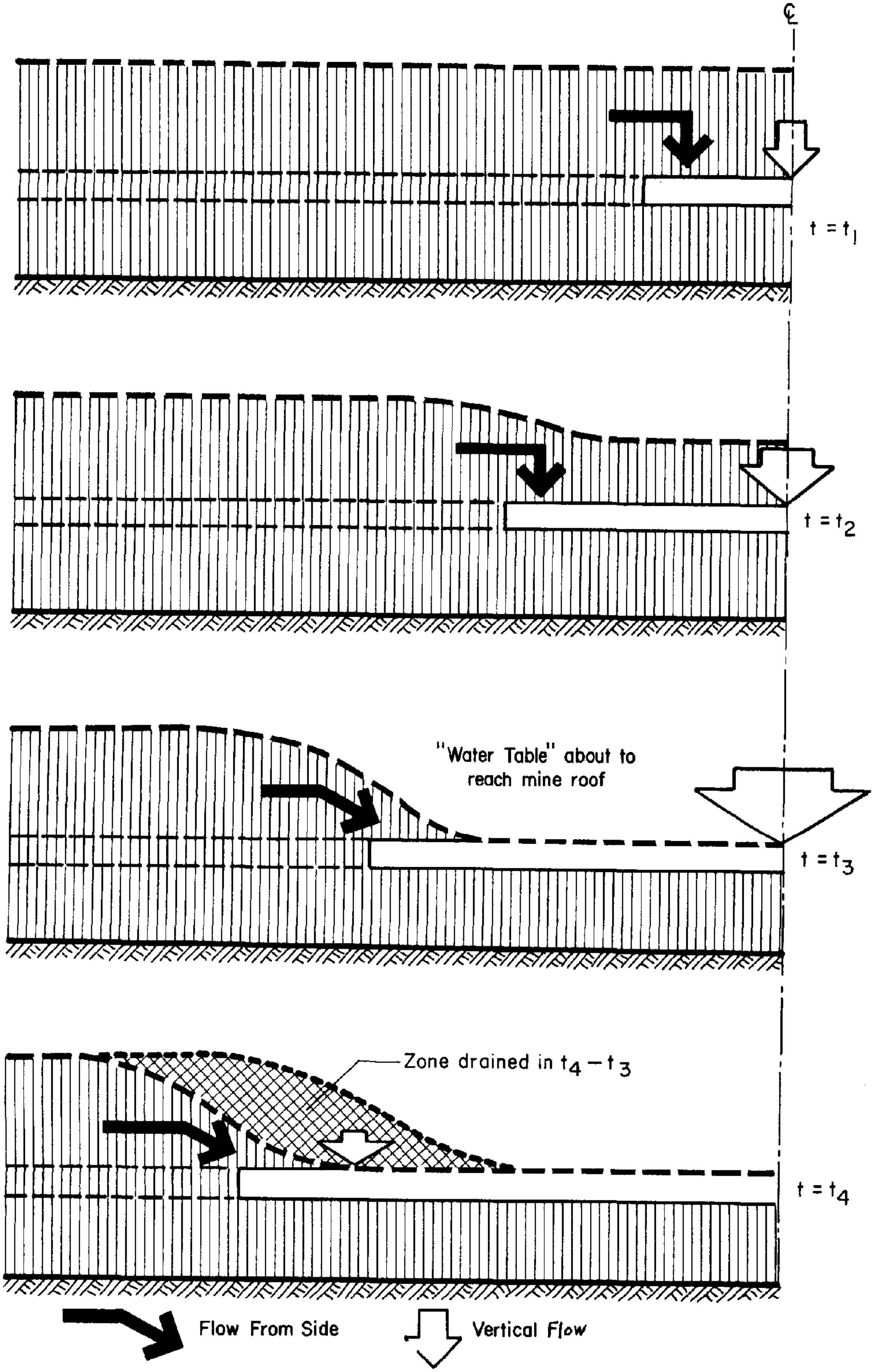
Element Method flow simulation computer program. An axisymmetric analysis study of Zone 1 was made, varying the following parameters:

i. Horizontal permeability
ii. Vertical permeability
iii. Thickness of Zone 1
iv. Radius of the mine
v. Elapsed time
vi. Material porosity

The actual method is shown in Appendix C. From this parametric study a relatively quick method of hand analysis of inflow to Zone 1 was developed.

For the case where the vertical permeability in Zone 1 is high, and the drainable porosity of the materials making up Zone 1 are low, the rate of movement of the "water table" (defined in this study as the upper limit of the zone of saturation in the medium) is quite rapid. After a time the condition is reached where the entire section above the center of the mine is desaturated. When this occurs, the flow to the mine roof will stabilize at an amount equal to the horizontal flow in the aquifer plus the flow required to de-saturate the perimeter area above the mine which has been opened up in the time period being considered. This dynamic concept is shown schematically in Figure 8-2. This effect theoretically takes from a few to hundreds of years to occur for mines in the Piceance Basin, and depends strongly on the absolute values of porosity and vertical permeability. Details appear in Appendix C.

Figure 8-2 DEVELOPMENT of DRAINAGE to MINE ROOF


℄
t = t_1
t = t_2
"Water Table" about to reach mine roof
t = t_3
Zone drained in $t_4 - t_3$
t = t_4
Flow From Side
Vertical Flow

8.2.1.2 Zone 2

The flow toward the mine zone in Zone 2 is simply equal to the flow from a relatively large well in Zone 2. For the time periods being considered in mining, this flow is virtually independent of the effective diameter of the mine. In general this flow is at least an order of magnitude less than the flow from Zone 1. Analytical details appear in Appendix C.

8.2.1.3 Zone 3

The conditions in Zone 3 are similar to those in Zone 1, except that the vertical flow originating from the material immediately beneath the mine is negligible. Thus the total flow from this zone originates in the rock beneath and outside the perimeter of the mine. As the mine expands it becomes easier and easier for the total flow from that region to move vertically through the strata beneath the mine, because of the increasing area available for this flow to occur. After a relatively short period of mining, the available area is such that almost the full horizontal flow available from the rock beneath the mine appears in the mine. In general flows from Zone 3 are also an order of magnitude less than flows from Zone 1. Computational details appear in Appendix C.

8.2.1.4 Low Permeability Special Case

In the cases where the permeability of the strata in which the mine is located are very low (i.e. for most of the deeper mines) the method of computation given above becomes inappropriately complicated. In the low permeability situation, the volume of flow has little impact on the hydrology of the relatively prolific rock mass above the mine host rock. Accordingly, a simpler inflow computation for Zone 1 is adopted where the head at the base of the prolific zone is assumed to be constant, and the vertical flow is computed from the resulting constant head gradient to the mine roof. This scheme is shown in Figure 8-3.

8.2.2 Underground Mine with Full Subsidence

In this analysis case, flows from Zones 2 and 3 are identical to the no subsidence case. However, it is assumed that the flow from Zone 1 enters the mine roof via a fully disturbed plug of rock of the same diameter as the mine, and over the entire depth of material from the surface to the mine roof. This arrangement is shown in Figure 8-4. The resulting cumulative inflow represents a maximum for the mine geometry used.

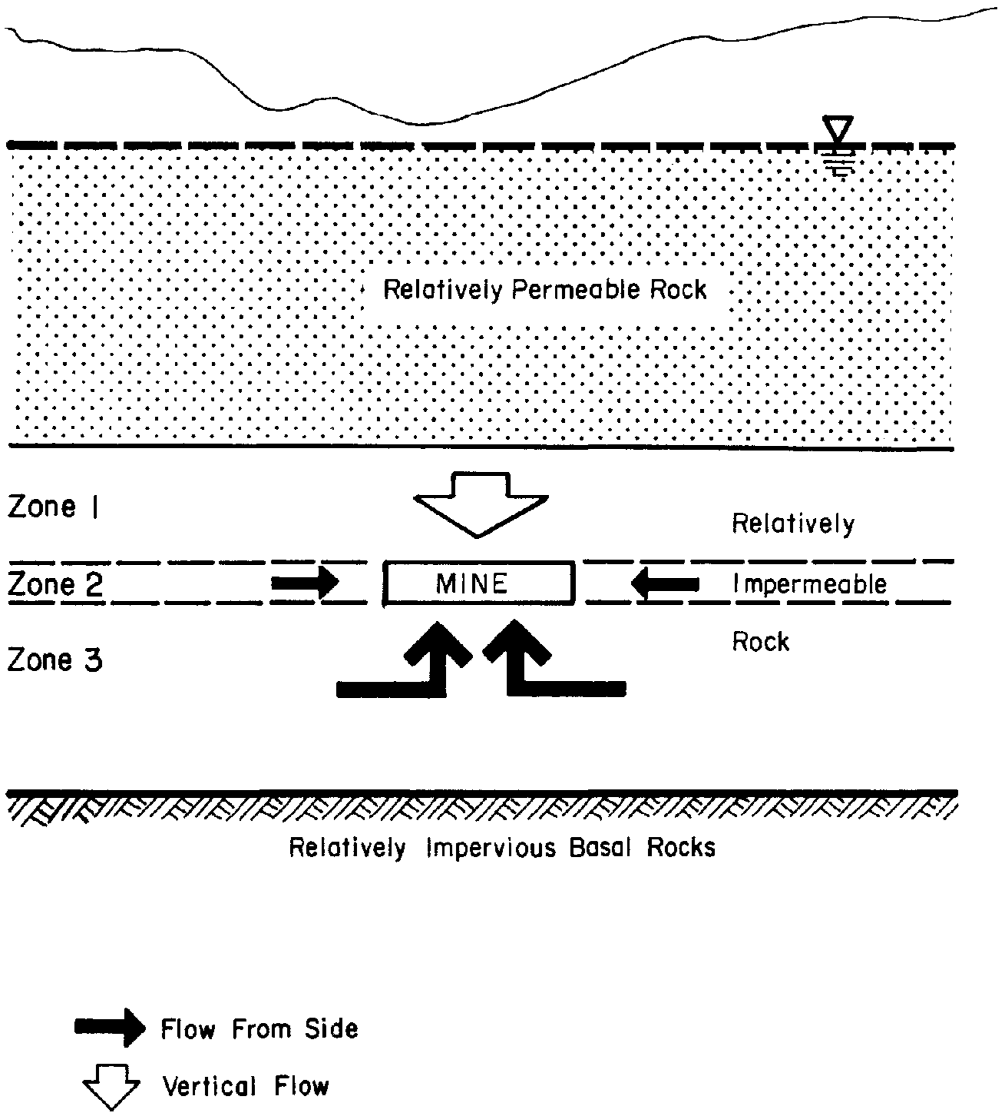
The inflow to the mine from Zone 1 in this case is simply the sum of the horizontal flow in the Zone 1 rock outside the fractured area above the mine, plus the flow rate resulting from the drainage of the rock which is directly above the area which has been mined in the incremental time period being considered. Analytical details are given in Appendix C.

The choice of vertical boundaries for the zone of mining disturbance was made on essentially pragmatic grounds. First, the computation of flow rates was simplified by this choice, and second, it can be shown that the inflow to the mine is not very sensitive to assumptions about the shape of the cave, as long as it extends to the top of the saturated zone. This should not be taken to imply that the caved area shown on Figure 8-4 is expected to bear much resemblance to the actual subsidence pattern.

8.2.3 Flow to an Open Pit Mine

For the purpose of this study it has been assumed that inflow to an open pit mine is identical to the inflow to a caved mine

Figure 8-3 SCHEME FOR HAND ANALYSIS OF INFLOW TO AN UNSUBSIDED MINE IN RELATIVELY IMPERMEABLE ROCK


Relatively Permeable Rock
Zone 1
Zone 2
Zone 3
MINE
Relatively
Impermeable
Rock
Relatively Impervious Basal Rocks
Flow From Side
Vertical Flow

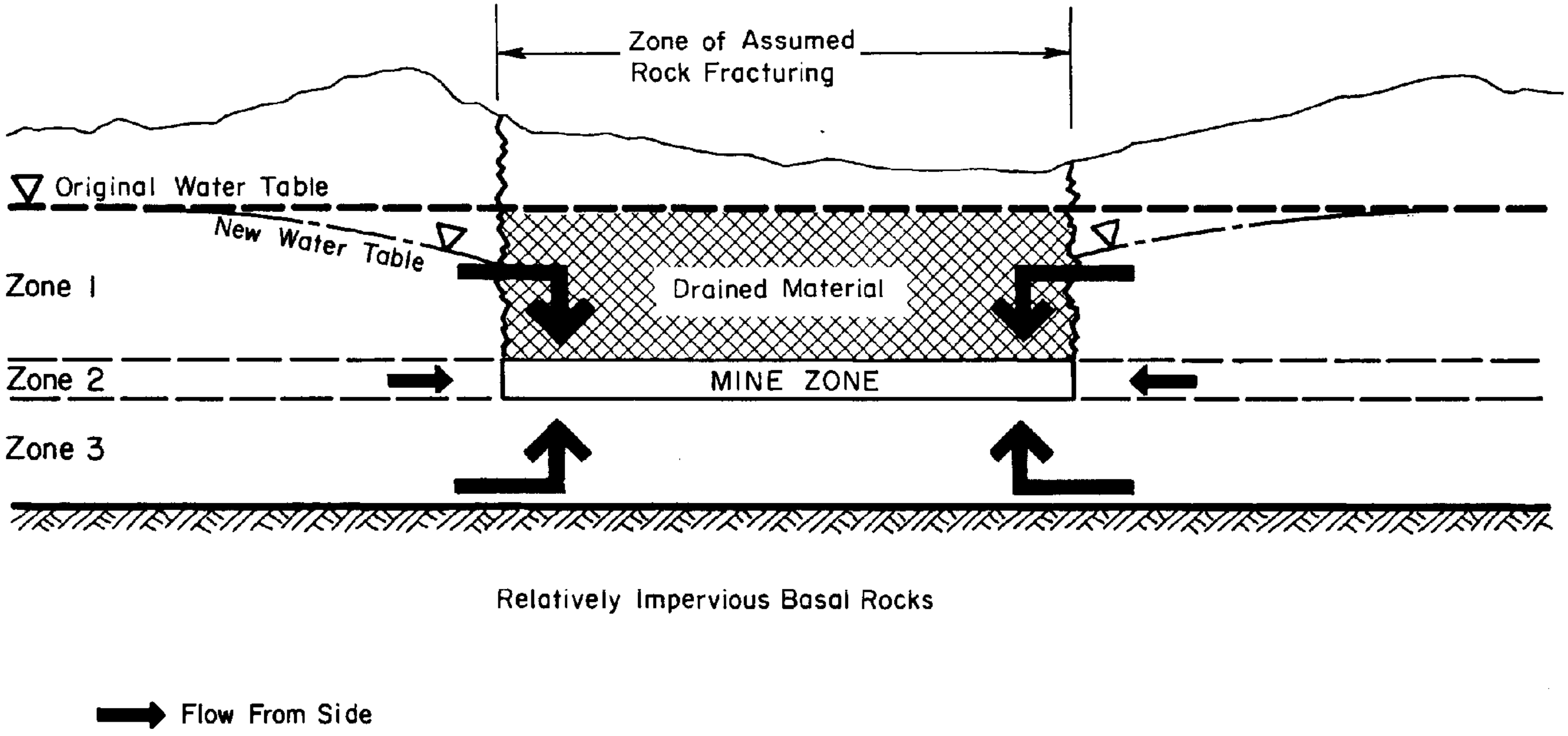

Zone of Assumed Rock Fracturing
Original Water Table
New Water Table
Drained Material
Zone 1
Zone 2
MINE ZONE
Zone 3
Relatively Impervious Basal Rocks
Flow From Side

Figure 8-4 SCHEME FOR HAND ANALYSIS of INFLOW to a FULLY SUBSIDED MINE

under the same rate of areal expansion. The rationale for this assumption is that the water which flows into the pit area will not in general be removed with the ore, but will either evaporate or pond, depending on quantity. Note that this section of the evaluation only covers the inflow, not the fate of the water once it has entered the mine. Once more, we have chosen to assume a vertical sided pit, for ease of computation and because it makes little difference to the total inflow. Finally the effect of removing the water from the rock by pumping wells around the periphery of the mine is not significant in terms of total quantity of water - the same total water flow will come to the project in either case.

8.3 ANALYSIS OF SITE 1

8.3.1 Geohydrology

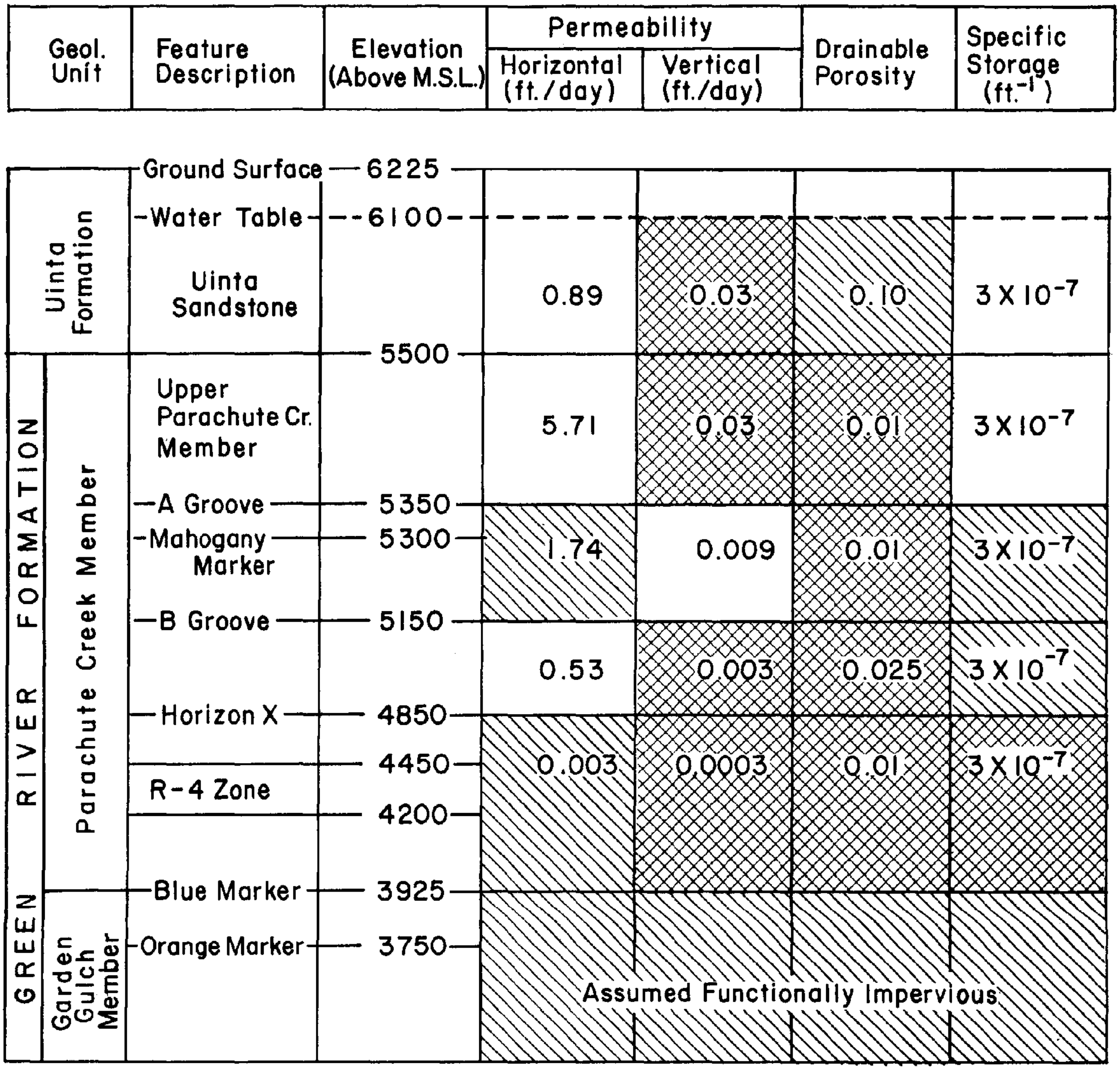
The geohydrology model used for Site 1 is shown in Figure 8-5. This was derived in Chapter 4 and has the following major features:

a. The Parachute Creek member above the Mahogany Zone is highly pervious by Basin standards. The transmissivity of this stratum alone is 1,142 sq.ft./day (8,600 gpd/ft.).

b. The Parachute Creek member below the Mahogany Zone is of relatively low permeability by Basin standards for this stratum.

c. The material between the lower leached zone and the Blue Marker appears to be of extremely low permeability based on one possibly questionable result. The upper half of this region did, however, show extremely competent rock in the core drilling.

Figure 8-5 GEOHYDROLOGY MODEL OF SITE I



Geol. Unit	Feature Description	Elevation (Above M.S.L.)	Permeability		Drainable Porosity	Specific Storage ($ft.^{-1}$)
			Horizontal (ft./day)	Vertical (ft./day)		
Uinta Formation	Ground Surface	6225				
	Water Table	6100				
	Uinta Sandstone		0.89	▦ 0.03	▨ 0.10	3×10^{-7}
GREEN RIVER FORMATION – Parachute Creek Member		5500				
	Upper Parachute Cr. Member		5.71	▦ 0.03	▦ 0.01	3×10^{-7}
	A Groove	5350				
	Mahogany Marker	5300	▨ 1.74	0.009	▦ 0.01	▨ 3×10^{-7}
	B Groove	5150				
			0.53	▦ 0.003	▦ 0.025	▨ 3×10^{-7}
	Horizon X	4850				
		4450	▨ 0.003	▦ 0.0003	▦ 0.01	▦ 3×10^{-7}
	R-4 Zone					
		4200				
GREEN RIVER FORMATION – Garden Gulch Member	Blue Marker	3925				
	Orange Marker	3750	▨ Assumed Functionally Impervious	▨	▨	▨

NOTES:

1. Geology based on USBM 01-A and USBM 02-A.
2. Hydrology data primarily from USBM 01-A, USBM 02-A, and USBM pilot hole "X" testing.
3. All elevations rounded to nearest 25 feet.
4. Not to scale.
5. Quality of information for the purposes of this study:
   - ☐ "Based on acceptable test data"
   - ▨ "Estimated or based on poor data"
   - ▦ "Experiential guess"
6. Available data indicates that this model is not valid at points 3 to 4 miles distance from Horse Draw. It should be used only with great caution, and with a complete understanding of the data upon which it is based.
7. Horizon X is defined in section 4.5.1.

d. A meaningful value of 0.009 ft./day for vertical permeability of the Mahogany Zone was obtained in a test across this zone. This is one of only three useable tests of this parameter in the Basin.

e. The 600 ft. saturated thickness of Uinta sandstone represents a very large stored water source, which ensures sustained flows of water to any mine development above the base of the leached zone.

8.3.2 Analyses Performed

A range of analyses have been performed for this site varying both mining type and stratigraphic location, as required in the contract. In order to span the actual requirements 48 analyses were performed, involving all combinations of the following variables:

a. Location of Mining. Three locations in the stratigraphic column were considered:
   i. Single-pass mining centered in the Mahogany Zone
   ii. Single-pass mining centered in the R-4 Zone
   iii. Multiple-pass mining to extract the entire resource between the "A" groove and the Blue marker

b. Type of Mining. All the types of mining called for in the contract were considered; namely:
   i. Room and pillar
   ii. Chamber and pillar
   iii. Sub-level stoping
   iv. Block caving

c. Type of Subsidence. Two extreme subsidence scenarios were considered:
   i. No subsidence
   ii. Full subsidence

   In the latter case the vertical permeability in the column of material above the mined section was assumed to be infinite whereas in the former case the original vertical permeability was used.

d. Rate of Mining. The contract called for two mining rates to be considered:
   i. 50,000 ton/day of ore (18 million TPY)
   ii. 100,000 ton/day of ore (36 million TPY)

8.3.3 Rate of Mine Expansion and Mine Geometry

Mine expansion rates and mine geometries for this evaluation are presented in Chapter 7. Table 8-1 summarizes the relevant parts of that chapter. Note that mine backfilling is assumed to have no significant impact on mine inflow.

8.3.4 Results

Results are presented in detail in Appendix D. The average inflows for various mines at Site 1 are given in Table 8-2. The most striking feature is the wide divergence of results. Note that in the case of very high flow rates most of this water would have to be re-injected, and so would simply circulate in the pumping system.

In general the flow rate builds up for the first few years, and then tends to stabilize as the rate of increase of mine circumference slows. On some analyses there is a dramatic drop in inflow when the zone of saturation reaches the mine roof. A typical example for all three sites is shown as Figure 8-6.

TABLE 8-1

MINE AREA EXPANSION RATES - SITE 1

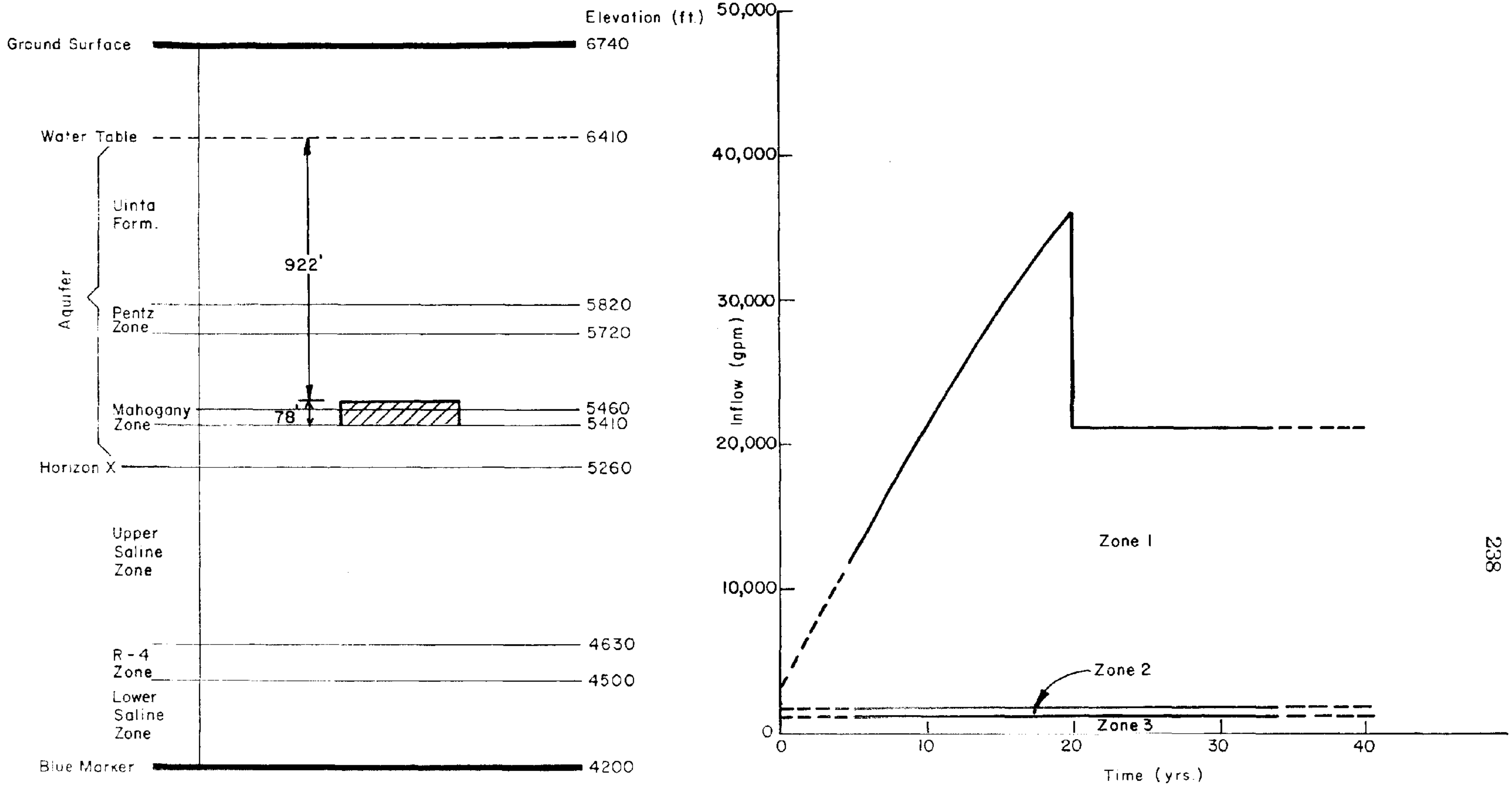
Mining Type	Development Height(ft.)	No. of Passes	Expected* Resource Recovery %	Expansion Rate (sq.mi./yr.) for Extraction of 50,000 TPD	100,000 TPD
Room & Pillar	100	1	37	.182	.364
		8	37	.023	.046
Chamber & Pillar	60	1	26	.364	.728
	60	11	26	.033	.066
Sublevel Stoping	280	1	78	.038	.076
	280	4	78	.009	.038
Sublevel Stoping With Backfill	280	1	40	.074	.148
	280	4	40	.020	.037
Block Caving	550	1	51	.030	.060
	550	2	51	.015	.030

* Resources recovery including sill pillars, barrier pillars, and shaft pillars. Recovery is defined as ratio of extracted ore volume to alienated volume, expressed as a percentage.

TABLE 8-2

AVERAGE INFLOWS FOR 30 YEARS OF MINING - SITE 1 (ACRE-FEET PER YEAR)

Location	Rate	Subsidence	Room & Pillar	Chamber & Pillar	Sublevel Stoping	Sublevel Stoping with Backfill	Block Caving
Single Pass in Mahogany Zone	50,000 TPD	None	40,300	48,400	--	29,800	--
		Full	48,900	60,300	26,000	33,700	24,200
	100,000 TPD	None	60,700	76,500	--	40,300	--
		Full	71,100	90,700	33,100	45,200	29,000
Single Pass in R-4 Zone	50,000 TPD	None	1,000	1,100	--	500	--
		Full	52,400	64,400	27,900	36,000	24,400
	100,000 TPD	None	1,600	2,300	--	800	--
		Full	77,000	97,900	35,300	49,000	29,500
Multiple Pass For Maximum Extraction	50,000 TPD	None	16,100	14,500	--	15,800	--
		Full	26,100	25,200	19,800	23,400	21,000
	100,000 TPD	None	21,800	20,200	--	21,800	--
		Full	31,600	30,200	23,100	27,900	24,200



MINE INFLOW (gpm)

Time - yrs	Radius - ft	Zone 1	(drain) Zone 1	Zone 2	Zone 3	Total
.5	5,189	11,073	-	182	1081	12,340
10	7,336	19,672	-	182	1082	20,940
20	10,373	34,415	-	182	1083	35,680
30	12,703	20,212	-	182	1083	21,470

DESCRIPTION:

Mining Method Room & Pillar, No Subsidence
Number of Passes 1
Location Mahogany
Mining Height 78 ft
Expansion Rate .606 mi^2/yr
Initial Radius 200 ft
Mining Rate 100,000 ton/day

Figure 8-6 MINE INFLOW - SITE 3

8.4 ANALYSIS OF SITE 2

8.4.1 Geohydrology

Site 2 is characterized by a dual aquifer system, as shown on Figure 8-7. The upper aquifer is relatively permeable by Basin standards, but is only about 300 feet thick, and so contributes little water to wells or mines located in it. The lower aquifer is only 200 feet thick, but is very permeable, and will initially provide large quantities of water to wells and mines penetrating it. The layer between the aquifers is highly impermeable and provides almost total isolation of one aquifer from the other in most places. This sealed-off effect creates the situation that yields from the lower aquifer will drop rapidly with time, as the recharge to the aquifer is probably very limited. However, in a mine inflow context this will not occur, as the inflow water will likely be re-injected into the lower aquifer, thus maintaining the water pressures in it.

8.4.2 Analyses Performed

The contract calls for a range of analyses as follows:

a. Location of Mining. Three locations in the stratigraphic column were considered:
   - i. Single-pass mining centered in the Mahogany Zone
   - ii. Single-pass mining centered in the R-4 Zone
   - iii. Multiple-pass mining to extract the entire resource between the "A" groove and the Blue marker

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Figure 8-7 GEOHYDROLOGY MODEL OF SITE 2

Geol. Unit		Feature Description	Elevation (Above M.S.L.)	Permeability		Drainable Porosity	Specific Storage (ft^{-1})
				Horizontal (ft./day)	Vertical (ft./day)		
		Ground Surface	6740				
Uinta Formation		Uinta Sandstone					
GREEN RIVER FORMATION	Parachute Creek Member	Water Table	6610				
		Upper Parachute Creek Member		▧ 1.33	▦ .003±	▦ 0.01	▧ 4×10^{-7}
		A Groove	6470				
		Mahogany Marker	6450	▧ 1.33	▦ .0014	▦ .01	▧ 4×10^{-7}
		B Groove	6330	▧ 1.33	▦ .003±	▦ .03	▧ 4×10^{-7}
		Horizon X	6290	☐ 0.03	☐ .0003	▦ .01	▦ 4×10^{-7}
			5890	☐ 7.0	▦ .03	▦ .01	☐ 4×10^{-7}
		R-4 Zone	5780				
			5690	☐ 0.2	▦ .003	▦ .01	▦ 4×10^{-7}
		Blue Marker	5560				
	Garden Gulch Member	Orange Marker	5360	▧ Assumed Functionally Impervious	▧	▧	▧

NOTES:

1. Based on Cameron Engineers CE 705.
2. All elevations rounded to nearest 10 feet.
3. Not to scale.
4. Quality of information for the purposes of this study:

☐	"Based on acceptable test data"
▧	"Estimated or based on poor data"
▦	"Experiential guess"

5. Horizon X is defined in section 4.5.1.

Golder Associates

b. Type of Mining. Two types were considered; namely:
   i. Room & Pillar Mining
   ii. Open Pit Mining

c. Rate of Mining. Three rates were considered; namely:
   i. 50,000 TPD
   ii. 100,000 TPD
   iii. 200,000 TPD (open pit only)

d. Type of Subsidence. Two extreme subsidence scenarios were considered for the room & pillar case only:
   i. No subsidence
   ii. Full subsidence

8.4.3 Mine Expansion Rates and Geometry

Mine expansion rates and mine geometries for this evaluation are presented in Chapter 7. Table 8-3 summarizes the relevant parts of that chapter.

8.4.4 Results

Results are presented in detail in Appendix D. Average inflow rates over the 30-year mine life are presented in Table 8-4. It is interesting to note the low flows in upper aquifer mining, but uniformly higher flows for all deeper mining activities. Note that extraction rate has little impact on average inflows.

TABLE 8-3

MINE AREA EXPANSION RATES - SITE 2

Mining Type	Development Height (ft.)	Number of Passes	Expected* Resource Recovery (%)	Mine Expansion Rate (sq.mi./yr.) for Extraction of 50,000 TPD	100,000 TPD	200,000 TPD
Room & Pillar	60	1	30	.315	.630	1.260
		9	30	.036	.070	.140
Open Pit						
(a) shallow	410	1	100	.050	.100	.200
(b) deep	1180	1	100	.012	.024	.048

* Resource recovery includes sill pillars, barrier pillars, and shaft pillars. Recovery is defined as ratio of extracted ore volume to alienated volume, expressed as a percentage.

TABLE 8-4

AVERAGE INFLOWS FOR 30 YEARS OF MINING - SITE 2 (ACRE-FEET PER YEAR)

Location	Rate	Subsidence	Room & Pillar	Open Pit
Single Pass in Mahogany Zone	50,000 TPD	None	1,800	--
		Full	1,800	1,500
	100,000 TPD	None	2,700	--
		Full	2,700	1,800
	200,000 TPD	None	--	--
		Full	--	2,300
Single Pass in R-4 Zone	50,000 TPD	None	11,800	--
		Full	15,800	--
	100,000 TPD	None	13,900	--
		Full	19,400	--
Multiple Pass For Maximum Extraction	50,000 TPD	None	12,300	--
		Full	12,300	11,900
	100,000 TPD	None	13,100	--
		Full	13,100	12,700
	200,000 TPD	None	--	--
		Full	--	13,700

8.5 ANALYSIS OF SITE 3

8.5.1 Geohydrology

Site 3 is generally of low permeability, as shown in Figure 8-8. The site can be characterized by 1,500 feet of low permeability material overlying virtually impervious rock. There are two significant bands of low permeability rock within this 1,500 feet.

8.5.2 Analyses Performed

The contract calls for two analyses: evaluation of inflow to a conventional room and pillar mine in the Mahogany Zone, at mining rates of 50,000 and 100,000 TPD.

8.5.3 Mine Expansion Rates and Geometry

Mine expansion rates are presented in Chapter 7. Table 8-5 summarizes the relevant parts of that chapter.

TABLE 8-5

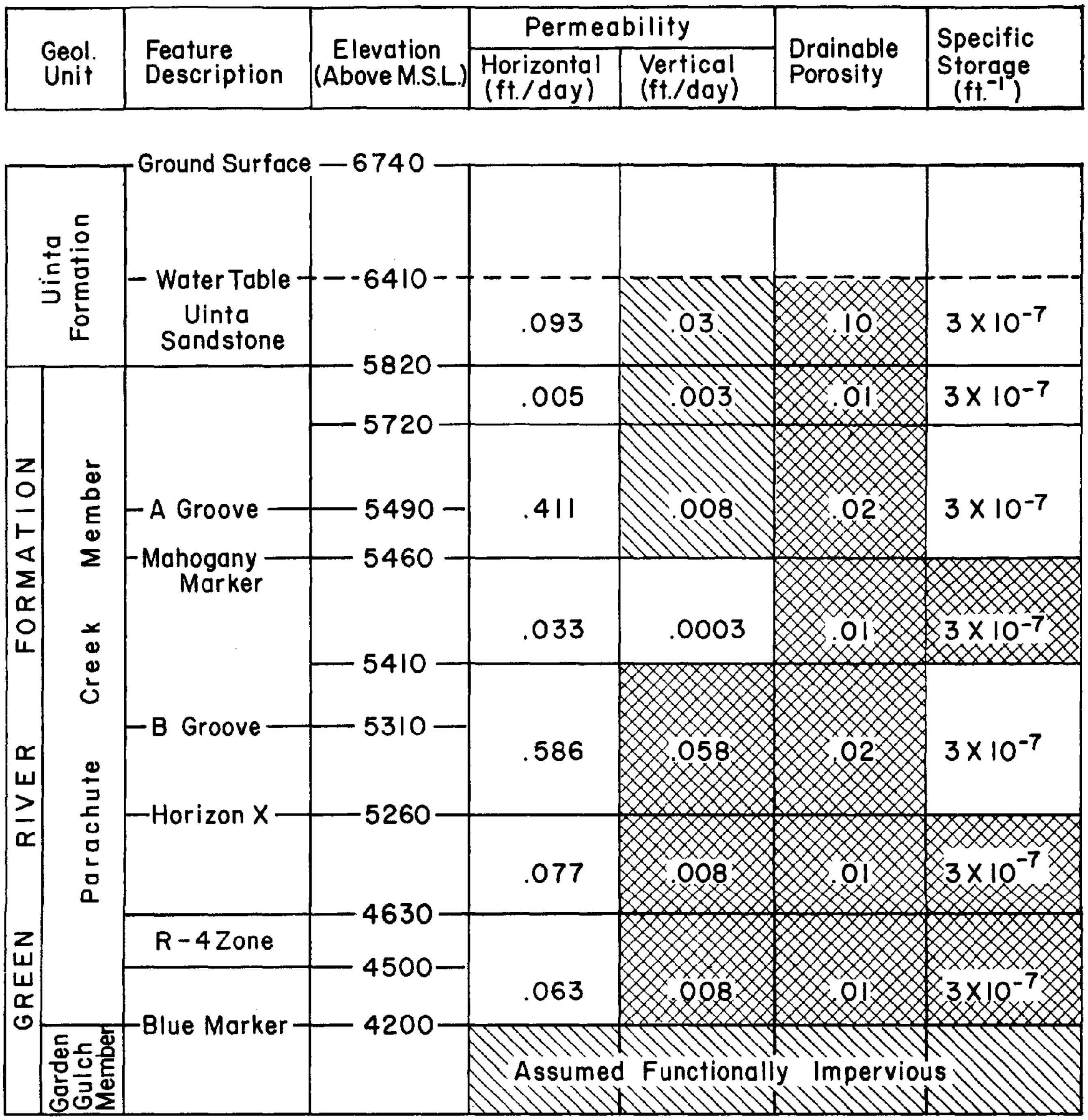
MINE AREA EXPANSION RATES - SITE 3

Mining Type	Development Height (ft.)	Number of Passes	Expected Resource Recovery %	Expansion Rate (sq.mi./yr. for Extraction of 50,000TPD	100,000TPD
Room & Pillar	78	1	26	0.303	0.606

8.5.4 Results

The results of the inflow analyses are presented in detail in Appendix D. Average flow rates over the assumed 30-year mine

Figure 8-8 GEOHYDROLOGY MODEL OF SITE 3



Geol. Unit	Feature Description	Elevation (Above M.S.L.)	Permeability Horizontal (ft./day)	Permeability Vertical (ft./day)	Drainable Porosity	Specific Storage ($ft.^{-1}$)
Uinta Formation	Ground Surface	6740				
	Water Table	6410				
	Uinta Sandstone		.093	▨ .03	▩ .10	$3 X 10^{-7}$
GREEN RIVER FORMATION – Parachute Creek Member		5820				
			.005	▨ .003	▩ .01	$3 X 10^{-7}$
		5720				
	A Groove	5490	.411	▨ .008	▩ .02	$3 X 10^{-7}$
	Mahogany Marker	5460				
			.033	.0003	▩ .01	▩ $3 X 10^{-7}$
		5410				
	B Groove	5310	.586	▩ .058	▩ .02	$3 X 10^{-7}$
	Horizon X	5260				
			.077	▩ .008	▩ .01	▩ $3 X 10^{-7}$
		4630				
	R - 4 Zone		.063	▩ .008	▩ .01	▩ $3 X 10^{-7}$
		4500				
	Blue Marker	4200				
GREEN RIVER FORMATION – Garden Gulch Member			▨ Assumed Functionally Impervious			

NOTES:

1. Based on TOSCO Cb-3.
2. All elevations rounded to nearest 10 feet.
3. Not to scale.
4. Quality of information for the purposes of this study:
   - ☐ "Based on acceptable test data"
   - ▨ "Estimated or based on poor data"
   - ▩ "Experiential guess"
5. Horizon X is defined in section 4.5.1.

life are presented in Table 8-6. Flows are relatively large due to the relatively deep location of the Mahogany Zone, and also because of the somewhat higher vertical permeabilities used in the model.

TABLE 8-6

AVERAGE INFLOWS FOR 30 YEARS OF MINING - SITE 3
(ACRE-FEET PER YEAR)

Location	Rate	Subsidence	Room & Pillar
Single Pass	50,000 TPD	None	19,500
		Full	19,500
in			
Mahogany Zone	100,000 TPD	None	34,700
		Full	34,700

CHAPTER 9
SURFACE RETORTING

Surface retorting is the term applied to various methods of removing kerogen or shale oil from crushed raw oil shale. All of these methods utilize heat to decompose the hydrocarbons to liquid and gaseous products. Surface retorting can be subdivided into two primary types: gas-combustion or heated-gas circulation retorts, and solid-to-solid heat exchange retorts. There are a large number of variations to these which differ in specific aspects of heat exchange, gas flow, and product oil properties. The contract for this study selected for consideration the Paraho, Union B, and TOSCO II processes. Paraho and Union B are of the gas combustion/heated gas circulation type, while TOSCO II is of the solid-to-solid heat exchange type. The following information on process background, description, and product properties comes primarily from a report by the TRW Corporation (1976).

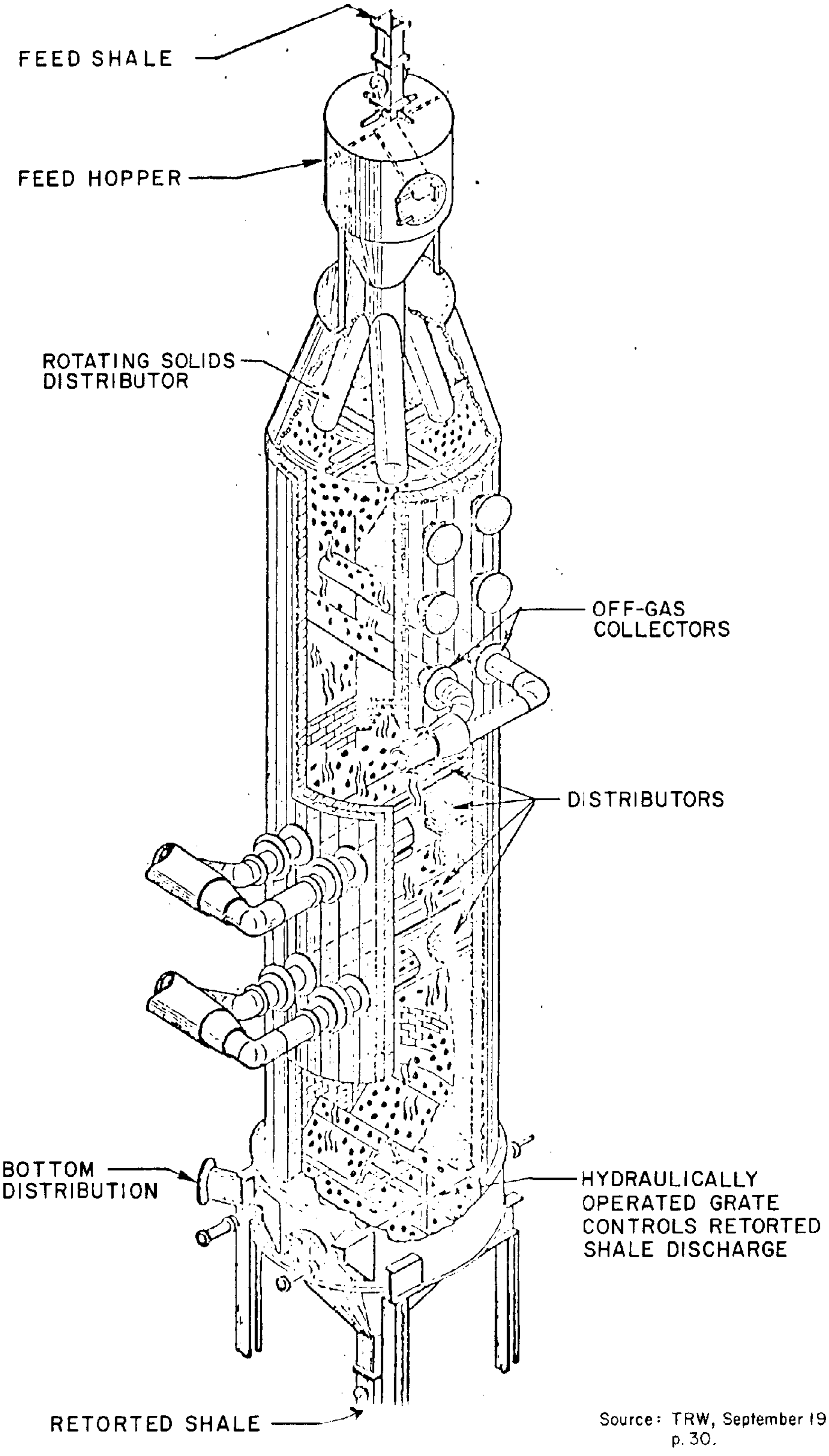
9.1 PARAHO RETORT

9.1.1 Mode of Operation

The Paraho retort may be operated with the source of heat energy for the retorting process being provided by combustion of gas and residual carbon in the retort (direct heating mode) or by heat exchange from hot gas (indirect mode). The retort is shown in Figure 9-1, and utilizes downward solid flow and upward gas flow.

In either mode of operation, crushed raw shale in the minus 3 inch to plus .25 inch size range is fed into the top of the Paraho retort by means of a rotary feed mechanism that distributes the shale uniformly around the top level of the retort. The shale moves downward by gravity successively

Figure 9-1 PARAHO RETORT


FEED SHALE
FEED HOPPER
ROTATING SOLIDS DISTRIBUTOR
OFF-GAS COLLECTORS
DISTRIBUTORS
BOTTOM DISTRIBUTION
HYDRAULICALLY OPERATED GRATE CONTROLS RETORTED SHALE DISCHARGE
RETORTED SHALE

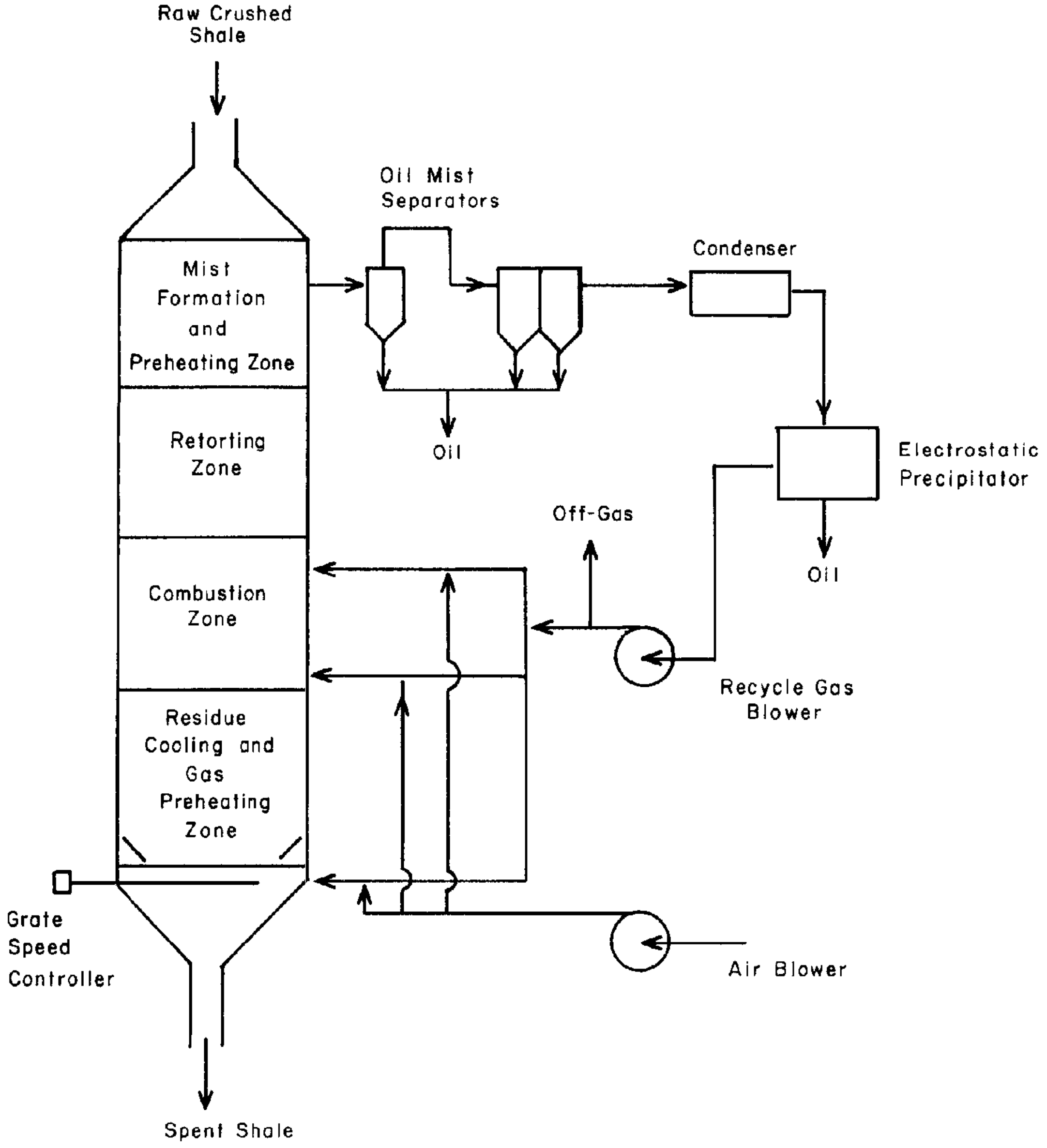
Source: TRW, September 1976, p. 30.

through a mist formation and preheating zone, a retorting zone, either a combustion zone (direct mode) or heating zone (indirect mode), and finally, a residue cooling and gas preheating zone. The spent shale is discharged from the bottom of the retort through a hydraulically-operated grate, which controls the desirable downward velocity and maintains uniform flow through the retort. The spent shale contains about 2% carbon (direct mode) to 4.5% carbon (indirect mode), and is discharged from the retort at about 300°F, essentially unchanged from its feed size distribution. The shale oil vapor produced in the retorting zone rises and is cooled to a stable mist by the incoming raw shale, and leaves the top of the retort at approximately 140°F (direct mode) or 280°F (indirect mode). The mist is sent to a separator, a condenser, and finally a wet electrostatic precipitator, for shale oil/retort gas separation and recovery.

In the direct heating mode (Figure 9-2) the cooled, oil-free, low-BTU retort gas is, in part, recycled to the retort. Some of this recycled retort gas is used to cool the spent shale on the grate in the lower level of the residue cooling and gas preheating zone. The remaining recycled retort gas is mixed with air entering the retort for combustion. This gas/air mixture and the residual carbon on the spent shale are burned in the combustion zone to provide the heat for retorting. The nonrecycled retort gas is sent to a thermal oxidizer, without prior treatment for sulfur or ammonia removal, and the resulting off-gas vented to atmosphere. In a commercial size plant the retort gas would be processed, as required, to be sulfur and ammonia free, and used as plant fuel or for power generation in low-BTU turbines.

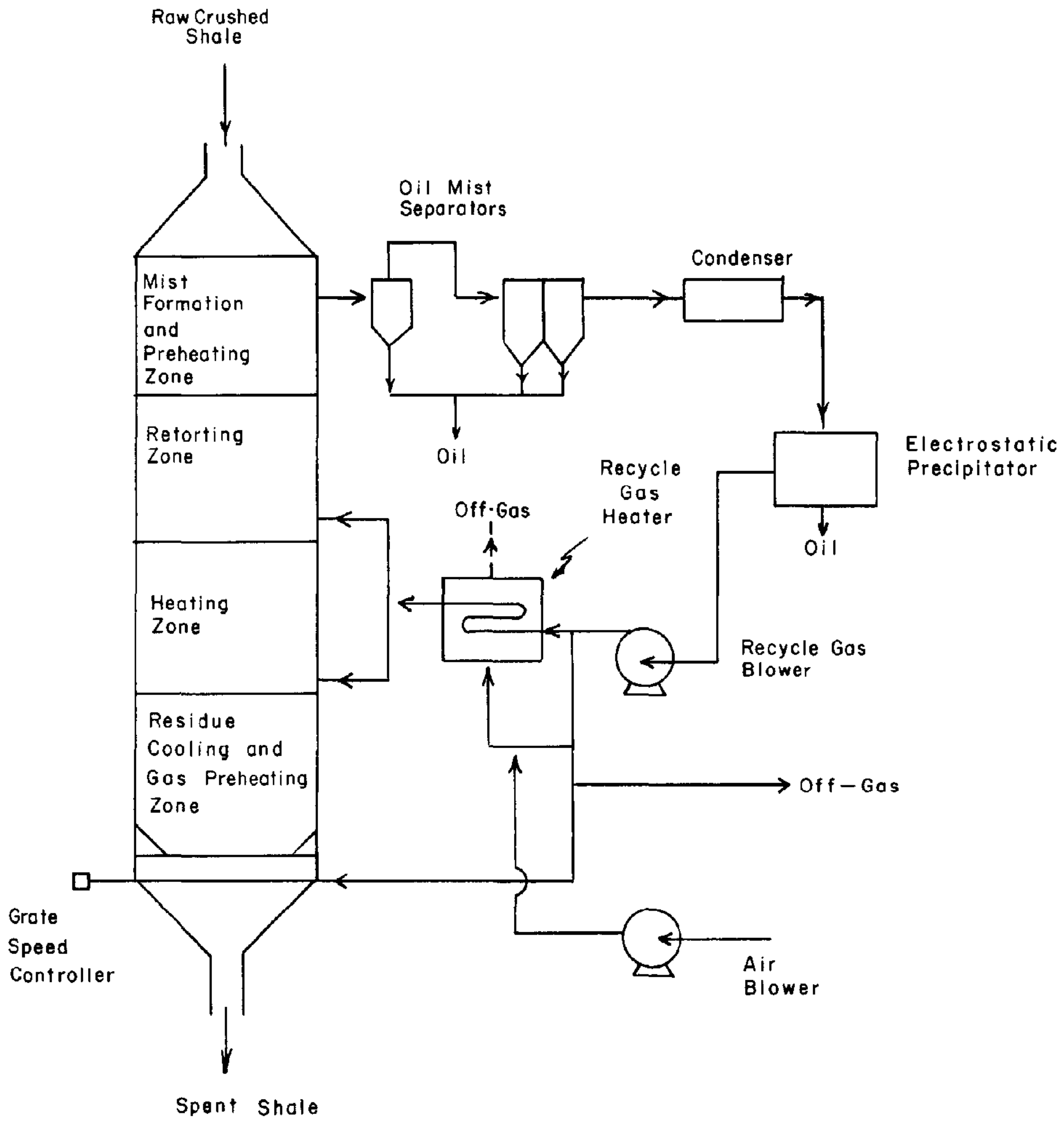
In the indirect heating mode (Figure 9-3) the retort gas handling is similar, except that it has a higher BTU value and no combustion occurs, so the sulfur and ammonia concentration is

Figure 9-2 PARAHO DIRECT MODE RETORT FLOW DIAGRAM


Raw Crushed Shale
Oil Mist Separators
Condenser
Mist Formation and Preheating Zone
Retorting Zone
Oil
Electrostatic Precipitator
Off-Gas
Oil
Combustion Zone
Recycle Gas Blower
Residue Cooling and Gas Preheating Zone
Grate Speed Controller
Air Blower
Spent Shale

After: TRW, September 1976, p. 31

Figure 9-3 PARAHO INDIRECT MODE RETORT FLOW DIAGRAM


Raw Crushed Shale
Oil Mist Separators
Condenser
Mist Formation and Preheating Zone
Retorting Zone
Oil
Electrostatic Precipitator
Recycle Gas Heater
Off-Gas
Oil
Heating Zone
Recycle Gas Blower
Residue Cooling and Gas Preheating Zone
Off — Gas
Grate Speed Controller
Air Blower
Spent Shale

After: TRW, September 1976, p.33

lower. Some of the recycled retort gas is reheated in an external heater, and distributed to the retort at several levels. It is these hot gases which supply the necessary heat for retorting, thus eliminating combustion in the retort and the products of combustion in the retort gas. The fuel for the external gas heater may be a side-stream of the recycled retort gas itself, or an outside fuel.

9.1.2 Product Properties

Selected properties of the Paraho shale oil from both direct and indirect modes of operation are shown in Table 9-1. While no sulfur or nitrogen contents have been reported, these would be expected to be in the range for shale oil from gas combustion/heated gas circulation type retorts. As a result of the combustion zone in the direct mode retort, the volume of retort gas produced in this mode is 12 times that from indirect heating. However, the heating value of the direct mode gas is 1/9 times the heating value of the indirect mode gas.

TABLE 9-1

PARAHO SHALE OIL PROPERTIES

	Heating Mode	
	Direct	Indirect
Specific Gravity, (°API)	21.4	21.7
Viscosity, (SUS @ 130°F.)	90.0	68.0
(SUS @ 210°F.)	46.0	42.0
Pour Point, (°F.)	85.0	65.0
Ramsbottom Carbon, (wt.%)	1.7	1.3
Water Content, (vol.%)	1.5	1.4
Solids, B.S., (wt.%)	0.5	0.6

NOTE: From semi-works retorting of 28 gallons per ton shale, at 97% Fischer assay yield.

SOURCE: TRW, September 1976, p.37.

9.1.3 Product Upgrading

Shale oil is not a finished usable product and is dissimilar to conventional crude oil. Oil cuts range from naptha through light and heavy gas oils to a bottoms residue. Shale oil contains many broken and incomplete molecules. The specific gravity is approximately 22° API, the pour point ranges from 60-85°F., and the viscosity is high. Arsenic, nitrogen, and sulfur content is fairly high compared to conventional crude oil. Some degree of on-site upgrading is therefore necessary to make the shale oil pipelineable to refineries, and in order to prepare it for use as refinery feedstock. Pipelineable shale oil must meet or exceed the following criteria:

Specific Gravity	28.6 °API
Pour Point	30°F. maximum
Viscosity	800 SSU @ 30°F.
Vapor Pressure	8.0 psia maximum

Minimal upgrading to produce a pipelineable shale oil involves visbreaking and blending. The bottoms residue is centifuged to remove any spent shale and the remaining oil joins the heavy gas oil cut. Heavy gas oils are thermally cracked (visbreaking) through a mild heat cycle with a low residence time. This produces the same cuts as the original shale oil, and the heavy cuts are separated and recycled through the visbreaker. The cracking tower residue is passed through a vacuum tower to separate gas oils and by-product cracked tar. Gas oil from the visbreaker is blended with the naptha and light gas oil cuts to produce a pipelineable shale oil.

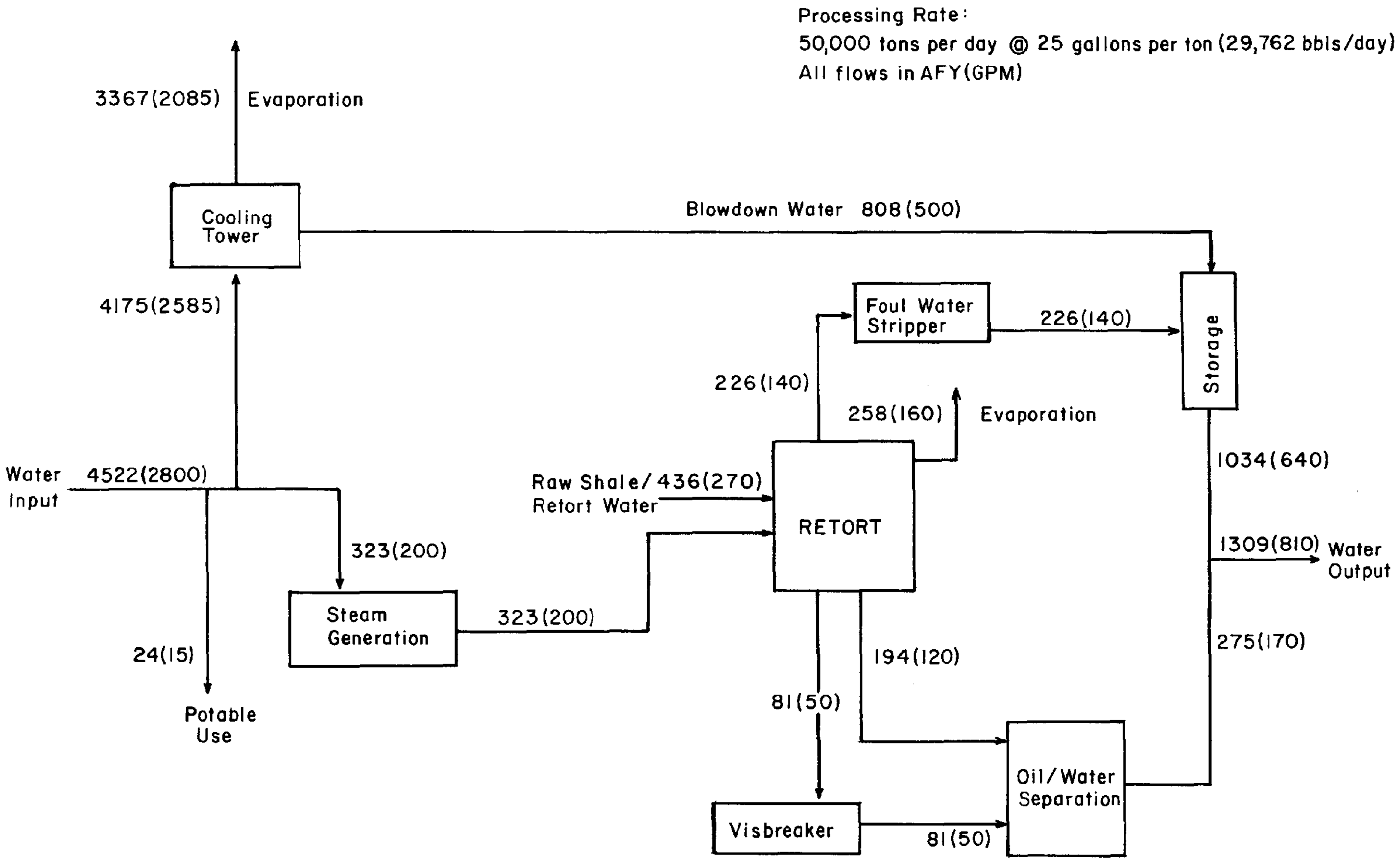
Another method of cleaning the bottoms residue and heavy oils of residual spent shale inclusions and converting them to lighter oils and naptha is through coking. Coking can be done continuously in a fluid coker, or discontinuously in a delayed coker. Fluid coking uses a higher temperature and produces coke pellets of very low porosity which are difficult to burn and less valuable as a by-product than the delayed coker by-product.

Further upgrading must be done in order to make the shale oil usable in conventional refineries. It is assumed that this will not be done on-site, but rather at the pipeline terminus and/or refinery. Arsenic must be removed from the shale oil prior to hydrotreating because it would cause catalyst deactivation. Hydrotreating or hydrogenation replaces the nitrogen and sulfur in the shale oil with hydrogen in the presence of a catalyst, thereby producing ammonia and liquid sulfur as by-products. Once this upgrading step has been done, the shale oil, now referred to as synthetic crude oil or syncrude, can be marketed as is or refined in conventional refineries like crude oil to produce high quality fuels.

9.1.4 Water Usage

Figure 9-4 shows a simplified water flow diagram for a 50,000 TPD Paraho plant. The required water input is 4,522 AFY (2,800 gpm). An additional 436 AFY (170 gpm) is produced in retorting from the raw shale surface, interstitial moisture, and combustion, and should be considered as an input. Waste water output is 1,309 AFY (810 gpm). The apparent consumptive use ("visible" input minus waste water output) is thus 3,213 AFY (1,990 gpm), while the actual consumptive use ("visible" input plus water produced in retorting minus waste water output) is 3,649 AFY (2,260 gpm). While these figures are for the indirect mode, we understand that the direct mode usage will be very similar.

The only water usage upgrading to the level specified in this contract is 81 AFY (50 gpm) to the visbreaker, which is


3367(2085)
Evaporation
Cooling Tower
Blowdown Water 808(500)
4175(2585)
Foul Water Stripper
226(140)
Storage
226(140)
258(160)
Evaporation
1034(640)
Water Input
4522(2800)
Raw Shale/ 436(270)
Retort Water
RETORT
323(200)
1309(810)
Water Output
Steam Generation
323(200)
24(15)
194(120)
275(170)
Potable Use
81(50)
Oil/Water Separation
Visbreaker
81(50)

Processing Rate:
50,000 tons per day @ 25 gallons per ton (29,762 bbls/day)
All flows in AFY(GPM)

Figure 9-4 WATER FLOW DIAGRAM PARAHO INDIRECT MODE RETORTING & UPGRADING PROCESS (SIMPLIFIED)

supplied in the form of steam and reappears as foul water after the visbreaking stage.

Of the 4,522 AFY (2,800 gpm) needed for input, 4,175 AFY (2,585 gpm) is service water quality and 347 AFY (215 gpm) is of boiler or drinking water quality. Output from the system is 1,309 AFY (810 gpm) of wastewater, which can be used in spent shale wetting and other low water quality uses.

A typical water quality analysis of retort water from the Paraho direct mode is shown in Table 9-2.

TABLE 9-2
PARAHO DIRECT MODE RETORT WATER ANALYSIS

Cations	mg/l
Calcium	76
Magnesium	58
Sodium	290
Potassium	35
Ammonia	4,910
Anions	
Carbonate	0
Bicarbonate	1,500
Sulfate	5,900
Chloride	5,300
pH	7.6
COD	17,000
Nitrogen (NH_3)	3,810
Total Kjeldahl Nitrogen	4,590
Sulfide(s)	0
Solids, Total	18,100
Solids, Dissolved	17,400
Solids, Suspended	700
Total CO_3	1,300
Dissolved Organic Carbon	3,420

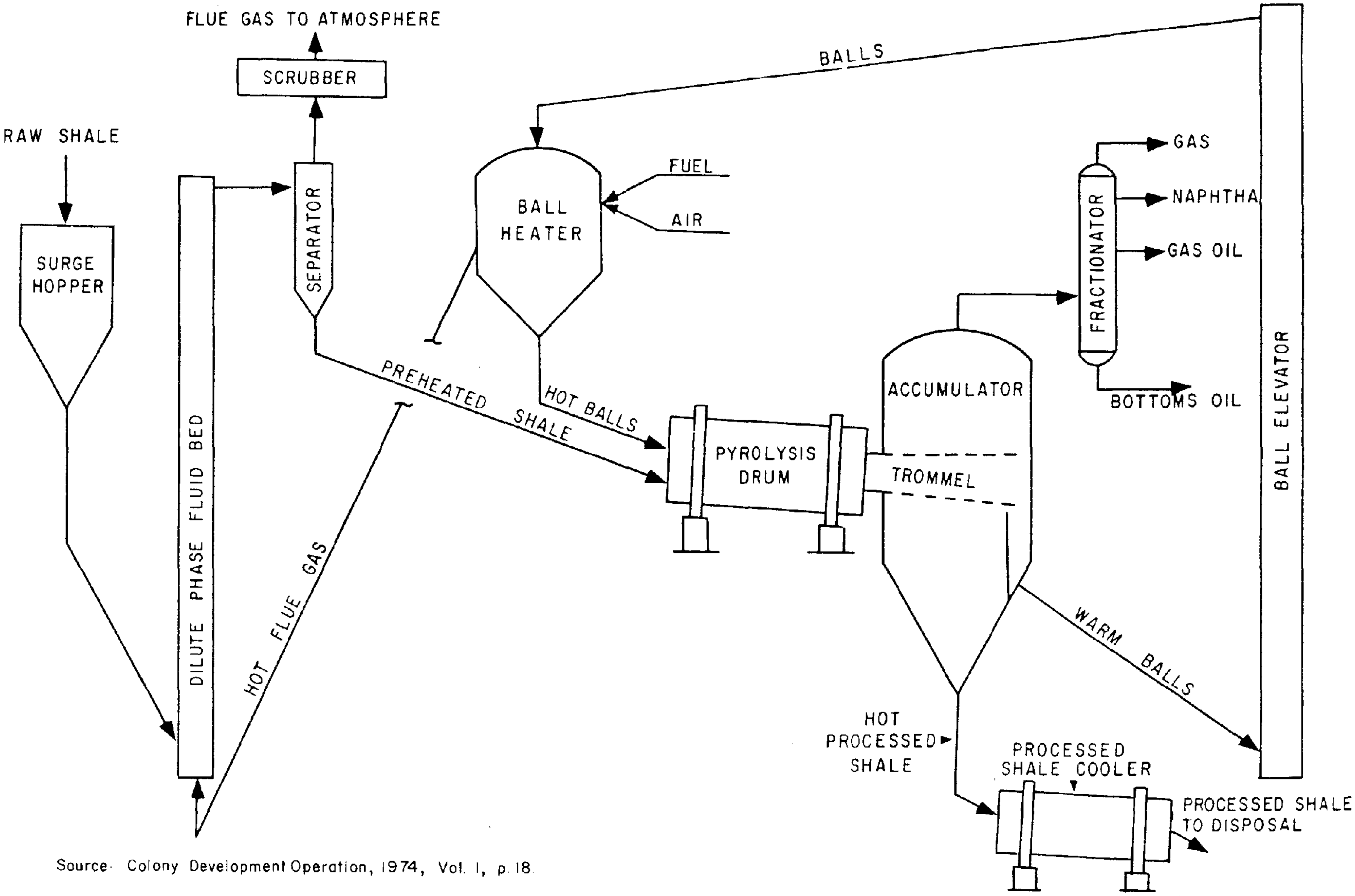
SOURCE: TRW, September 1976, p.40.

9.2 TOSCO II RETORT

9.2.1 Mode of Operation

The TOSCO II retort has been developed by The Oil Shale Corporation, and achieves its retorting action by indirect heating, using ceramic balls mixed with the crushed raw shale.

The minus 0.5 inch size crushed raw shale is first fed to a dilute phase fluidized bed, where it is preheated to about 500^{O}F. with flue gas from the ball heater (Figure 9-5). The residual hydrocarbons in the flue gas are simultaneously burned. The cooled flue gas is separated from the preheated shale, wet-scrubbed to remove particulates, which are disposed as a sludge, and vented to the atmosphere at about 130^{O}F. The preheated shale is fed to a horizontal rotating retort (pyrolysis drum), together with approximately 1.5 times its weight in hot ceramic balls from a ball heater. The balls heat the shale to pyrolysis temperature (900^{O}F.) and convert its contained organic matter to shale oil vapor. The shale oil vapor is withdrawn and fed to a fractionator for shale oil/gas separation. The mixture of balls and spent shale is discharged through a trommel screen, in order to separate the now only warm balls from the spent shale. The warm balls are purged of dust with flue gas from a steam preheater, and the dust removed from the flue gas by wet scrubbing. The scrubbed flue gas is discharged to the atmosphere. The dust-free warm balls are returned to the ball heater via the ball elevator. In the ball heater they are reheated to about 1,300^{O}F., using in-plant fuel, and recirculated to the pyrolysis drum. The hot spent shale is cooled to about 300^{O}F. in a rotating drum cooler. The spent shale particles are smaller in size than the feed, due to collisions with the ceramic balls.


FLUE GAS TO ATMOSPHERE
SCRUBBER
BALLS
RAW SHALE
SURGE HOPPER
DILUTE PHASE FLUID BED
SEPARATOR
BALL HEATER
FUEL
AIR
GAS
NAPHTHA
GAS OIL
FRACTIONATOR
BOTTOMS OIL
ACCUMULATOR
BALL ELEVATOR
PREHEATED SHALE
HOT BALLS
PYROLYSIS DRUM
TROMMEL
HOT FLUE GAS
WARM BALLS
HOT PROCESSED SHALE
PROCESSED SHALE COOLER
PROCESSED SHALE TO DISPOSAL

Source: Colony Development Operation, 1974, Vol. I, p. 18

Figure 9-5

TOSCO II RETORT FLOW DIAGRAM

9.2.2 Product Properties

Selected properties of the TOSCO II shale oil are shown in Table 9-3.

TABLE 9-3
TOSCO II SHALE OIL PROPERTIES

Specific Gravity, (°API)	22.0
Viscosity, (SUS @ 100°F.)	106.0
Pour Point, (°F.)	30.0*
Sulfur, (wt. %)	0.8
Nitrogen, (wt. %)	1.8

* This is for oil that has been "heat treated", conditions unknown. After storage, it will return to a more normal 80°F. level.

NOTE: 35 gallons per ton shale.

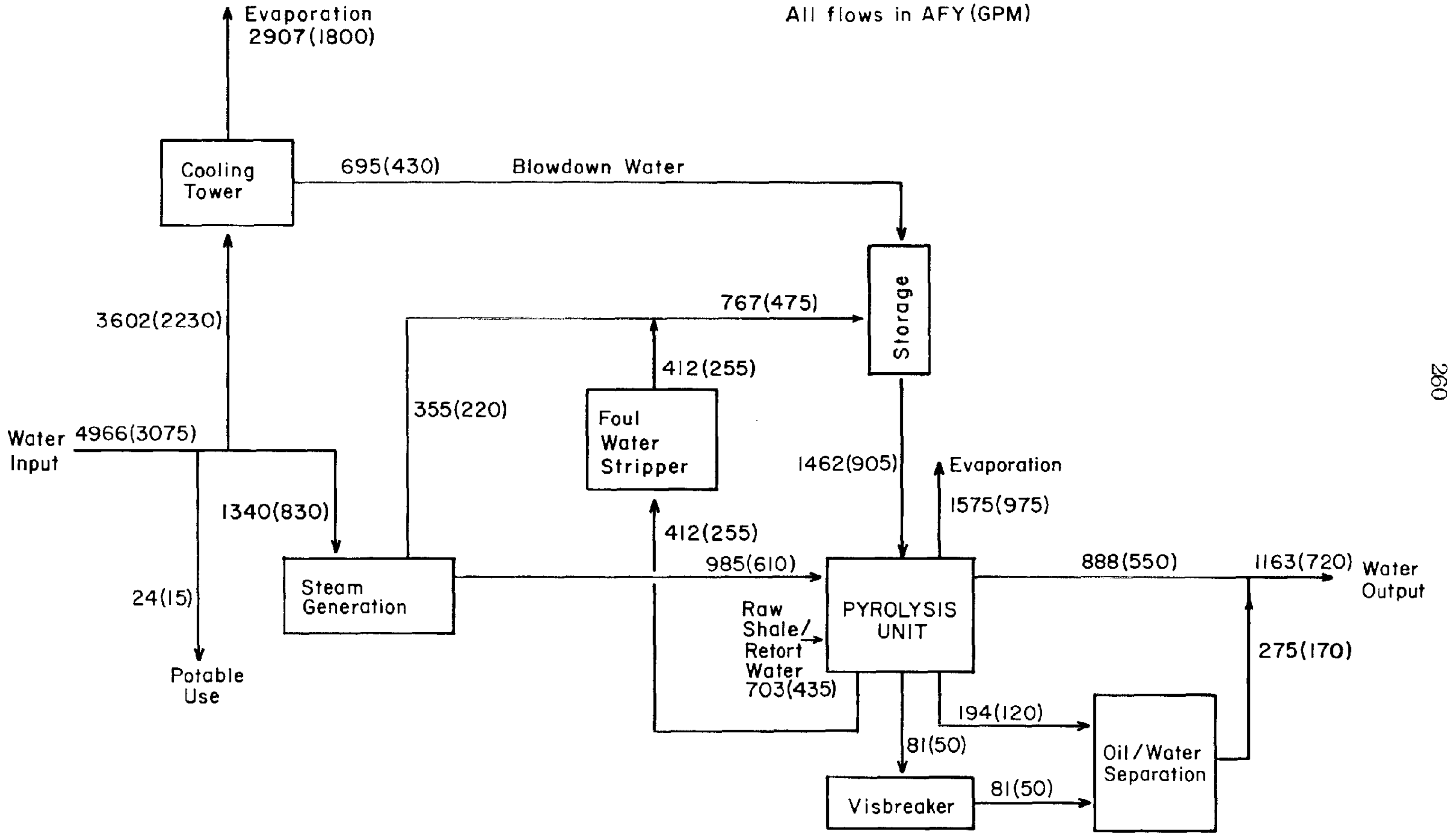
SOURCE: Colony Development Operation, 1974, Vol.1, p.11.

9.2.3 Upgrading

The *minimal* upgrading to pipelineable standards will be similar to that needed for the Paraho product. This involves visbreaking, and is discussed in more detail in Section 9.1.3 above.

9.2.4 Water Usage

Figure 9-6 shows a simplified water flow diagram for a 50,000 TPD TOSCO II plant. This diagram has been developed from the information in the C-b DDP and from material made available by TOSCO. The required water input for the TOSCO II process is 4,966 AFY (3,075 gpm). An additional 703 AFY (435 gpm) is


Evaporation
2907(1800)
Cooling Tower
695(430)
Blowdown Water
Storage
767(475)
3602(2230)
412(255)
355(220)
Foul Water Stripper
Water Input
4966(3075)
1462(905)
Evaporation
1575(975)
1340(830)
412(255)
985(610)
888(550)
1163(720)
Water Output
24(15)
Steam Generation
Raw Shale/ Retort Water
703(435)
PYROLYSIS UNIT
275(170)
Potable Use
194(120)
81(50)
Oil/Water Separation
Visbreaker
81(50)

Process Rate:
50,000 tons per day @ 25 gallons per ton (29,762 bbls/day)
All flows in AFY (GPM)

Figure 9-6 WATER FLOW DIAGRAM TOSCO II RETORTING & UPGRADING PROCESS (SIMPLIFIED)

produced in retorting from the raw shale surface and interstitial moisture, and should be considered as an input. Waste water output is 1,163 AFY (720 gpm). The apparent consumptive use ("visible" input minus waste water output) is thus 3,803 AFY (2,355 gpm), while the actual consumptive use ("visible" input plus water produced in retorting minus waste water output) is 4,509 AFY (2,790 gpm).

All figures are for a 50,000 TPD operation. These flows are somewhat greater than for the Paraho process, reflecting the higher steam usage in the TOSCO system.

Of the 4,966 AFY (3,075 gpm) of input water, 1,364 AFY (845 gpm) is required to be of boiler water or drinking water standard, and 3,602 AFY (2,230 gpm) is required to be of service water standard. The quality of the output water is similar to that of the Paraho system, as shown by the data presented on Table 9-4.

9.3 UNION B RETORT

The Union B retort has been developed by Union Oil of California, and is a direct mode, countercurrent retort system.

9.3.1 Mode of Operation

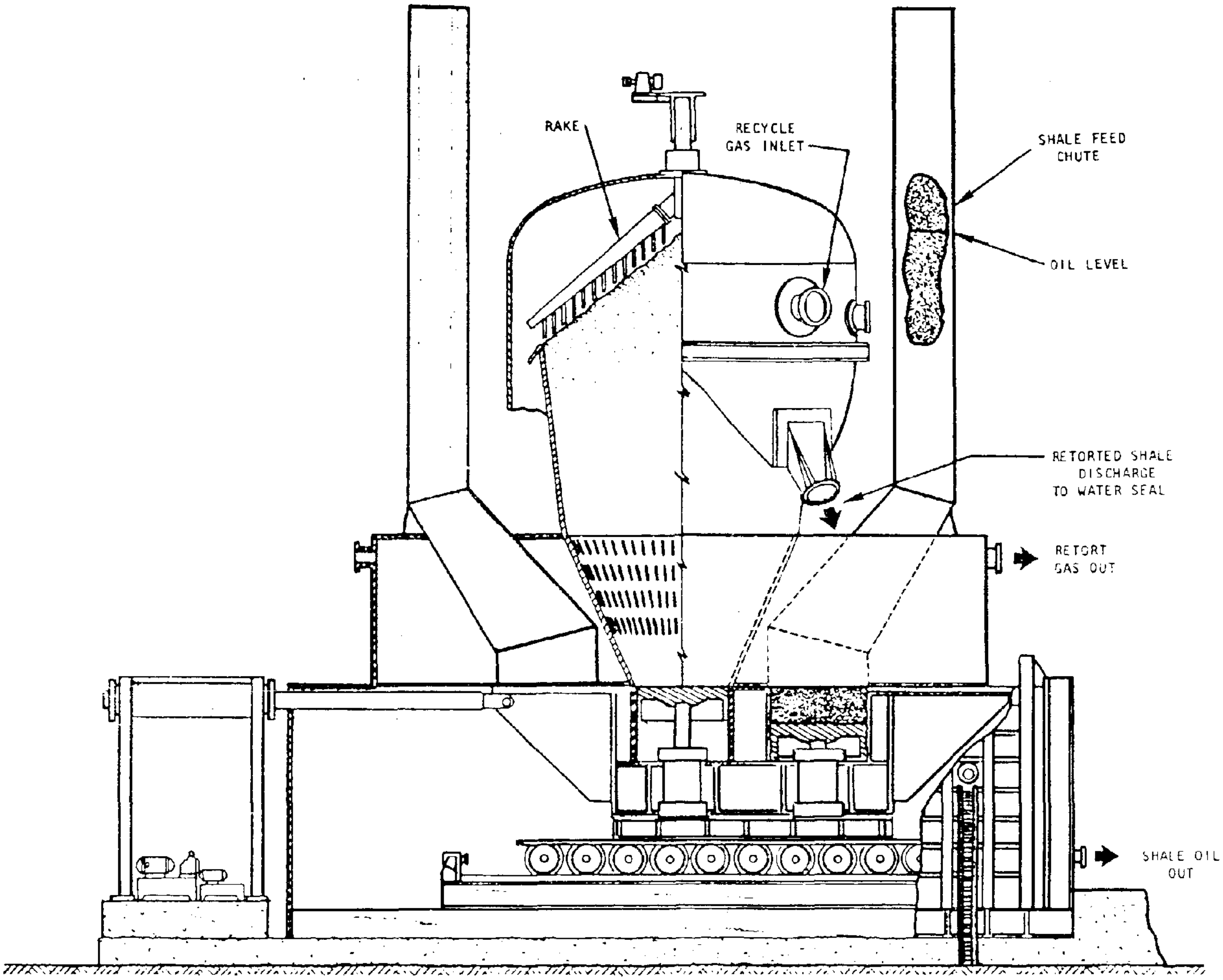
In the Union B retort (Figure 9-7) crushed raw shale in the minus 2 inch to plus 1/8 inch size range flows downward through two feed chutes to the solids pump. The solids pump is a positive displacement hydraulic pump and consists of two piston and cylinder assemblies which alternatively feed shale to the retort. It is mounted on a movable carriage and completely enclosed within the feeder housing and immersed in oil. As shale is moved upward through the retort by the upstroke of the piston, it is met by a downward flowing stream of 950 to

TABLE 9-4

FOUL WATER ANALYSES BY METCALF AND EDDY

Analysis	Production day			
	1	2	3	4
	mg/l	mg/l	mg/l	mg/l
Total sulfur	855	1,210	775	1,240
Sulfide	848	1,200	768	1,230
Sulfate	8	8	8	8.0
Elemental sulfur	<1.0	<1.0	<1.0	<1.0
Ammonia (NH_3)	3,685	4,025	3,960	1,740
Bicarbonate (HCO_3)	5,400	12,660	6,920	12,900
Carbonate (CO_3)	1,560	2,550	2,130	2,850
Chloride (Cl)	1,300	855	1,090	1,160
Nitrate (NO_3)	330	330	320	170
Phosphate (PO_4)	<0.5	0.21	15.6	<0.5
Fluoride (F)	<1.0	<1.0	<1.0	<1.0
Cyanide (Cn)	<0.01	<0.01	<0.01	<0.01
Silica	8	4	12	12
Calcium (Ca)	45	9.8	25	12
Magnesium (Mg)	<0.1	6.2	<0.1	19
Sodium (Na)	<1.0	<1.0	<1.0	<1.0
Potassium (K)	<5.0	<5.0	<5.0	<5.0
Arsenic (As)	0.07	0.09	0.08	0.06
Selenium (Se)	0.03	0.04	0.03	0.05
Molydenum (Mo)	<1.0	<1.0	<1.0	<1.0
Lithium (Li)	<10.	<10	<10	<10
Total dissolved solids (organics removed)	6,660	1,980	5,940	15,300
Neutral oil	2,560	2,840	2,115	1,950
Amines	602	856	916	1,600
Carboxylic acids	6,480	1,680	1,215	515
Phenols	390	220	270	115
Total organic carbon	16,300	21,000	18,200	14,200
COD	24,600	31,000	27,100	23,500
BOD_5	10,800	9,400	27,100	9,000
pH	8.6	8.7	8.1	8.6
Specific conductance, micromhos per cm	12,500	14,800	15,300	13,300

SOURCE: Metcalf and Eddy, October 1975, p.A2-2.


RAKE
RECYCLE GAS INLET
SHALE FEED CHUTE
OIL LEVEL
RETORTED SHALE DISCHARGE TO WATER SEAL
RETORT GAS OUT
SHALE OIL OUT

Source: TRW, September 1976, p. 11

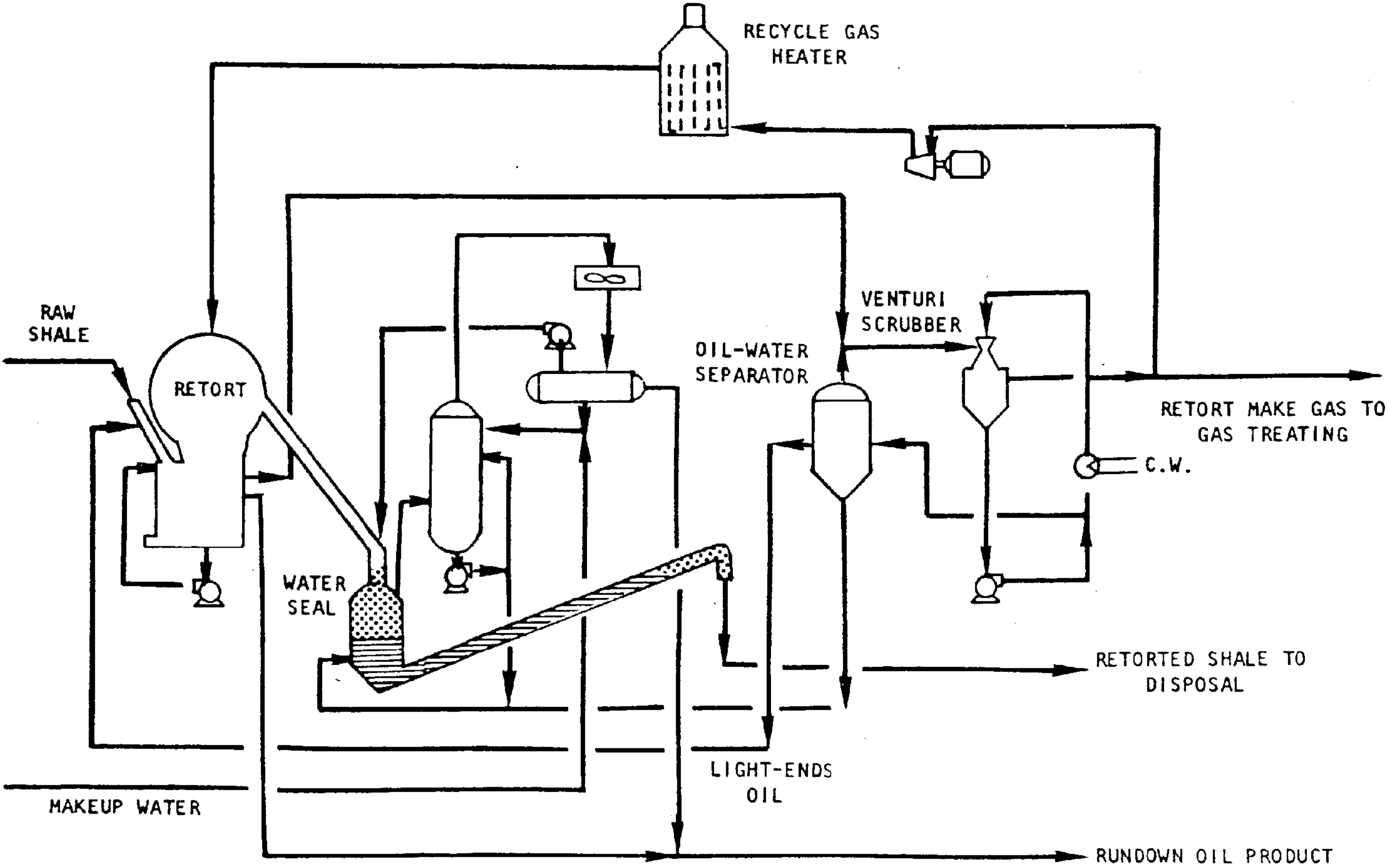
Figure 9-7 UNION B RETORT

1,000°F. recycled retort gas from the recycle gas heater. The rising shale bed is heated to retorting temperature by countercurrent contact with the hot recycled retort gas, resulting in the evolution of shale oil vapor. This shale oil vapor mixture of shale oil and retort gas is forced downward by the recycled retort gas, and cooled by contact with the cold incoming crushed raw shale in the lower section of the retort cone. In the disengaging section surrounding the lower cone, the liquid level is controlled by withdrawing the shale oil, and the retort gases are removed from the space above the liquid level. As the shale reaches the top of the column, it is mechanically raked off into a collector and passes through a water pressure seal which maintains retort back pressure and cools and moistens the spent shale prior to disposal. The size distribution is essentially unchanged from that of feed size. The flow diagram for the Union B retort is presented in Figure 9-8.

The high-BTU retort gas is first sent to a wet scrubber for cooling and heavy ends removal by oil scrubbing. A portion of the retort gas is then processed by compression and oil scrubbing to remove additional heavy ends, followed by removal of sulfur. The sweetened retort gas is used as plant fuel. The remaining retort gas, taken off after the wet scrubber, is recycled to the retort through the recycle gas heater to provide the heat for retorting.

9.3.2 Product Properties

Shale oil and retort gas from the Union B retort are expected to be similar to that from the Paraho indirect mode retort. Selected properties of the Union B shale oil are shown in Table 9-5.



RECYCLE GAS HEATER
RAW SHALE
RETORT
VENTURI SCRUBBER
OIL-WATER SEPARATOR
RETORT MAKE GAS TO GAS TREATING
C.W.
WATER SEAL
RETORTED SHALE TO DISPOSAL
LIGHT-ENDS OIL
MAKEUP WATER
RUNDOWN OIL PRODUCT

Source: TRW, September 1976, p. 12.

Figure 9-8 UNION B RETORT FLOW DIAGRAM

TABLE 9-5
UNION B SHALE OIL PROPERTIES

Specific Gravity, (°API)	22.7
Viscosity, (SUS @ 100°F.)	98.2
Pour Point, (°F.)	60.0
Sulfur, (wt. %)	0.81
Nitrogen, (wt. %)	1.74

SOURCE: TRW, September 1976, p.7.

9.3.3 Upgrading

The minimal upgrading to pipelineable standards will be similar to that needed for the Paraho and TOSCO II products. This involves visbreaking and is discussed in Section 9.1.3 above.

9.3.4 Water Usage

Figure 9-9 shows a water flow diagram for a 50,000 TPD Union B retorting and upgrading plant. The water usage values for the Union B process do not include water for the water seal as this usage is included in spent shale disposal (cooling and moisturizing) which is presented in Chapter 10. The required water input for the Union B process is 4,684 AFY (2,900 gpm). An additional 436 AFY (270 gpm) is produced in retorting from the raw shale surface, interstitial moisture, and combustion, and should be considered as an input. Waste water output is 1,325 AFY (820 gpm). The apparent consumptive use ("visible" input minus waste water output) is thus 3,359 AFY (2,080 gpm), while the actual consumptive use ("visible" input plus water produced in retorting minus waste water output) is 3,795 AFY (2,350 gpm).

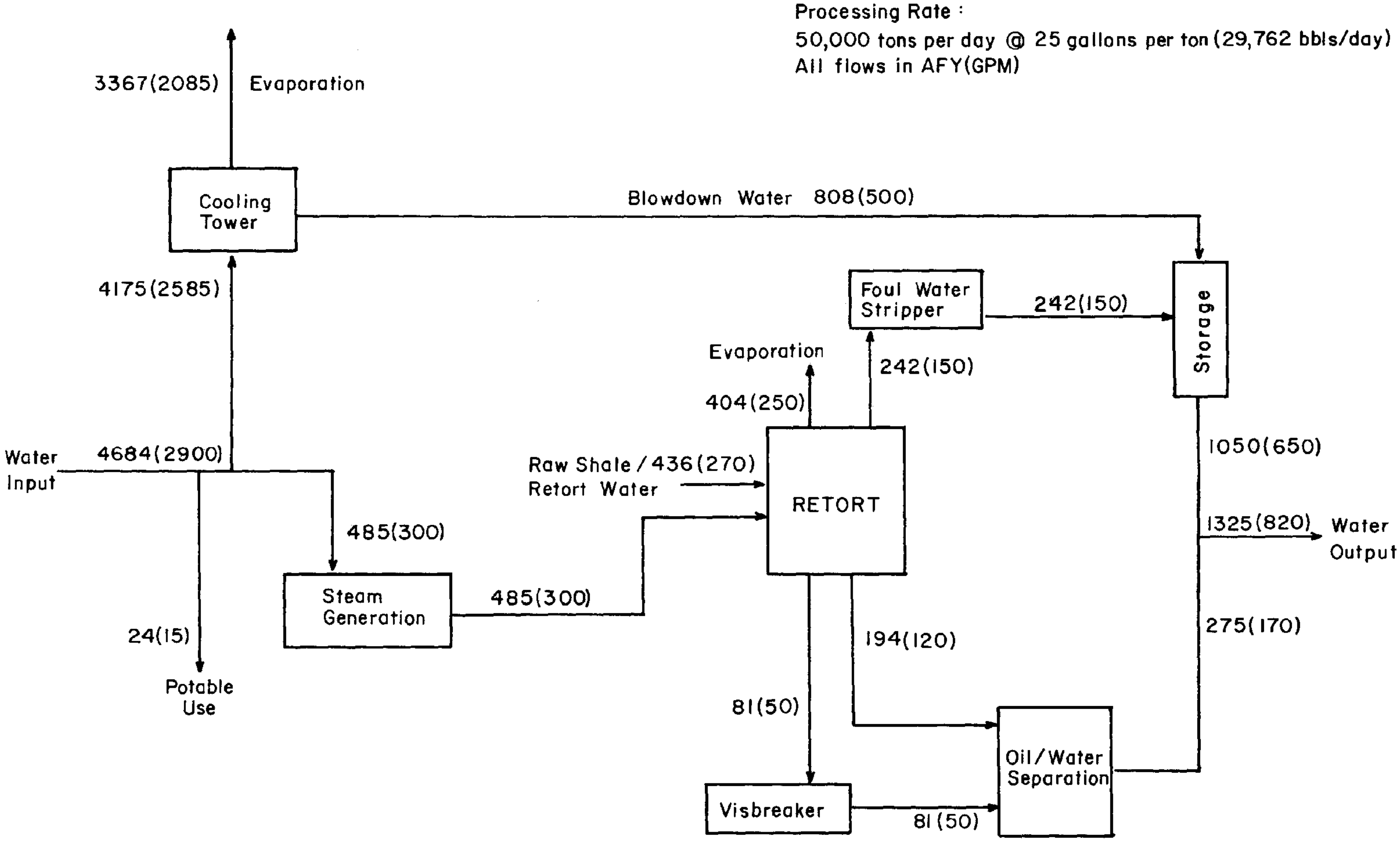

Processing Rate :
50,000 tons per day @ 25 gallons per ton (29,762 bbls/day)
All flows in AFY(GPM)
3367(2085)
Evaporation
Cooling Tower
Blowdown Water 808(500)
4175(2585)
Foul Water Stripper
242(150)
Storage
Evaporation
242(150)
404(250)
1050(650)
Water Input
4684(2900)
Raw Shale / 436(270)
Retort Water
RETORT
1325(820)
Water Output
485(300)
Steam Generation
485(300)
24(15)
194(120)
275(170)
Potable Use
81(50)
Oil/Water Separation
Visbreaker
81(50)

Figure 9-9 WATER FLOW DIAGRAM UNION B RETORTING & UPGRADING PROCESS (SIMPLIFIED)

Of the 4,684 AFY (2,910 gpm) input, 509 AFY (315 gpm) is required at boiler or drinking water quality, and 4,175 AFY (2,585 gpm) is required at service water quality. The quality of the output water is expected to be similar to that for the Paraho and TOSCO processes.

9.4 ANCILLARY ACTIVITIES

Power generation and other miscellaneous activities are ancillary to an oil shale facility, and are a function of shale oil production rather than mining rate. Thus these activities are related to surface processing.

9.4.1 Power Generation

An estimated 30 megawatts of power will be required by a 30,000 barrel per day oil shale facility, with the majority of this for the surface processing plant. For onsite power generation of this magnitude, approximately 850 acre-feet per year (526 gallons per minute) of water is required (U.S.D.I., 1973). The water quality must be good since it is to be used in cooling towers: filtered to remove sediments, clarified with lime, and rust inhibitors added. Waste water output is 50 acre-feet per year (31 gallons per minute), so 800 acre-feet per year (495 gallons per minute) is consumptively used.

9.4.2 Miscellaneous

Miscellaneous or plant support activities include water treatment, sewage treatment, storage of shale oil prior to pipelining, heating and cooling of buildings, grounds dust control and maintenance, fire protection, and dust control that has not previously been accounted for. Evaporation loss from water storage reservoirs and a very small amount of potable water for human consumption are also involved. A total of 950 acre-feet per year (588 gallons per minute) of water is required for all of these activities, and it can be of any quality. There is no waste water output and all of the input water is consumptively used.

CHAPTER 10
SOLID WASTE DISPOSAL

The water-related aspects of the disposal of solid wastes, including spent shale, other solid wastes, raw shale, overburden, and sub-ore, are presented here. This chapter also discusses reclamation and revegetation of disposal areas.

10.1 SPENT SHALE DISPOSAL

The amount of spent shale to be disposed of after retorting of the raw oil shale is dependent upon the amount of raw shale mined, grade of the raw shale (gallons of shale oil contained in one ton of raw shale), and retort efficiency. A 50,000 tons per day, 25 gallons per ton mining operation and a retort efficiency of 100% will produce an amount of spent shale that is 85% by weight of the raw shale, or 42,500 tons per day (based on data from Colony Development Operation and Cameron Engineers). Spent shale must be disposed of on the surface or in the subsurface, and there are two basic methods for doing this: slurry and non-slurry. Water is required in the spent shale disposal operation for cooling, dust control, and compaction, and the amount and quality required varies with slurry or non-slurry handling. This water is normally added before the spent shale leaves the processing facility.

10.1.1 SURFACE SPENT SHALE DISPOSAL

10.1.1.1 Non-Slurry Methods

Non-slurry, mechanical, surface disposal is the conventional technique of spent shale disposal, either surface or subsurface. It is a mechanical method that involves the use of conveyor belts or trucks to transport the spent shale from the processing

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facility and place it on the disposal pile. This disposal pile is an embankment constructed either by uniform spreading and compaction of the spent shale or by stacking. Compaction requires more water, provides more stability or material strength, and results in less total volume than stacking.

Both the TOSCO II spent shale and Paraho spent shale have been extensively tested to determine the engineering material properties related to stable disposal by non-slurry methods. The Union B spent shale has not been examined to the same degree of thoroughness, but would probably closely resemble Paraho and, for the purposes of this report, will be considered identical to it. Tables 10-1 and 10-2 contain a synopsis of the material properties of TOSCO II and Paraho-Union B spent shales.

Figure 10-1 and Table 10-3 show the flow and numerical relations of spent shale and water in surface and sub-surface spent shale disposal by the non-slurry, mechanical method. The minimum water content of the disposal pile for dust suppression is 8% by weight of the spent shale and the maximum is 20% (this is a range of values quoted by various other oil shale researchers). All of the water required is consumptively used and remains in the disposal pile; none is reclaimed.

Another form of non-slurry surface disposal is pneumatic. This involves the use of compressed air to transport and place the spent shale. Cleveland-Cliffs Iron Company have examined this method (1977). No water is required in the actual operation of this method, but this advantage is far outweighed by the high cost of equipment and the serious dust problem that is created at the disposal pile. It would be virtually impossible to completely remedy the dust problem by adding water at the disposal pile instead of adding water

TABLE 10-1

PHYSICAL PROPERTIES OF TOSCO II SPENT SHALE

GRADATION

Maximum Particle Size	0.5 inch
Gravel Size (+ No.4 sieve)	5.0 %
Sand Size (No.200 to No.4 sieves)	57.4 %
Silt and Clay (- No.200 sieve)	37.6 %
(No hydrometer analyses were run)	

PLASTICITY

Liquid Limit	30.0 %
Plasticity Index	6.0 %

SPECIFIC GRAVITY

Apparent (All Sizes)	2.52

COMPACTION

	Compactive Effort (ft.-lb./ft.^{3})	Optimum Moisture	Maximum Density @ Optimum Moisture (lb./ft.^{3})
Loose	None	--	60.0
Moderate	12,375	21.3%	91.8
High	56,250	19.4%	101.2
Field	6 Passes w/ 27-ton Roller	11.5%	

PERMEABILITY

Saturated Media	25 ft./yr.
Partially Saturated	*

* See Metcalf & Eddy for discussion of variation of flow rate into mass vs. initial moisture content

After Culbertson, et al., 1974.

TABLE 10-2

PHYSICAL PROPERTIES OF PARAHO SPENT SHALE

GRADATION

Maximum Particle Size	2 inches
Gravel Size (+ No.4 sieve)	55 %
Sand Size (No.200 to No.4 sieves)	23 %
Silt and Clay Size (- No.200 sieve)	22 %
Clay Size (0.005 mm)	2 % *

PLASTICITY

Liquid Limit	--
Plasticity Index	Non-Plastic

SPECIFIC GRAVITY

Apparent (All Sizes)	2.59 *

RELATIVE DENSITY **

Loose (0%)	71.5 lb./ft.^{3}
Dense (100%)	89.4 lb./ft.^{3}

COMPACTION **

	Compactive Effort (ft./lb./ft.^{3})	Optimum Moisture	Maximum Density @ Optimum Moisture (lb./ft.^{3})
Low	6,200	23.7 %	88.0
Moderate	12,375	22.0 %	92.5
High	56,250	22.0 %	98.0

PERMEABILITY **

	Compactive Effort (ft.-lb./ft.^{3})	Permeability at Loading (ft./yr.)		
		50 psi	100 psi	200 psi
Low	6,200	15.5	5.5	1.7
Moderate	12,375	7.0	1.4	0.8
High	56,250	1.1	0.6	0.08

* Average of Two Values
** Minus 1-1/2 Inch Fraction

After White River Shale Project, 1976, Vol. 1, p.3.10-3.

Figure 10-1 SURFACE AND SUBSURFACE SPENT SHALE DISPOSAL BY NON-SLURRY, MECHANICAL METHOD

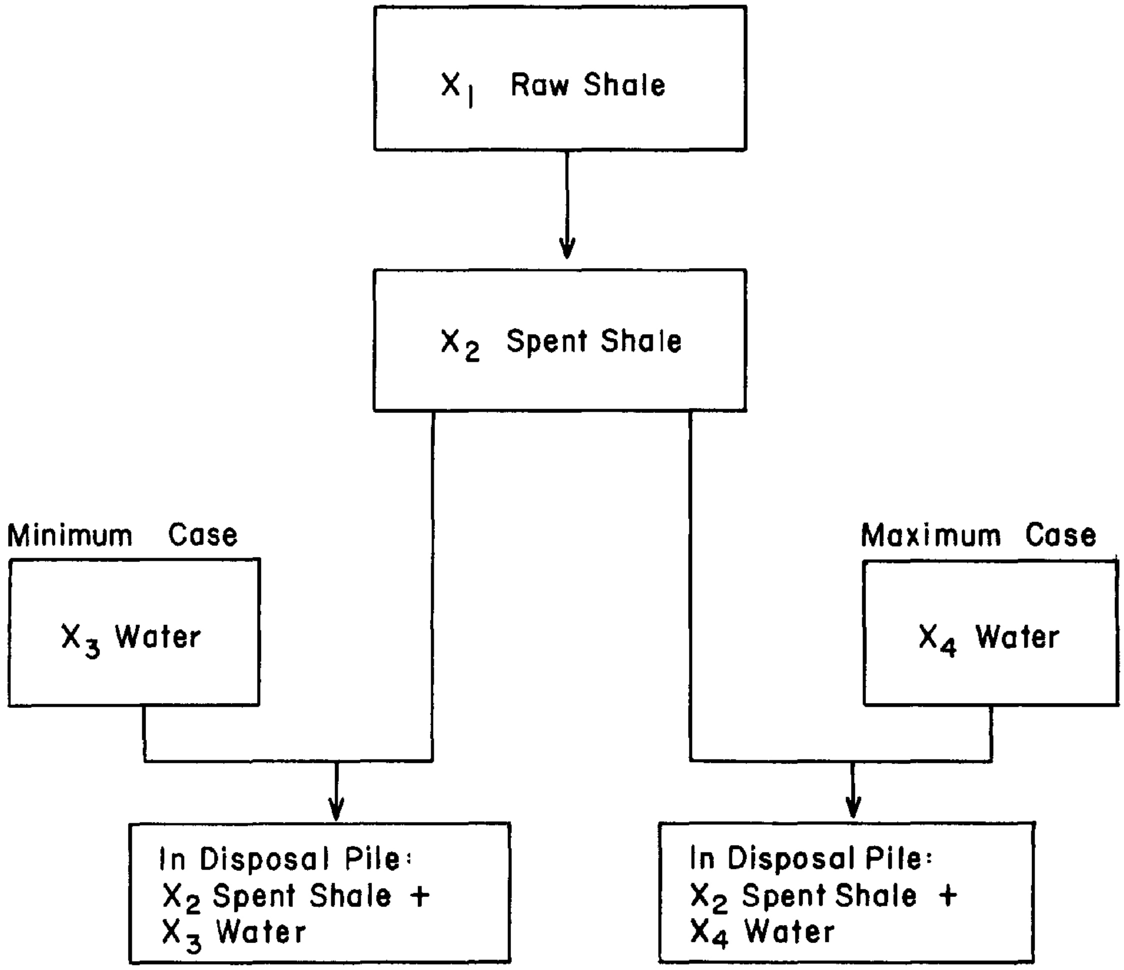

X_1 Raw Shale
X_2 Spent Shale
Minimum Case
X_3 Water
Maximum Case
X_4 Water
In Disposal Pile: X_2 Spent Shale + X_3 Water
In Disposal Pile: X_2 Spent Shale + X_4 Water

TABLE 10-3

SURFACE AND SUBSURFACE SPENT SHALE DISPOSAL BY NON-SLURRY, MECHANICAL METHOD

Unknown Weights	Equivalent Expressions	Weights as a percentage of X_1 (and in tons when X_1=1 ton) calculated using our assumed values for independent variables and setting X_1=1 ton	Weight in tons when X_1=50,000 tons	Water in acre-feet per year (gallons per minute) when X_1= 50,000 tons per day
X_1		1.00	50,000	--
X_2	aX_1	.85	42,500	--
X_3	$\frac{b}{(1-b)}X_2$ or $\frac{ab}{(1-b)}X_1$	.07	3,500	942 (583)
X_4	$\frac{c}{(1-c)}X_2$ or $\frac{ac}{(1-c)}X_1$	.21	10,500	2,825 (1,749)
Net water usage:				
Minimum	X_3 or $\frac{ab}{(1-b)}X_1$	.07	3,500	942 (583)
Maximum	X_4 or $\frac{ac}{(1-c)}X_1$	.21	10,500	2,825 (1,749)

Water content of disposal pile: Minimum = $X_3/(X_2+X_3)$ = b = .08 as a weight percentage of the disposal pile

Maximum = $X_4/(X_2+X_4)$ = c = .20 as a weight percentage of the disposal pile

Our assumed values for independent variables:
a = Spent shale as a weight percentage of raw shale = .85
b = Minimum water content of disposal pile for workability, as a weight percentage of the disposal pile = .08
c = Maximum water content of disposal pile for workability, as a weight percentage of the disposal pile = .20

before the spent shale leaves the processing facility. As a result, the pneumatic method is not considered to be a viable alternative for non-slurry surface disposal of spent shale.

10.1.1.2 Slurry Method

Slurry surface disposal is a hydraulic method that involves the use of water to transport the spent shale in a slurry from the processing facility to the disposal site. Our information on this method comes from the Cleveland-Cliffs Iron Company (1977). The normal value for solids in this slurry is 40% by weight of the slurry. Water is 60% by weight of the slurry, and the water used to achieve this can be of very poor quality. For large spent shale particles like those produced by the Paraho and Union processes, an even lower percentage of solids or a faster flow rate will probably be required. Spent shale degrades rapidly during slurry transport, forming a significant slime portion of approximately 3-35% by weight of the slurry. The disposal site for the slimes is an impervious-bottom settling pond located behind a retaining dam. Some of the water used in the slurry can be reclaimed from the settling pond. The reclaimed water is made up of 65-70% by weight of the water in the non-slime portion of the slurry, plus 50% by weight of the water in the slime portion of the slurry, for a total of 59-64% by weight of the water in the total slurry. 36-41% by weight of the water in the total slurry is left in the settling pond and so is consumptively used. The major advantage of this method is that there is no dust problem.

Figure 10-2 and Table 10-4 show the flow and numerical relations of spent shale and water in surface spent shale disposal by the slurry method.

Figure 10-2 SURFACE SPENT SHALE DISPOSAL BY SLURRY METHOD

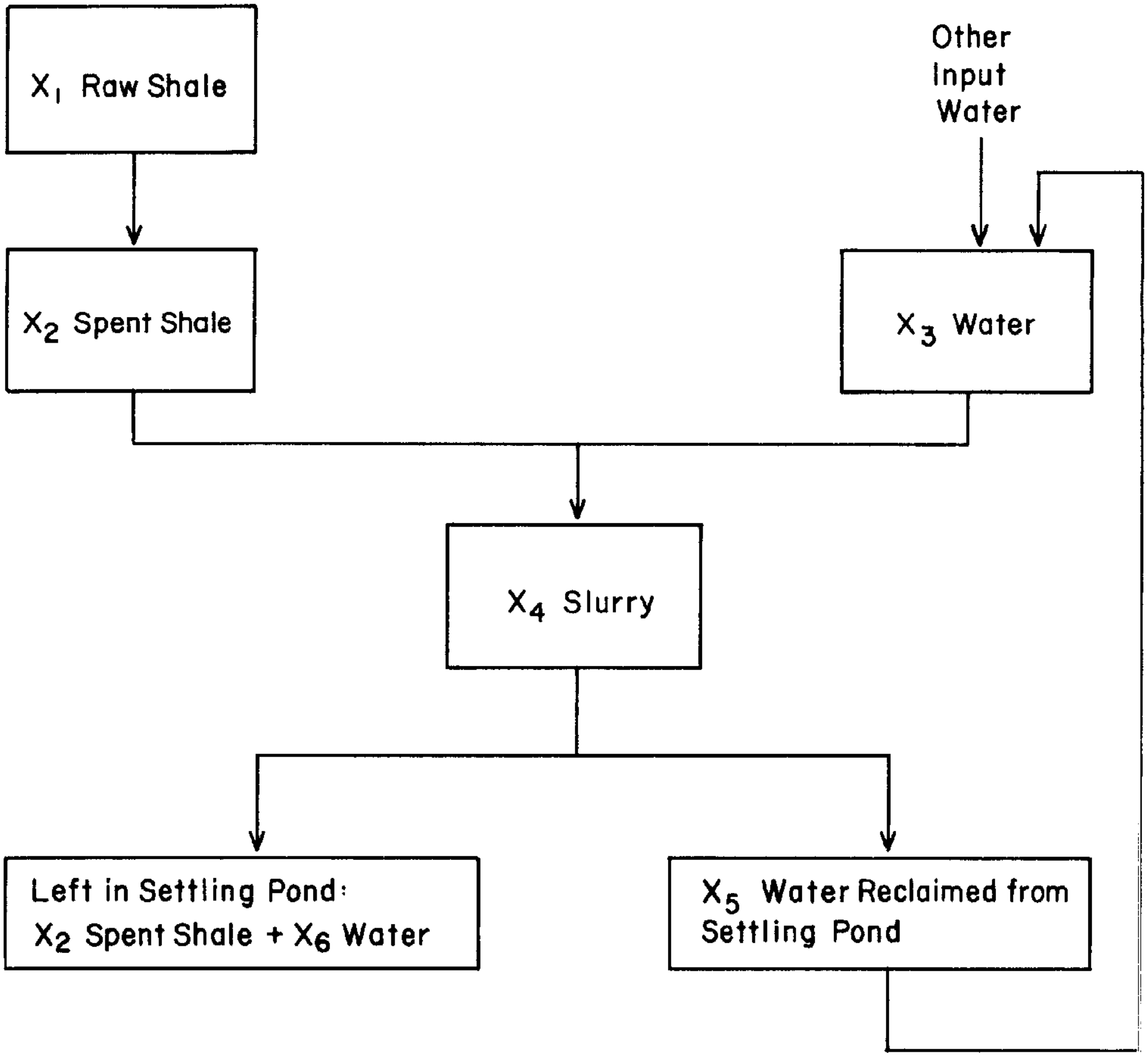

X_1 Raw Shale
X_2 Spent Shale
Other Input Water
X_3 Water
X_4 Slurry
Left in Settling Pond: X_2 Spent Shale + X_6 Water
X_5 Water Reclaimed from Settling Pond

TABLE 10-4

SURFACE SPENT SHALE DISPOSAL BY SLURRY METHOD

Unknown Weights	Equivalent Expressions	Weights as a percentage of X_1 (and in tons when $X_1=1$ ton) calculated using our assumed values for independent variables and setting $X_1=1$ ton	Weight in tons when $X_1=50{,}000$ tons	Water in acre-feet per year (gallons per minute) when $X_1=$ 50,000 tons per day
X_1		1.00	50,000	--
X_2	aX_1 or bX_4	.85	42,500	--
X_3	$(1-b)X_4$ or $(1-b)\frac{a}{b}X_1$	1.27	63,500	17,086 (10,579)
X_4	$\frac{a}{b}X_1$ or X_2+X_3	2.12	106,000	--
X_5	$[cd+(1-c)e]\,X_3$	.76 -.81, average .78	average 39,250	average 10,561 (6,539)
X_6	X_3-X_5 or $[c(1-d)+(1-c)(1-e)]\,X_3$	.51 -.45, average .49	average 24,250	average 6,525 (4,040)
Net water usage	X_3-X_5 or $(1-b)\frac{a}{b}X_1\{1-[cd+(1-c)e]\}$	.51 -.45, average .49	average 24,250	average 6,525 (4,040)

Water content of material left in settling pond $= X_6/(X_2+X_6) = \dfrac{(1-b)\frac{1}{b}[c(1-d)+(1-c)(1-e)]}{1+(1-b)\frac{1}{b}[c(1-d)+(1-c)(1-e)]} = .37 -.35$, average .36 as a weight percentage of the material left in settling pond

Our assumed values for independent variables:

a = Spent shale as a weight percentage of raw shale = .85
b = Solids in slurry as a weight percentage of slurry = .40
c = Non-slime portion of slurry as a weight percentage of slurry = .70 -.65
d = Water reclaimed from non-slime portion of slurry as a weight percentage of water in non-slime portion of slurry = .65 -.70
e = Water reclaimed from slime portion of slurry as a weight percentage of water in slime portion of slurry = .50

10.1.2 SUBSURFACE SPENT SHALE DISPOSAL

Subsurface spent shale disposal is an alternative to surface disposal to lessen the environmental impact of disposal piles or settling ponds. It is a technique that can be used with non-subsiding or slowly-subsiding underground mines (i.e. room and pillar, chamber and pillar, and sub-level stoping). Subsurface disposal or backfilling of the mine can begin after mining operations have ceased in a portion or on a certain level of the mine. It can stabilize the working mine and prevent or control ground surface subsidence when saturation by groundwater is not a problem. When it is a problem, the possibility of internal failure of the backfill material is added to the general instability of the mine. Since the volume of the spent shale to be disposed of is approximately 20% greater than the in-place raw shale, and since it is physically impossible to compact the backfill enough in order to place all of the spent shale back into the mine, subsurface disposal can never completely replace surface disposal.

10.1.2.1 Non-Slurry Methods

Non-slurry, mechanical disposal is the most conventional method of subsurface spent shale disposal, and it involves the use of conveyor belts or trucks to transport the spent shale from the processing facility and place it in the mine. Compaction is necessary in order to place the maximum amount of spent shale back into the mine.

Figure 10-1 and Table 10-3 show the flow and numerical relations of spent shale and water in surface and subsurface spent shale disposal by the non-slurry, mechanical method. The minimum water content of the disposal pile for workability is 8% by weight of the disposal pile and the maximum is 20%. All of the water required is consumptively used and remains in the disposal pile.

Another form of non-slurry subsurface disposal is the pneumatic method that involves the use of compressed air to transport and place the spent shale. No water is required in the actual operation of this method, but this advantage is far outweighed by the high cost of equipment and the serious dust problem that is created at the disposal pile within the mine. The pneumatic method is thus not considered to be a viable alternative for non-slurry subsurface disposal of spent shale, even though it can place more spent shale back into the mine than the mechanical method, filling the mine as much as 90% full.

10.1.2.2 Slurry Method

Slurry subsurface disposal is a hydraulic method that involves the use of water to transport the spent shale in a slurry from the processing facility and place it in the mine. The technology is similar to the surface disposal of spent shale by slurry methods, except that the coarse cyclone fraction is placed underground. After the slimes are cycloned off from the original slurry, the coarse fraction slurry goes down into the mine to a settling pond. Bulkheads seal off the settling pond from the rest of the mine. 65-70% of the spent shale in the original slurry is stowed in this subsurface settling pond. Water reclaimed from the mine is 65-70% by weight of the water in the mine slurry or 42-49% by weight of the water in the original slurry. So a total of 59-64% by weight of the water in the original slurry can be reclaimed, leaving 36-41% by weight of the water in the original slurry in the slime pond and mine settling pond that is consumptively used.

The major advantage of this method is that there is no dust problem. The slurry method provides less stability for the working mine and less prevention or control of ground surface subsidence than other methods of subsurface spent shale disposal.

Figure 10-3 and Table 10-5 show the flow and numerical relations of spent shale and water in subsurface spent shale disposal by the slurry method.

10.2 SOLID WASTE DISPOSAL

Solid wastes that must also be disposed of come from both processing and non-processing related activities. Processing wastes are crushing fines, lime clarifier sludge and spent zeolite water softening resins from the water treatment facility, and the non-recyclable types of spent upgrading catalysts. Non-processing wastes are the paper, wood and metal items that are non-recyclable, and sanitary wastes. All of these wastes can be disposed of with the spent shale or in sanitary landfills. Amounts and water requirements are insignificant compared with the spent shale.

10.3 RAW SHALE DISPOSAL

Raw shale produced during pre-production mining may possibly need to be disposed of. The raw shale is mined, goes through primary crushing, and is removed from the mine. It can be crushed by secondary crushers, stockpiled, and later retorted, used as construction fill during site development, or placed in a surface or subsurface disposal pile by the non-slurry, mechanical method. As the quantities of raw shale to be disposed of in conventional retorting are small, water use in this activity is negligible.

10.4 OVERBURDEN AND SUB-ORE DISPOSAL

With open pit mining the problem of overburden and sub-ore disposal arises. Overburden is the rock lying above the commercial-

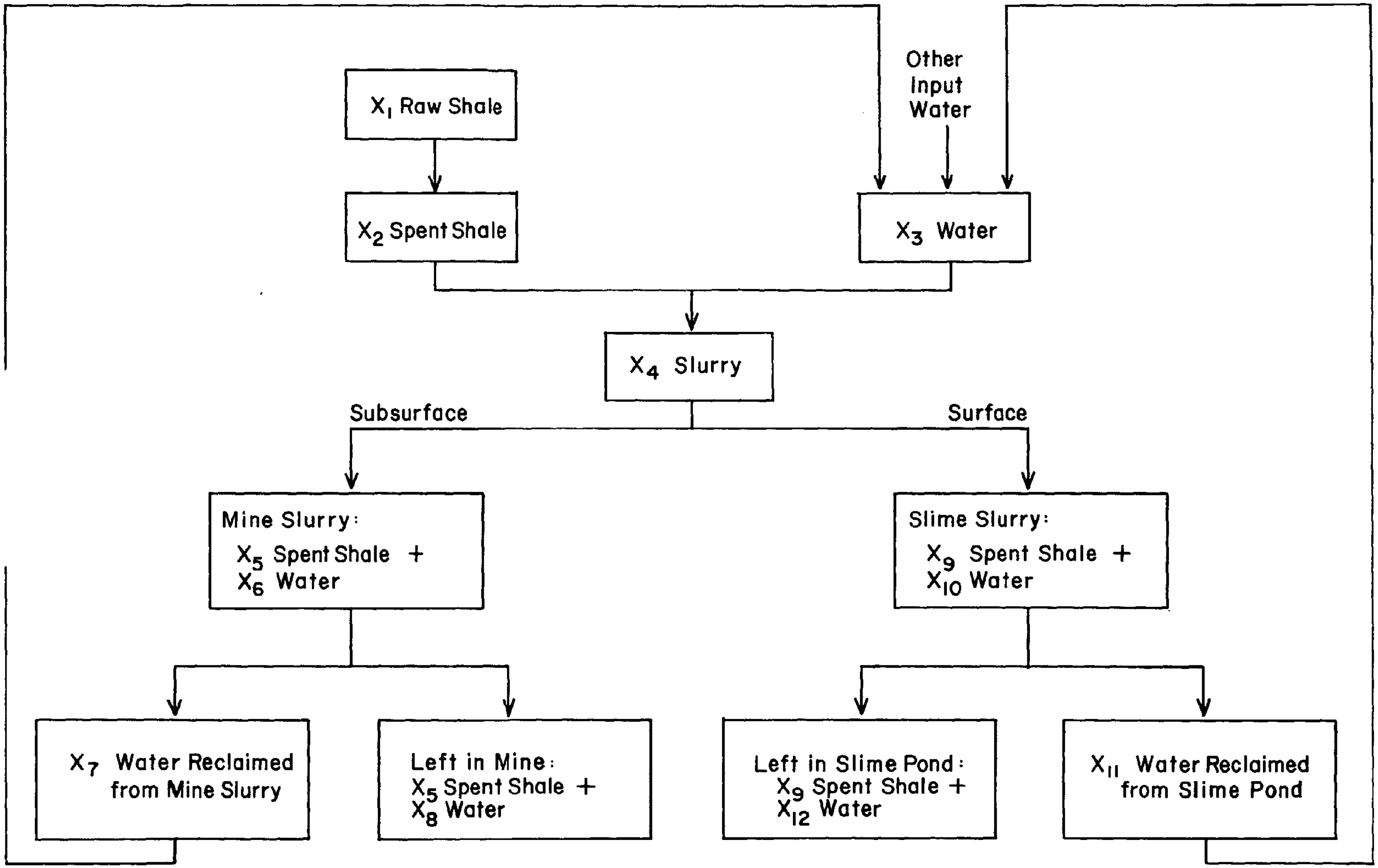

X_1 Raw Shale
X_2 Spent Shale
Other Input Water
X_3 Water
X_4 Slurry
Subsurface
Surface
Mine Slurry: X_5 Spent Shale + X_6 Water
Slime Slurry: X_9 Spent Shale + X_{10} Water
X_7 Water Reclaimed from Mine Slurry
Left in Mine: X_5 Spent Shale + X_8 Water
Left in Slime Pond: X_9 Spent Shale + X_{12} Water
X_{11} Water Reclaimed from Slime Pond

Figure 10-3 SUBSURFACE SPENT SHALE DISPOSAL BY SLURRY METHOD

TABLE 10-5

SUBSURFACE SPENT SHALE DISPOSAL BY SLURRY METHOD

Unknown Weights	Equivalent Expressions	Weights as a percentage of X_1 (and in tons when X_1=1 ton) calculated using our assumed values for independent variables and setting X_1=1 ton	Weight in tons when X_1=50,000 tons	Water in acre-feet per year (gallons per minute) when X_1= 50,000 tons per day	
X_1		1.00	50,000	--	
X_2	aX_1 or bX_4	.85	42,500	--	
X_3	$(1-b)X_4$ or $(1-b)\frac{a}{b}X_1$	1.27	63,500	17,086	(10,579)
X_4	$\frac{a}{b}X_1$ or X_2+X_3	2.12	106,000	--	
X_5	cX_2 or $b(X_5+X_6)$	.59 -.55, average .57	average 28,500	--	
X_6	cX_3 or $(1-b)(X_5+X_6)$	.89 -.82, average .86	average 43,000	average 11,570	(7,164)
X_7	dX_6	.57 -.59, average .58	average 29,000	average 7,803	(4,831)
X_8	X_6-X_7 or $(1-d)X_6$	.32 -.23, average .28	average 14,000	average 3,767	(2,332)
X_9	$(1-c)X_2$ or $b(X_9+X_{10})$	.26 -.30, average .28	average 14,000	--	
X_{10}	$(1-c)X_3$ or $(1-b)(X_9+X_{10})$	.38 -.44, average .41	average 20,500	average 5,516	(3,415)
X_{11}	eX_{10}	.19 -.22, average .21	average 10,250	average 2,758	(1,708)
X_{12}	$X_{10}-X_{11}$ or $(1-e)X_{10}$	.19 -.22, average .21	average 10,250	average 2,758	(1,708)
Net water usage	$X_3-(X_7+X_{11})$ or X_8+X_{12} or $(1-b)\frac{a}{b}X_1\{1-[cd+(1-c)e]\}$	.51 -.45, average .49	average 24,250	average 6,525	(4,040)

Water content of material left in mine = $X_8/(X_5+X_8)$ = $(1-b)\frac{1}{b}(1-d)/[1+(1-b)\frac{1}{b}(1-d)]$ = .34 -.31, average .33 as a weight percentage of the material left in mine

Water content of material left in slime pond = $X_{12}/(X_9+X_{12})$ = $(1-b)\frac{1}{b}(1-e)/[1+(1-b)\frac{1}{b}(1-e)]$ = .42 as a weight percentage of the material left in slime pond

Our assumed values for independent variables:
a = Spent shale as a weight percentage of raw shale = .85
b = Solids in any slurry as a weight percentage of that slurry = .40
c = Mine slurry as a weight percentage of original slurry = .70 -.65
d = Water reclaimed from mine as a weight percentage of water in mine slurry = .65 -.70
e = Water reclaimed from slime pond as a weight percentage of water in slime slurry = .50

grade oil shale that must be removed during preproduction and normal mining operations. Sub-ore is low-grade ore within the commercial-grade zone of oil shale that is removed but is not economically feasible to retort. The amount of overburden and sub-ore to be disposed of is dependent upon the amount and grade of ore required, mine, depth and stripping ratio. A 30,000 BPD operation requires 50,000 tons per day of 25 gallons per ton ore and will produce 43,200 tons per day of overburden and sub-ore with a shallow mine, and 25,600 tons per day with a deep mine, not taking into account preproduction mining. The average of 34,400 tons per day is almost half of the material mined. Overburden and sub-ore must be disposed of on the surface by the non-slurry, mechanical method. The overburden and sub-ore are mined, primary crushed, and transported to the disposal site. A portion of the overburden can be used as construction fill during site development, but the rest of it and the sub-ore must be placed in a disposal pile, preferably keeping the overburden and sub-ore segregated. The section on surface spent shale disposal by the non-slurry, mechanical method is directly applicable. A modification is to place some or all of the overburden and sub-ore as a covering on the spent shale disposal pile, and possibly to cover that layer with soil. This is discussed in more detail in the section on reclamation and revegetation.

Figure 10-4 and Table 10-6 show the flow and numerical relations of overburden and sub-ore and water in surface disposal by the non-slurry, mechanical method. Water is required in the disposal operation for dust control and compaction and is normally added before the overburden and sub-ore leaves the mine site. The minimum water content of the disposal pile for workability is 2% by weight of the disposal pile (Wymore, 1974) and the maximum is assumed to be 10%. All of the water required is consumptively used and remains in the disposal pile; none is reclaimed.

Figure 10-4 SURFACE OVERBURDEN AND SUB-ORE DISPOSAL BY NON-SLURRY, MECHANICAL METHOD

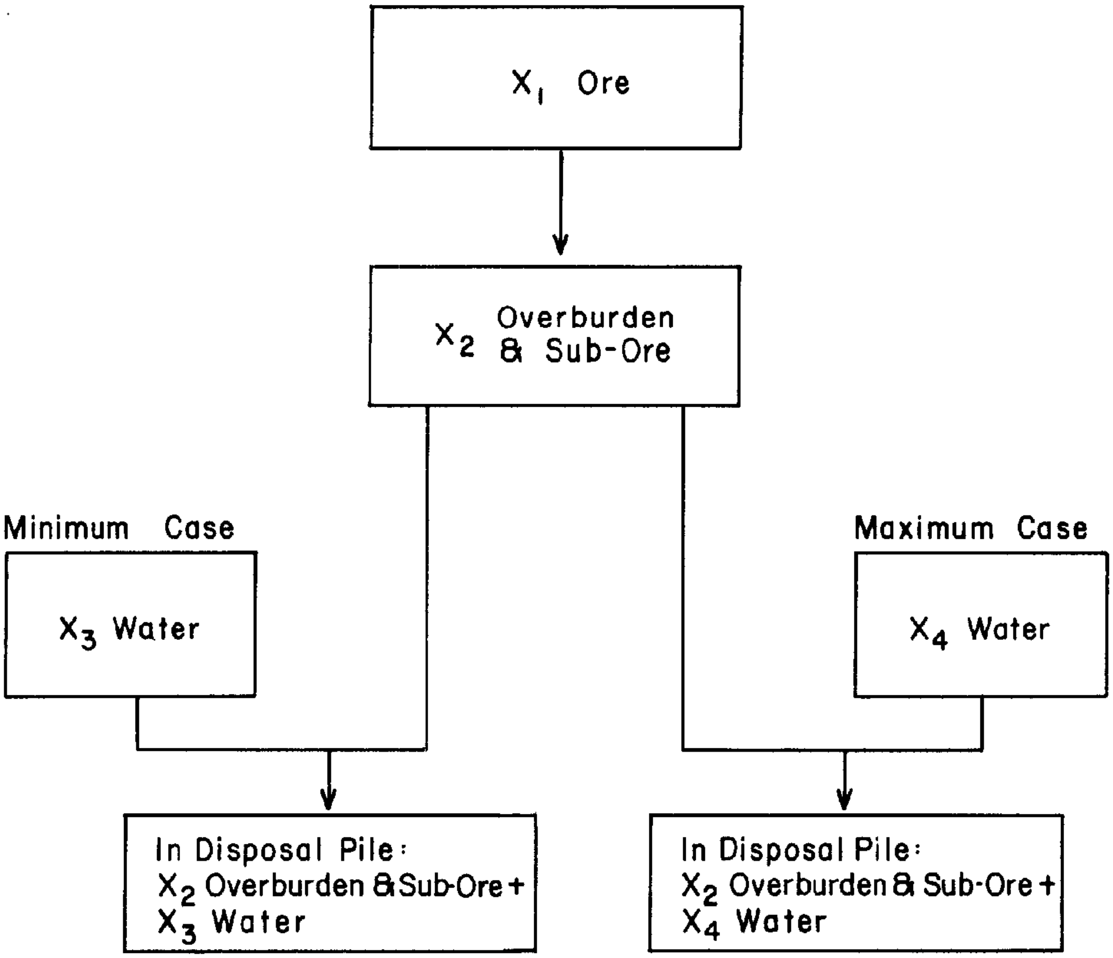

X1 Ore
X2 Overburden & Sub-Ore
Minimum Case
X3 Water
Maximum Case
X4 Water
In Disposal Pile: X2 Overburden & Sub-Ore + X3 Water
In Disposal Pile: X2 Overburden & Sub-Ore + X4 Water

TABLE 10-6

SURFACE OVERBURDEN AND SUB-ORE DISPOSAL

BY NON-SLURRY, MECHANICAL METHOD

Unknown Weights	Equivalent Expressions	Weights as a percentage of X_1 (and in tons when X_1=1 ton) calculated using our assumed values for independent variables and setting X_1=1 ton	Weight in tons when X_1=50,000 tons	Water in acre-feet per year (gallons per minute) when X_1= 50,000 tons per day
X_1		1.00	50,000	--
X_2	aX_1	.688	34,400	--
X_3	$\frac{b}{(1-b)}X_2$ or $\frac{ab}{(1-b)}X_1$	.01	500	135 (84)
X_4	$\frac{c}{(1-c)}X_2$ or $\frac{ac}{(1-c)}X_1$	.08	4,000	1,076 (666)
Net water usage:				
Minimum	X_3 or $\frac{ab}{(1-b)}X_1$	.01	500	135 (84)
Maximum	X_4 or $\frac{ac}{(1-c)}X_1$	.08	4,000	1,076 (666)

Water content of disposal pile: Minimum = $X_3/(X_2+X_3)$ = b = .02 as a weight percentage of the disposal pile

Maximum = $X_4/(X_2+X_4)$ = c = .10 as a weight percentage of the disposal pile

Our assumed values for independent variables:
a = Overburden and sub-ore as a weight percentage of ore = .688
b = Minimum water content of disposal pile for workability, as a weight percentage of the disposal pile = .02
c = Maximum water content of disposal pile for workability, as a weight percentage of the disposal pile = .10

10.5 RECLAMATION AND REVEGETATION

The projected land use in the area after mining operations cease has a major effect upon the degree of land reclamation that is required. It is possible that the land may be unsafe for any use as the worked-out mines below collapse and the ground surface subsides, or because of the unreclaimable settling ponds that would be created if slurry disposal was used. At the other extreme, the area may become agricultural. Neither extreme is likely and the limited land use at present, cattle grazing and some big-game hunting is expected to continue.

The minimum degree of land reclamation that is required to support the present land use is stabilization of the surface disposal pile. Temporary stabilization coverings are: straw, jute netting or matting, plastic netting or matting, cellulose fibers, chemical binders and emulsions, and other synthetic coverings. Permanent forms of stabilization are pavement, rock cover and revegetation. After permanent stabilization is accomplished, runoff dams around the disposal pile can be removed.

For the purposes of this study it is assumed that the land will be returned to its former level of productivity through revegetation.

10.5.1 REVEGETATION OF SPENT SHALE

The first step in revegetation of the spent shale pile is to leach the soluble salts to a depth below the root zone (thus lowering the pH also). An intense but slow and continuous application of 5 acre-feet of water per acre of area revegetated is required (Wymore, 1974). The pile may then be covered with mulch and fertilized with sewage effluent, clarifier sludge, or commercial fertilizer. The pile is replanted with native grasses, forbs, shrubs and trees, and irrigated with 3 acre-feet of water per acre of area revegetated over two growing seasons (Wymore, 1974). This will produce sufficient root development for the vegetation to exist under natural conditions without further assistance.

The total water requirement for revegetation is 8 acre-feet of water per acre of area revegetated, all of which is consumptively used. Assuming 42,500 tons per day of spent shale has a compacted density of 95 pounds per cubic foot and will be placed in piles averaging 200 feet thick (C-a DDP estimates 260 feet on the 84 Mesa site; C-b DDP and Modified DDP estimate 160 feet), the disposal site land use will expand at a rate of 37 acres per year. So the water requirement for revegetation is 296 acre-feet per year (183 gallons per minute). This water must not contain sediment and must have a total dissolved solids concentration not exceeding 700 milligrams per liter, since the watering is done by sprays and to avoid salt loading.

One alternative to leaching the soluble salts from the spent shale pile prior to replanting is to cover the pile with a thin layer of rock - raw shale from preproduction mining, overburden and sub-ore in the case of an open pit mine, or rock from another source. This speeds soil development and thus vegetation establishment. The only water requirement would be for irrigation over two growing seasons and this would be 2 acre-feet per acre of area revegetated (Wymore, 1974). This is 74 acre-feet per year (46 gallons per minute). A disadvantage of this alternative is that the large particle size may decrease the water-holding capacity of the pile.

A second alternative to the leaching step is to cover the pile with soil removed from the mine/processing/disposal site or from another source. This creates an artificial soil profile that results in better and faster vegetation establishment and growth. As above, the only water requirement would be 2 acre-feet per acre of area revegetated for irrigation over two growing seasons. Disadvantages of this alternative are that the water-holding capacity may be less than spent shale and that the soluble salts may move upward by capillary action into the soil cover and root zone.

A third alternative to the leaching step is to cover the pile with a thin layer of rock and then cover the rock with soil. This creates an artificial soil profile and eliminates the problem of upward movement of soluble salts by capillary action into the root zone and reduces the problem of low water-holding capacity. Again, the only water requirement would be 2 acre-feet per acre of area for irrigation over two growing seasons.

10.5.2 REVEGETATION OF OVERBURDEN AND SUB-ORE

The first step in revegetation of a pile composed only of overburden and sub-ore in the case of an open pit mine is to cover the pile with mulch and fertilize it with sewage effluent, clarifier sludge, or commercial fertilizer. The pile is then replanted with native grasses, forbs, shrubs, and trees, and irrigated with 2 acre-feet of water per acre of area revegetated, all of which is consumptively used, over two growing seasons. This will produce sufficient root development for the vegetation to exist under natural conditions without further assistance. Assuming an average of 34,400 tons per day of overburden and sub-ore has a compacted density of 95 pounds per cubic foot and will be placed in piles averaging 200 feet, the disposal site land use will expand at a rate of 30 acres per year. So the water requirement for revegetation is 60 acre-feet per year (37 gallons per minute). This water must not contain sediment and must have a total dissolved solids concentration not exceeding 700 milligrams per liter, since the watering is done by sprays and to avoid salt loading. A disadvantage is that the large particle size may result in a low water-holding capacity of the pile.

An option to be considered in the revegetation of an overburden and sub-ore pile is covering it with soil removed from the mine/processing/disposal site or from another source prior to replanting. This creates an artificial soil profile that results in better and faster vegetation establishment and growth. It also reduces the problem of low water-holding capacity. The water requirement would be the same as before.

To revegetate a pile composed of spent shale and overburden and sub-ore (not just as a thin covering), the procedure is the same as for a pile composed only of overburden and an optional soil covering. The disposal site land use will expand at a rate of 67 acres per year, so the water requirement for revegetation is 134 acre-feet per year (83 gallons per minute).

10.5.3 ENVIRONMENTAL CONSIDERATIONS

An environmental concern in revegetation is the leaching of soluble salts from the disposal piles into the groundwater system. This would follow from the addition of reclamation and revegetation water, as well as precipitation. In general, disposal piles will have relatively high permeabilities, so it will be necessary to construct the piles in such a way as to prevent groundwater degradation. Both the developers of C-a Tract and C-b Tract have stated that they will construct impervious seepage liners on their disposal piles, and will collect and treat any leachate. It is expected that this flow quantity will be negligible in terms of water management.

CHAPTER 11

WATER MANAGEMENT SYSTEMS FOR CONVENTIONAL SHALE OIL INDUSTRIES

The general water management system for a conventional oil shale industry comprises the following elements:

i. Water Acquisition - from groundwater, mine inflow, or external surface supplies.

ii. Treatment - to raise water quality to appropriate standards for use.

iii. Use - in mining, transporting, retorting, or spent shale disposal activities.

iv. Disposal - of excess mine inflow water (if any) and of excess foul water from the process.

The optimal method of performing these activities depends on process requirements, water availability, disposal requirements, and unit costs of each activity. This chapter summarizes the material presented in the preceding chapters, and integrates the information into optimal water management strategies for conventional shale oil industries at the selected sites.

11.1 WATER USAGE

The active element in the water management system is water usage. Once a production rate for the plant is selected, this implies a relatively fixed water demand. As shown in Chapter 6, there are three basic qualities of water which are required in the mining/retorting/disposal complex:

i. Boiler Feedwater. All of the retorting processes use steam as a major source of heat, and often for upgrading the quality of the off-gas of the process. Input boiler feedwater must be very pure, with a TDS level below 100 mg/l and negligible hardness and organic content.

ii. Service Water. The largest water requirement is for service water. This has to be sprayable, and suitable for all normal service requirements including irrigation. Accordingly, it is limited to 750 mg/l of TDS, with 50 mg/l of suspended solids, and negligible hydrocarbons.

iii. Wastewater. This water can be of any quality, although the suspended solids content must be low enough to allow pumping, and the pH must be between 6 and 9 to reduce pipe corrosion.

The quantities of each quality of water which is used in a 50,000 TPD operation (producing about 30,000 BPD of shale oil) are presented in detail in Chapter 9. The quantities turn out to be very similar for schemes using the Union B and Paraho IH retorting systems, with the TOSCO II retorting system consuming much more boiler feedwater and somewhat less service water.

Table 11-1 presents the details of water usage for a 50,000 TPD/30,000 BPD industry using conventional mining, transporting, retorting, and spent shale disposal. The "base case" presented applies to Paraho and Union retorting. The requirements for any other mining/retorting/disposal option can be obtained by adding the appropriate amounts indicated in the "increments to base case" table.

TABLE 11-1
WATER CONSUMPTION FOR A 50,000 TPD MINE/RETORT COMPLEX
(ACRE-FEET PER YEAR)

	Input					
Use	Boiler	Service	Foul	Total	Output	Net
Base Case						
Site Development	-	57	-	57	-	57
In Mine Use	-	178	130	308	-	308
Raw Shale Delivery	-	134	364	498	80	418
Retorting & Upgrading	400	4,200	-	4,600	1,300	3,300
Disposal of Spent Shale (Dry)	-	-	941	941	-	941
Reclamation & Revegetation	-	296	-	296	-	296
Power Generation	850	-	-	850	50	800
Miscellaneous	50	900	-	950	-	950
BASE CASE TOTALS	1,300	5,765	1,435	8,500	1,430	7,070
Increments to Base Case						
TOSCO II Retorting	+1,000	-600	-	+400	-100	+500
Slurry Spent Shale Disposal	-	-	+16,000	+16,000	10,000	+6,000
Open Pit Mining	-	-162	-	-162	-	-162
Offsite Power Generation	-850	-	-	-850	-50	-800

NOTE: 1. To obtain actual usage, add increment required to base case totals, observing sign of increment.

2. Usage is linear with respect to mine tonnage (approximately).

It is fortunate, though hardly surprising, that the figures are not much influenced by many of the possible parameters. Differences in mining and shale transport methods barely influence the water usage, and the same is true of the reclamation method. The major variable in total usage is the method of spent shale handling. If slurry transport of spent shale is used, this almost doubles the consumptive water use. Thus, in broad terms, the consumptive water use per barrel of oil produced is 5 barrels of water per barrel of oil for dry spent shale transport, and 9 barrels of water per barrel of oil for slurry transport of spent shale.

11.2 WATER ACQUISITION

Having determined the water input requirement for a shale oil production complex, it is necessary to evaluate the methods, and cost, of obtaining the required amounts of water. Detailed evaluations of water supply and cost were presented in Chapter 5. Leaving aside the question of required water quality for the moment (to be discussed under Section 11.3 - Water Treatment), the type, cost, availability, and quality of the major water sources are presented here.

i. Groundwater. Groundwater is available to the project in two ways. First, a certain amount of groundwater will flow into the mine from which the shale is removed, at a rate dependent on a large number of variables, as evaluated in Chapter 8. Second, if this groundwater inflow is below the requirements of the project, further supplies may be available by pumping from wells. In either case the quality will be about 1,500 mg/l of dissolved salts. The cost of obtaining the water will be zero in the case of inescapable mine inflow (as it will have to be removed from the mine in any case). Groundwater will cost $30/AF at Sites 1 and 2, and $90/AF at Site 3. Site 3 is a less attractive hydrogeologic setting for water well operation.

ii. Surface Water. Surface water may be obtained from the Colorado, White, or Yampa Rivers. While the cost of surface water supply, and the quality of supplied water, vary somewhat between sources, a reasonable mean cost is $140/AF and the mean quality is 350 mg/l TDS, with up to 2,000 mg/l of suspended solids.

iii. Reclaimed Wastewater. This water is available from the process, and is of low to very low quality. For the purposes of this study it is assumed to have 25,000 mg/l TDS, substantial hydrocarbon content, and limited suspended solids. The quantity of supply is limited to the production of wastewater in the process, but is available at no incremental cost.

11.3 INPUT WATER TREATMENT

The subject of water treatment is covered in detail in Chapter 6. As far as treating input water is concerned, there are three qualities of available water (groundwater, river water, and wastewater) and two qualities of water required for the process (boiler feedwater and service water). It is assumed that wastewater does not need treatment prior to use as wastewater. As explained in Chapter 6, only one treatment method is used (reverse osmosis) because this is the preferred method of developers to date, and costs are similar to those for substitute methods.

In the reverse osmosis method of purification, a proportion of the input feed (usually about 25% for a full cycle) is rejected with almost all of the dissolved solids, leaving some 75% of the input feed available as purified water. This has an impact on the economics of water supply, as the quantity of input water to produce a unit volume of purified water is a function of input concentration. A summary of the details of cost, and input volumes necessary to produce an acre-foot of various qualities of water, using various input waters, is presented in Table 11-2.

11.4 SELECTION OF WATER SUPPLY

Based on the material above it is now possible to evaluate the cost per acre-foot of various water supply options. The possible sources of water are mine inflow, groundwater, river water, and reclaimed foul water. The uses to which the water is to be put are boiler water, service water, and wastewater. The cost of supply has two basic components--cost of acquisition and delivery, and cost of treatment to the required quality. These costs are summarized in Table 11-3.

From this table it can be seen that mine inflow water is the cheapest source of water for any use. For water needed above the total mine inflow quantity (if any), groundwater is cheapest at Sites 1 and 2, but is slightly more expensive than river water at Site 3. A caution is, however, in order. The unit cost of river water for low flow rates (say 5,000 AFY or less) is probably considerably higher than the $140/AF used. This value was derived from data relating to flows in the 18,000 AFY to 75,000 AFY range (see Chapter 5). Thus we feel that, for excess flows less than 5,000 AFY, groundwater is the cheapest alternative option in all cases. The only use for which wastewater is in any way competitive is, of course, as wastewater. It can be treated to drinking water standard

TABLE 11-2
INPUT WATER TREATMENT DETAILS

A. BOILER FEEDWATER PRODUCTION

	Water Source		
	River Water	Groundwater	Wastewater
Input Water			
Quality (TDS-mg/l)	350	1,500	25,000
Quantity (Acre-Feet)	1.034	1.226	1.571
Filtrate			
Quality (TDS-mg/l)	100	100	100
Quantity (Acre-Feet)	1.000	1.000	1.000
Concentrate			
Quality (TDS-mg/l)	7,700	7,700	68,600
Quantity (Acre-Feet)	0.034	0.226	0.570
Costs (1974 Dollars)			
Cost Per Acre-Foot of Filtrate	$220	$280	$840

B. SERVICE WATER PRODUCTION

	Water Source		
	River Water	Groundwater	Wastewater
Input Water			
Quality (TDS-mg/l)	350	1,500	25,000
Quantity (Acre-Feet)	1.000	1.158	1.521
Filtrate			
Quality (TDS-mg/l)	350	750	750
Quantity (Acre-Feet)	1.000*	1.000	1.000
Concentrate			
Quality (TDS-mg/l)	-	5,775	71,600
Quantity (Acre-Feet)	-	0.158	0.521
Costs (1974 Dollars)			
Cost Per Acre-Foot of Filtrate	$83	$189	$721

*Requires only filtration to remove suspended solids.

TABLE 11-3
COST TO SUPPLY ONE ACRE-FOOT OF WATER FOR VARIOUS INTENDED USES (1974 Dollars)

	Intended Use		
Source	Boiler	Service	Wastewater
River Water			
Input Quantity (AF)	1.034	1.000	1.000
Unit Acquisition Cost	$140	$140	$140
Acquisition Cost	$145	$140	$140
Treatment Cost	$220	$ 83	-
TOTAL COST	$365	$223	$140
Groundwater (Sites 1 & 2)			
Input Quantity (AF)	1.226	1.158	1.000
Unit Acquisition Cost	$ 30	$ 30	$ 30
Acquisition Cost	$ 38	$ 35	$ 30
Treatment Cost	$280	$189	-
TOTAL COST	$318	$224	$ 30
Groundwater (Site 3)			
Input Quantity (AF)	1.226	1.158	1.000
Unit Acquisition Cost	$ 90	$ 90	$ 90
Acquisition Cost	$110	$104	$ 90
Treatment Cost	$280	$189	-
TOTAL COST	$390	$293	$ 90
Mine Inflow			
Input Quantity (AF)	1.226	1.158	1.000
Unit Acquisition Cost	-	-	-
Acquisition Cost	-	-	-
Treatment Cost	$280	$189	-
TOTAL COST	$280	$189	-
Wastewater			
Input Quantity (AF)	1.571	1.521	1.000
Unit Acquisition Cost	-	-	-
Acquisition Cost	-	-	-
Treatment Cost	$836	$721	-
TOTAL COST	$836	$721	-

for about $2.50 per 1,000 gallons, which is quite economical for domestic supply in this location. This is the only economically attractive alternative to simply disposing of it in the spent shale pile.

11.5 WATER MANAGEMENT SYSTEMS

The selection of optimal water management systems depends upon the following factors:

i. Source of Water Used - i.e. either groundwater or river water.

ii. Processing Method - i.e. either TOSCO II or Paraho IH/ Union B.

iii. Size of Industry - i.e. either 50,000 TPD, 100,000 TPD, or 200,000 TPD.

The choice in the first case is based on the relative economics of water supply and use. It is assumed that the choice in the latter two cases would be made external to this project.

The subject of mine inflow is not a central part of the water management scheme, for reasons which are discussed in Section 11.7. Likewise, it transpires that the disposal of water by direct discharge is unnecessary in any scenario which has been developed. The only two disposal techniques used are direct reinjection of excess inflow water (Section 11.7) and disposal of untreated foul water in the spent shale pile.

The use of water is a linear function of the size of the industry. As a consequence, all of the analyses have been conducted for a 50,000 TPD industry producing 30,000 BPD of shale oil. Other sizes can be directly scaled.

The general system involves water acquisition, treatment to usable quality, use, and wastewater disposal. Each of these subsystems can be broken up into specific parts to produce the system shown in Figure 11-1.

Any mixture of water supply between 100% groundwater and 100% river water is feasible. The results of the analyses of water systems for the extreme cases, using Paraho/Union processing and TOSCO processing, are presented below.

i. Paraho/Union Processing, Groundwater Input. This system is shown in Figure 11-2. Of the 8,270 AFY input, 7,070 AFY is consumptively used and 1,200 AFY appears as wastewater. As the wastewater capacity of the spent shale pile in a 50,000 TPD operation is 1,370 AFY, this could all be discharged in the spent shale, raising its moisture content to 18.5%, which is close to the optimum moisture content for compaction (20%-23%).

ii. Paraho/Union Processing, River Water Input. This system is shown in Figure 11-3. Of the 7,109 AFY input, 7,070 AFY is consumptively used, with 39 AFY remaining for disposal. If disposed of in the spent shale pile, it would add 1/3% moisture content raising the total to 8-1/3%.

iii. TOSCO Processing, Groundwater Input. This system is shown in Figure 11-4. Of the 8,800 AFY input, 7,570 AFY is consumed, with 1,230 AFY remaining

Figure II-1 GENERAL WATER MANAGEMENT SYSTEM FOR AN OIL SHALE INDUSTRY

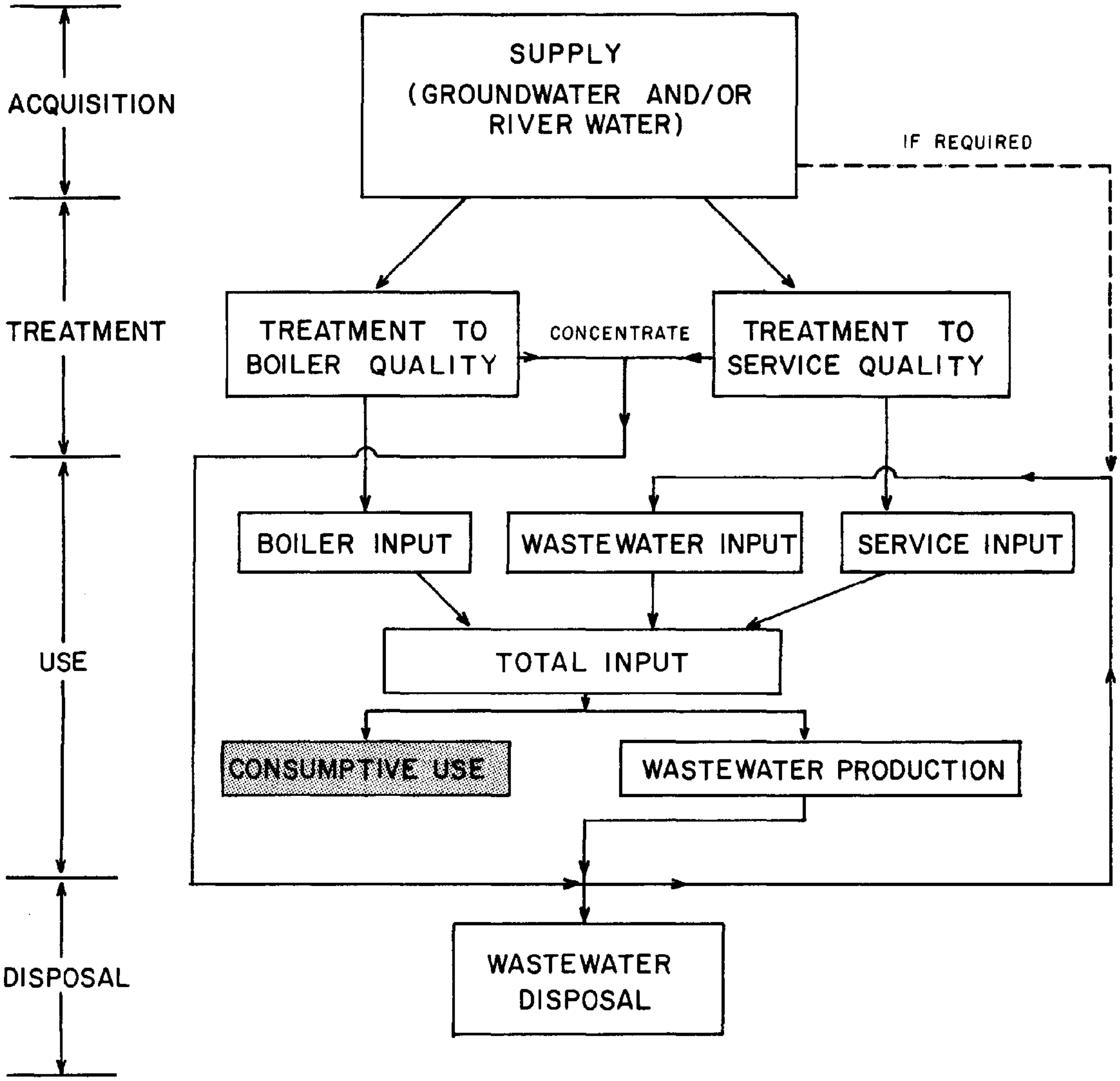
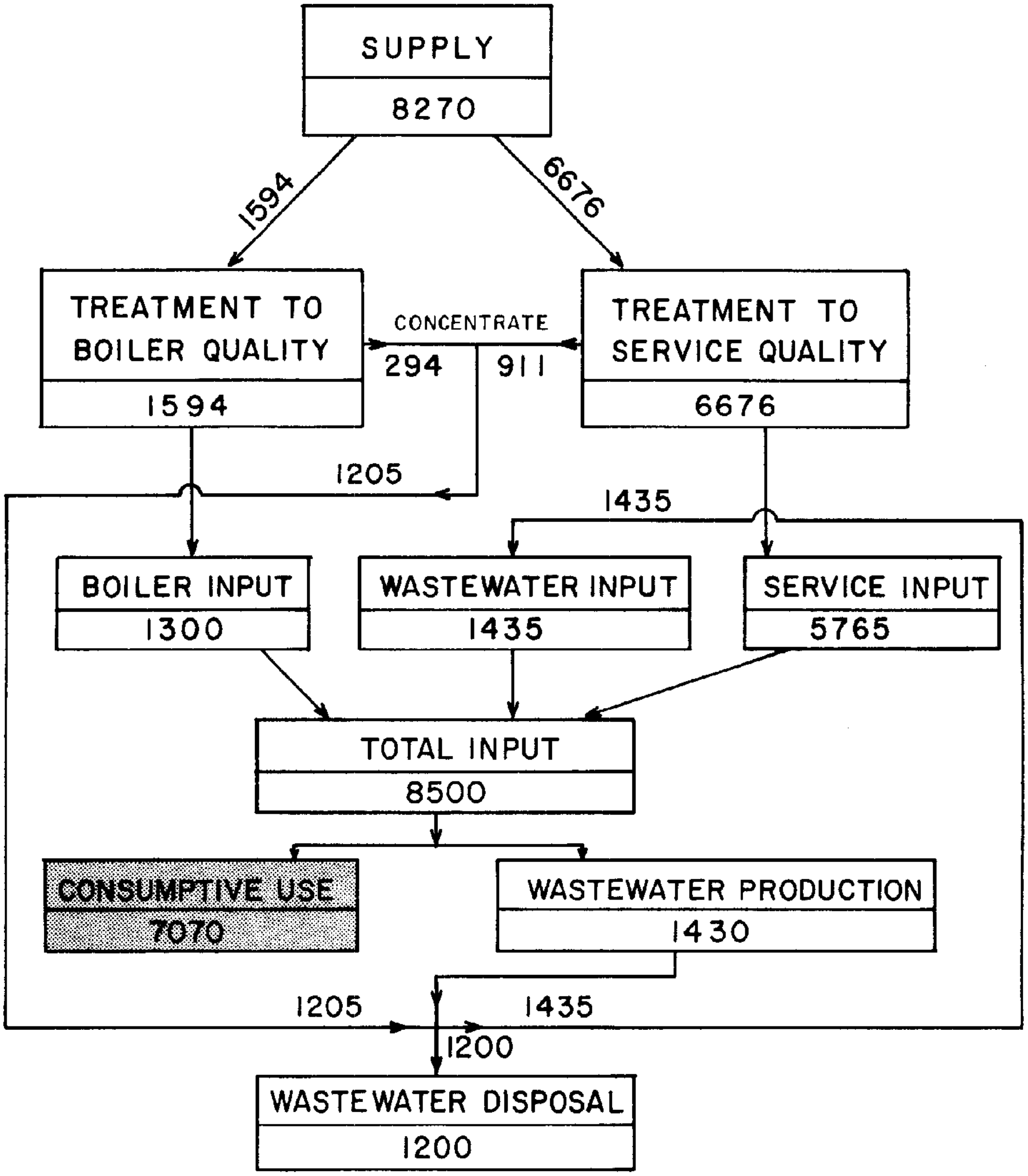
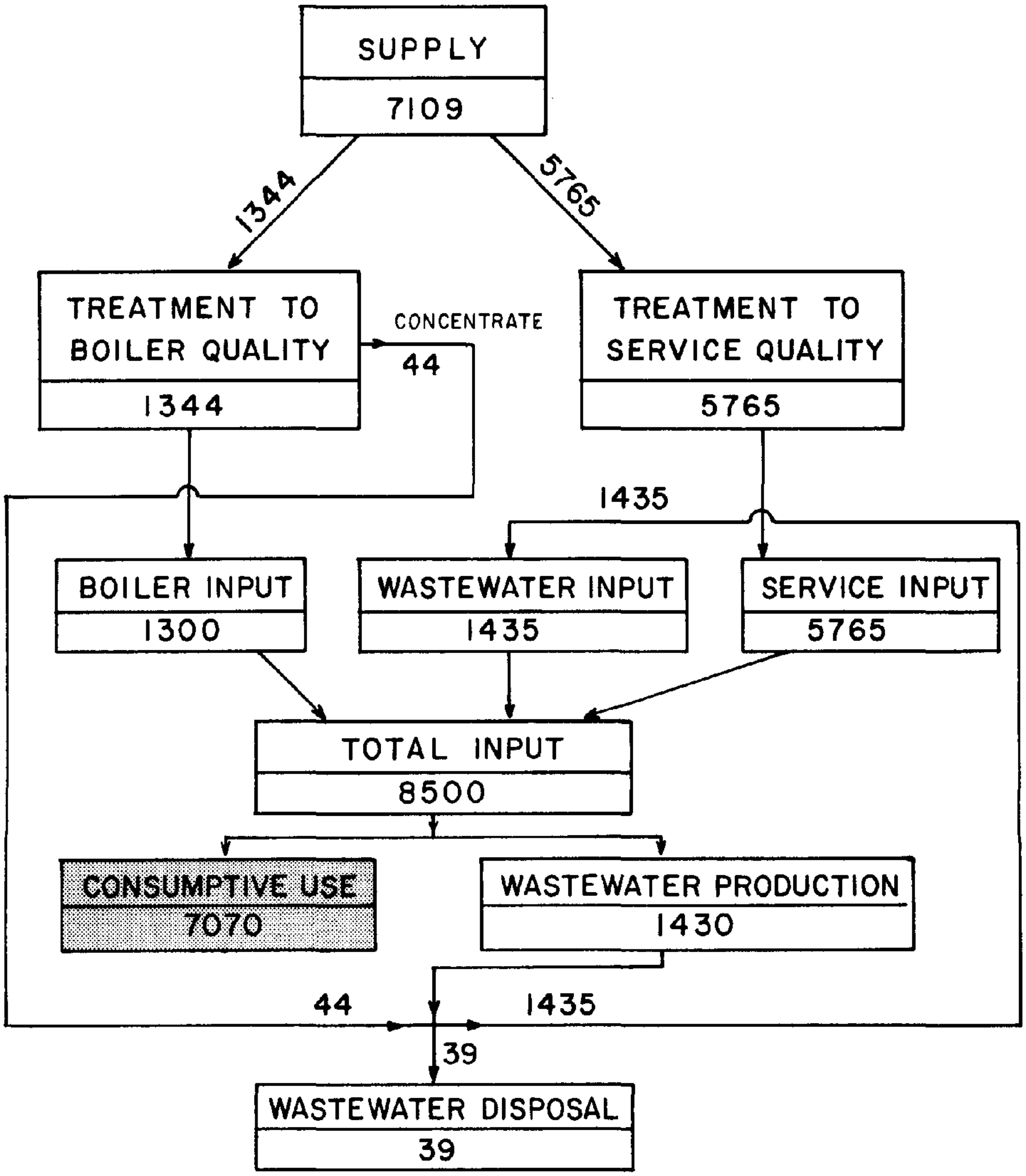

ACQUISITION
TREATMENT
USE
DISPOSAL
SUPPLY
(GROUNDWATER AND/OR RIVER WATER)
IF REQUIRED
TREATMENT TO BOILER QUALITY
CONCENTRATE
TREATMENT TO SERVICE QUALITY
BOILER INPUT
WASTEWATER INPUT
SERVICE INPUT
TOTAL INPUT
CONSUMPTIVE USE
WASTEWATER PRODUCTION
WASTEWATER DISPOSAL

Figure II-2 WATER MANAGEMENT SYSTEM FOR PARAHO/UNION PROCESSING WITH GROUNDWATER INPUT


SUPPLY
8270
1594
6676
TREATMENT TO BOILER QUALITY
1594
CONCENTRATE
294
911
TREATMENT TO SERVICE QUALITY
6676
1205
1435
BOILER INPUT
1300
WASTEWATER INPUT
1435
SERVICE INPUT
5765
TOTAL INPUT
8500
CONSUMPTIVE USE
7070
WASTEWATER PRODUCTION
1430
1205
1435
1200
WASTEWATER DISPOSAL
1200

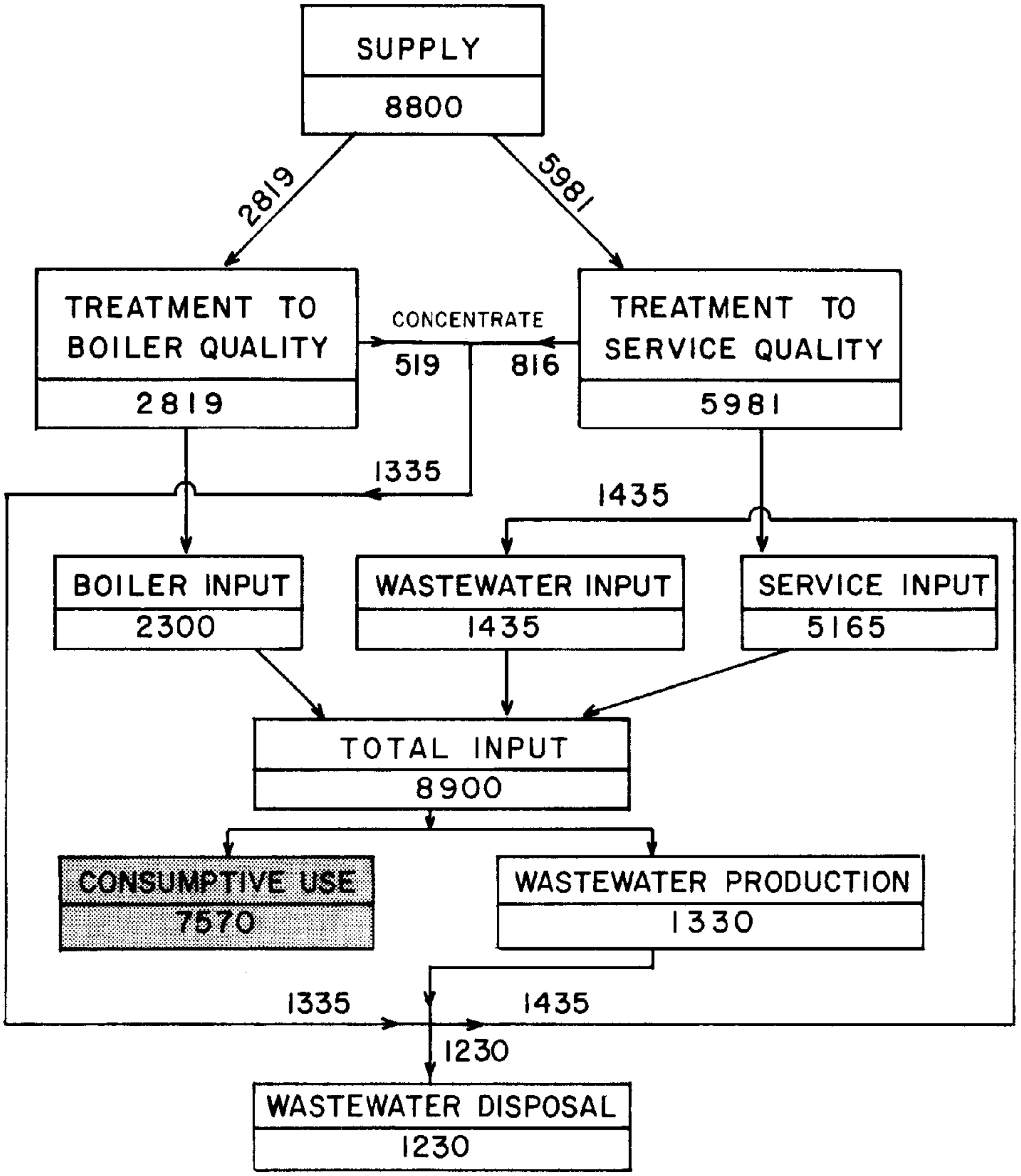
Notes: i. All flows are in acre-feet/year.
ii. Flows are for a 50,000 TPD/30,000 BPD operation.

Figure 11-3 WATER MANAGEMENT SYSTEM FOR PARAHO/UNION PROCESSING WITH RIVER WATER INPUT


SUPPLY
7109
1344
5765
TREATMENT TO BOILER QUALITY
1344
CONCENTRATE
44
TREATMENT TO SERVICE QUALITY
5765
1435
BOILER INPUT
1300
WASTEWATER INPUT
1435
SERVICE INPUT
5765
TOTAL INPUT
8500
CONSUMPTIVE USE
7070
WASTEWATER PRODUCTION
1430
44
1435
39
WASTEWATER DISPOSAL
39

Notes: i. All flows are in acre-feet/year.
ii. Flows are for a 50,000 TPD/30,000 BPD operation.

Figure 11-4 WATER MANAGEMENT SYSTEM FOR TOSCO PROCESSING WITH GROUNDWATER INPUT


SUPPLY
8800
2819
5981
TREATMENT TO BOILER QUALITY
2819
CONCENTRATE
519
816
TREATMENT TO SERVICE QUALITY
5981
1335
1435
BOILER INPUT
2300
WASTEWATER INPUT
1435
SERVICE INPUT
5165
TOTAL INPUT
8900
CONSUMPTIVE USE
7570
WASTEWATER PRODUCTION
1330
1335
1435
1230
WASTEWATER DISPOSAL
1230

Notes: i. All flows are in acre-feet/year.
ii. Flows are for a 50,000 TPD/30,000 BPD operation.

for disposal. If disposed of in the spent shale pile, it would raise the water content to 18.8%, which is again close to the optimum for compaction.

iv. TOSCO Processing, River Water Input. This system is shown in Figure 11-5. The 7,570 AFY of water supplied is all consumptively used. Note that the 27 AFY of river water used to augment the wastewater could be eliminated by lowering the spent shale water content to 4-1/3%.

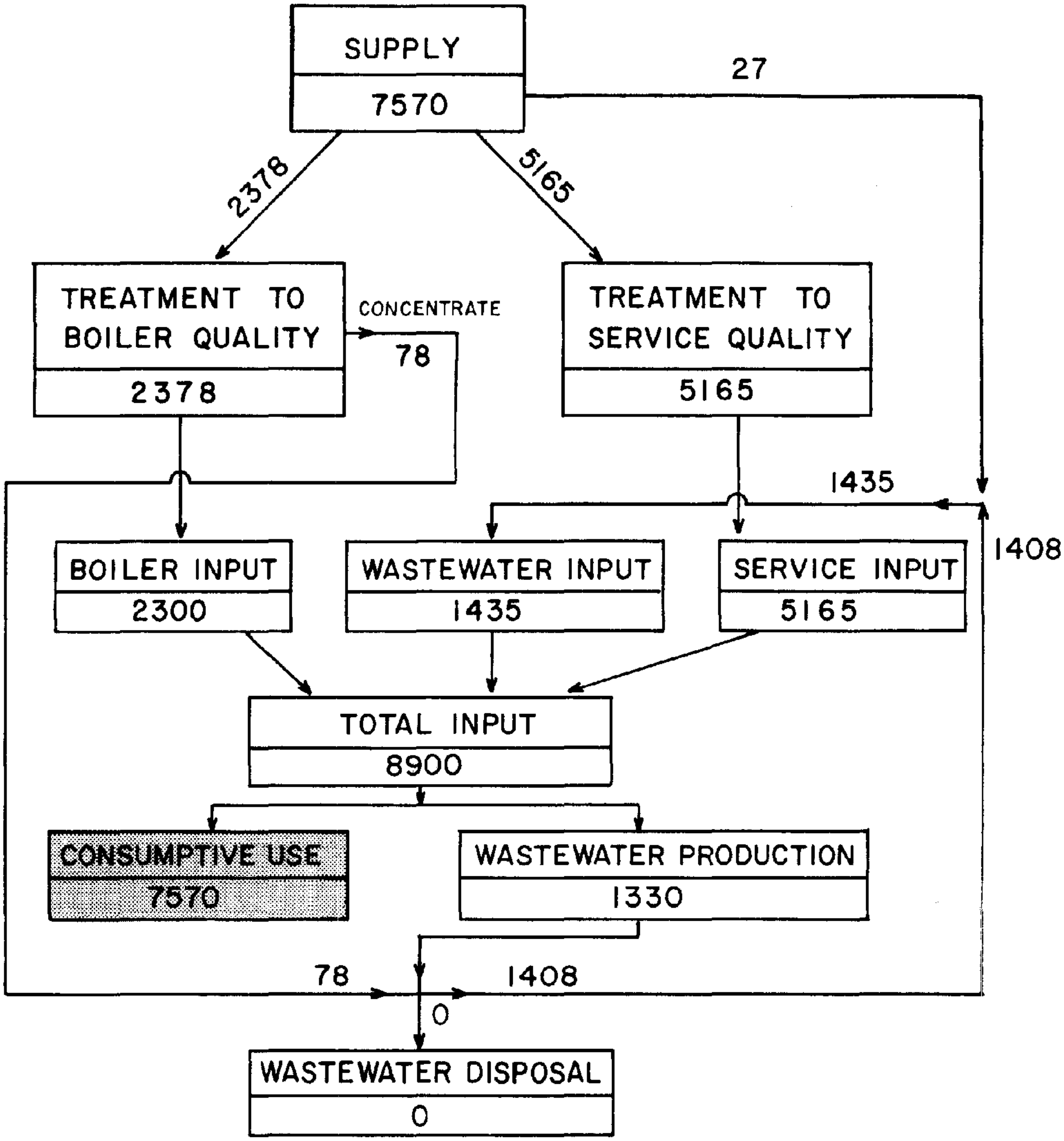
These extreme values are shown plotted on Figure 11-6. The relation is virtually linear, with river water and groundwater interchangeable at the rate of approximately 1.16 AF of groundwater for 1 AF of river water. This arises because of the difference in the quality of input water.

11.6 COST CONSIDERATIONS

Costs of all of the elements of the above water management system have been already discussed, and the systems presented represent optimal choices between supply and processing alternatives. It is, however, useful to evaluate the burden which water supply, treatment, and disposal places upon a conventional shale oil industry. Table 11-4 presents the cost of water per barrel of oil produced, for a spectrum of processing and water source choices. The totals are a relatively small part of the total cost of a barrel of shale oil, which is estimated to be in the range of $10 to $15 in 1974 dollars.

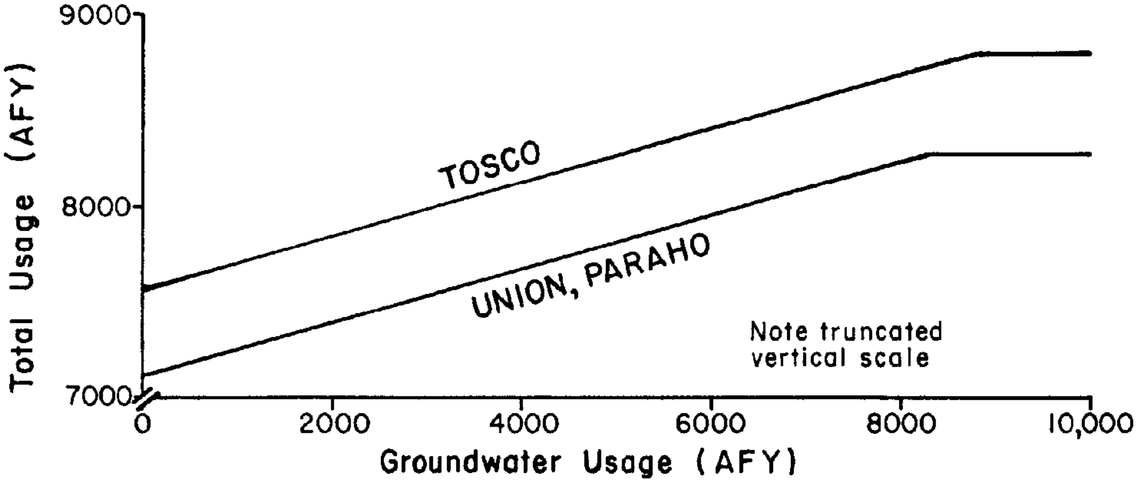
It should be noted that Table 11-4 also illustrates the economic selections discussed in Section 11.4 above, and provides an

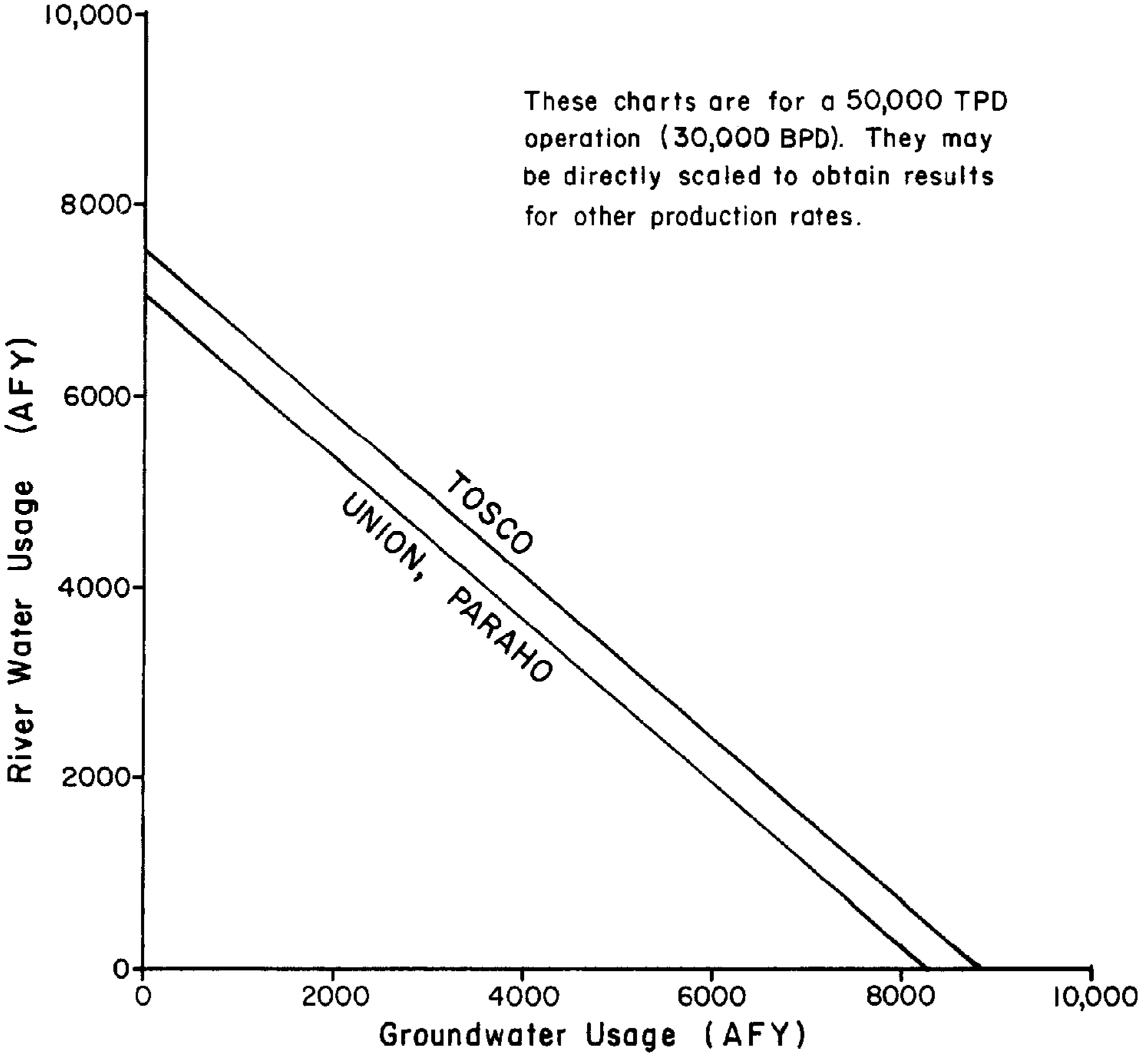
Figure 11-5 **WATER MANAGEMENT SYSTEM FOR TOSCO PROCESSING WITH RIVER WATER INPUT**


SUPPLY
7570
27
2378
5165
TREATMENT TO BOILER QUALITY
2378
CONCENTRATE
78
TREATMENT TO SERVICE QUALITY
5165
1435
1408
BOILER INPUT
2300
WASTEWATER INPUT
1435
SERVICE INPUT
5165
TOTAL INPUT
8900
CONSUMPTIVE USE
7570
WASTEWATER PRODUCTION
1330
78
1408
0
WASTEWATER DISPOSAL
0

Notes: i. All flows are in acre-feet/year.
ii. Flows are for a 50,000 TPD/30,000 BPD operation.

Figure 11-6 RELATIONSHIP BETWEEN GROUNDWATER, RIVER WATER, AND TOTAL USAGE-50,000 TPD OPERATION





These charts are for a 50,000 TPD operation (30,000 BPD). They may be directly scaled to obtain results for other production rates.

TABLE 11-4
COST OF WATER SUPPLY PER BARREL OF PRODUCT OIL
(1974 Dollars)

	Union/Paraho With Wastewater:		TOSCO With Wastewater:	
Water Source	Disposed	Reclaimed*	Disposed	Reclaimed
Mine Inflow	$0.13	$0.19	$0.15	$0.21
River Water	$0.16	$0.16	$0.18	$0.18
Groundwater				
Site 1 & 2	$0.16	$0.22	$0.17	$0.23
Site 3	$0.20	$0.26	$0.22	$0.28

*NOTE: This assumes the water is reclaimed and discharged. If it is reclaimed and used in the process, the cost differential for groundwater is about $0.03-$0.04 per barrel of oil instead of $0.06 per barrel. There is so little net wastewater in the systems using river water that reclamation is irrelevant to the per barrel economics.

easy comparison between the economics of water supply for TOSCO and Paraho/Union processing.

11.7 MINE INFLOW CONSIDERATIONS

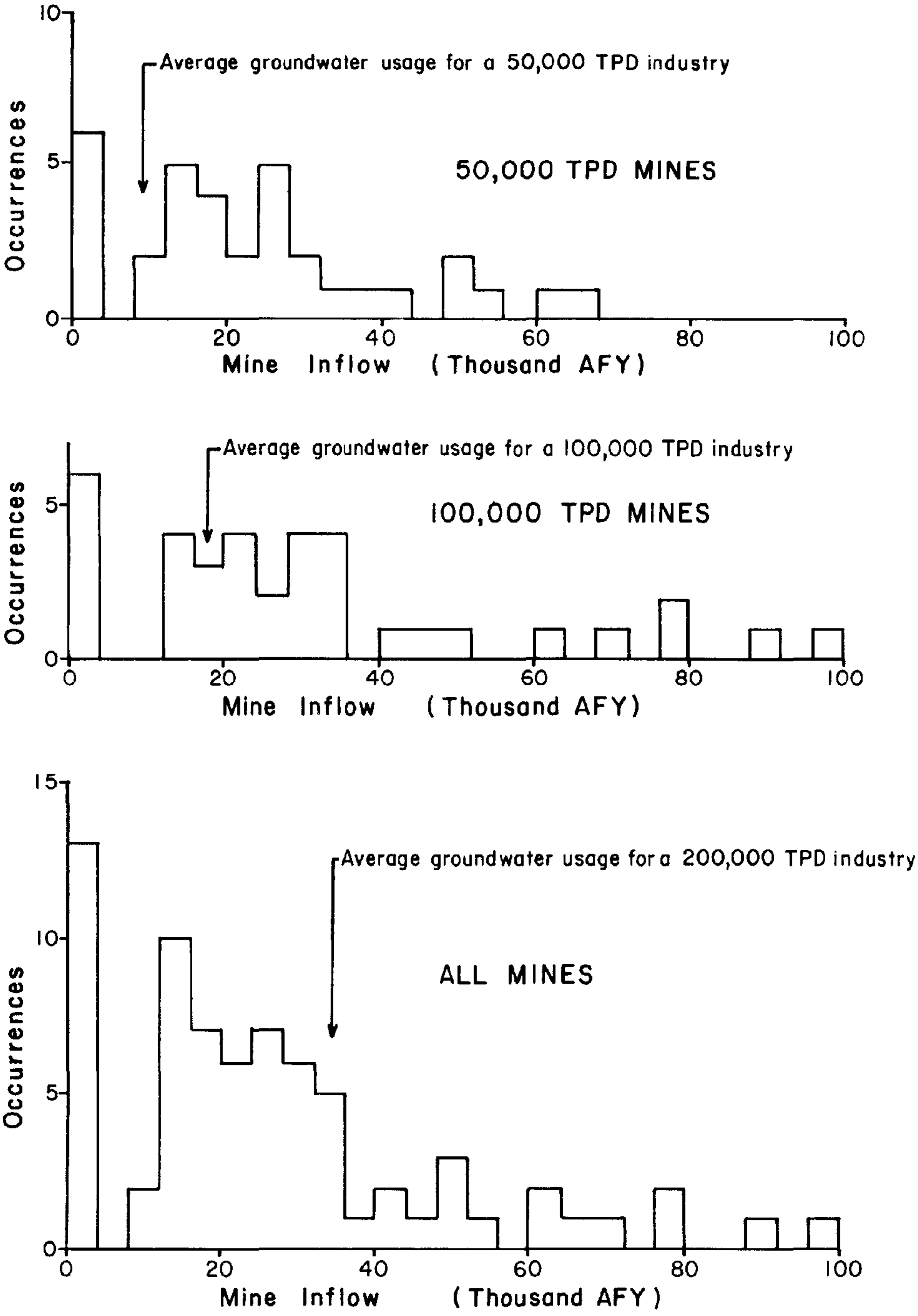
As stated above, mine inflow plays an important but indirect role in the water management system. This is a result of the economics of water supply. Any mine inflow up to the total inflow needs of the process will be used in the process. If this inflow is inadequate, then the economically prudent course for a developer to take would be to extract groundwater by the use of wells to make up the shortfall. Thus the result on the geohydrology of the area is to extract about 8,270 AFY (Paraho/ Union) or 8,800 AFY (TOSCO) from the groundwater resource (for a 50,000 TPD industry).

On the other hand, consider the situation where inflow exceeds the input quantities required. In this case, any excess is simply reinjected into the formation from which it came at a small distance from the mine (say 1 mile). Thus the net flow from the aquifer in either case will be the same (i.e. the total input quantity for the process) and the effect on the Basin will be virtually identical for all mine inflow conditions.

The probable mine inflow rates at each site have been evaluated in Chapter 8 using the best available data.

A wide spectrum of mine inflow rates were obtained, and the average inflow rates over a 30-year mine life are plotted on Figure 11-7. It can be seen that a group of conditions result in inflows of the order of 2,000 AFY or less. These mines are primarily deep, single pass, non-subsidence mines in the R-4 Zone, plus Mahogany Zone mines at Site 2. All the rest of the

Figure II-7 AGGREGATE MINE INFLOW RESULTS



NOTE: Occurrences is defined as the number of times a particular mine inflow rate was obtained in our analyses.

mines have inflows of 10,000 AFY or more, with the highest inflow being of the order of 100,000 AFY. The median flow of this upper group is 25,000 AFY, and the median flow of the lower group is 1,000 AFY.

Thus, it would appear that most mine types will be in a condition of water excess at a production rate of 50,000 TPD, which requires a groundwater input of about 8,500 AFY. The same is true of a 100,000 TPD industry, for which average input is 17,000 AFY. For a 200,000 TPD industry, it seems likely that there would be a substantial shortfall of mine inflow water in most cases, necessitating wells or surface water imports.

11.8 WATER AVAILABILITY CONSIDERATIONS

A conventional oil shale mining and retorting industry is consumptive of water. Assuming that the ore resource is large compared with the water resource, it is necessary to evaluate the restraints which might be placed on an industry by the lack of availability of water.

11.8.1 Availability of Groundwater

In the long term, groundwater in the Basin can come from three sources:

i. Water presently stored in the Basin rock and alluvium.

ii. Precipitation water which percolates to the groundwater system.

iii. Streamflow which is diverted to the subsurface system due to groundwater depletion.

The first source is a single use resource. It has been estimated that the Basin contains between 2.5 million and 25 million acre-feet of stored water (Weeks, et al., 1974). Limitations of extraction techniques would possibly restrict available stored water to the lower value of 2.5 million acre-feet. Recharge to the groundwater system has been estimated at 24,000 acre-feet/year (Weeks, et al., 1974) and this value is supported by several independent evaluations. Average surface water flow in the streams of the Basin is 20,500 AFY, and this could, presumably, all be influent to the groundwater system under extreme mining conditions.

As shown above, a 50,000 TPD/30,000 BPD operation requires an average of about 8,000 AFY of groundwater input. Based on this value, the limits of production of oil implied by only using in-Basin water resources are shown in Table 11-5. All of these approaches would have significant environmental impacts, which are evaluated in Chapter 15.

TABLE 11-5

LIMITATIONS ON BASIN-WIDE SHALE OIL PRODUCTION BY CONVENTIONAL MEANS USING GROUNDWATER

	Maximum Size of Industry Which Can Be Supplied by Nominated Groundwater Source	
Groundwater Source	Tons/Day	Barrels Oil/Day
Recharge (24,000 AFY)	150,000	90,000
Recharge + Runoff (Total 44,500 AFY)	278,000	170,000
Recharge + Runoff + Storage Used in 100 Years (Total 133,000 AFY)	830,000	500,000
Recharge + Runoff + Storage Used in 30 Years (Total 340,000 AFY)	2,125,000	1,275,000

It is clear, therefore, that in terms of large scale shale oil production, groundwater is a very limited resource, and for any but the smallest industry, use of groundwater will constitute mining of this resource. The stored water is, however, renewable once mining ceases.

11.8.2 Availability of Surface Water

Based on the material in the previous section, it seems inevitable that large scale development of the oil shale reserves in the Piceance Basin by conventional means will require externally acquired water. While a detailed evaluation of the availability of surface water in the Colorado River Basin is beyond the scope of this contract, some published figures are available which gives at least a starting point for this evaluation.

Based on a recent evaluation by Water Resources Management Workshop of the University of Wisconsin-Madison (Petrie, et al., 1975), there are 2-1/2 - 3 million acre-feet of Colorado Basin water allocated to Colorado each year, of which presently 800,000 acre-feet are unused. The U.S. Bureau of Reclamation projects that this will be entirely committed and will be totally used (principally for agriculture) by the year 2030. The Wisconsin study concludes that changing priorities in Colorado make this degree of commitment to agriculture unlikely, and that a considerable amount of this water is, in fact, available for consumptive use in an oil shale industry. In the interests of adopting a usable number, we have assumed that 1/4 of the presently unused flow, or 200,000 AFY could be available for oil shale. Table 11-6 shows the limits that the available surface water supplies place upon an oil shale industry, assuming no groundwater is used.

TABLE 11-6
LIMITATIONS ON BASIN-WIDE SHALE OIL PRODUCTION BY CONVENTIONAL MEANS USING RIVER WATER

	Maximum Size of Industry Which Can Be Supplied	
River Water Quantity	Tons/Day	Barrels Oil/Day
In Basin Surface Water (20,500 AFY)	128,000	77,000
Estimated Available Water from Colorado Basin (200,000 AFY)	1,250,000	750,000
Present Available Water from Colorado Basin (800,000 AFY)	5,000,000	3,000,000

11.8.3 Combined Availability

Thus it seems likely that the limit of production of an oil shale industry would be in the order of 1,000,000 barrels/day of product oil, using both surface and subsurface water, unless a different process was used. This implies a steady combined availability of 24,000 AFY of groundwater and 200,000 AFY of surface water.

11.9 SLURRY SPENT SHALE HANDLING CONSIDERATIONS

The handling of spent shale using slurry techniques has been discussed in Chapter 10. This mode of shale disposal consumes an additional 6,000 AFY for a 50,000 TPD operation, thus tripling consumptive use for the project. Environmentally the creation of large slime ponds and water pollution potential makes it difficult to believe that approval for this form of disposal would be forthcoming.

Assuming the method to be viable, however, the water management situation would be altered by having to supply 6,000 AFY of waste quality water for a 50,000 TPD industry. Because of total availability of water, it seems likely that this would necessitate river water import at any of the sites considered, although Site 1 could probably sustain a total extraction of groundwater of 24,000 AFY for a period of 30 years.

11.10 SUMMARY

We have presented above a water management assessment for a conventional shale oil production industry. This industry utilizes about 5 barrels of water per barrel of oil produced, at a cost per barrel of oil of between 13¢ and 26¢ for water supply, treatment, and disposal. If slurry disposal of spent shale is utilized, the water requirement jumps to 9 barrels of water per barrel of oil.

In all cases, it is not of much economic significance whether the water comes from groundwater or surface water. Obviously mine inflow water will be used first, and then either river or groundwater will be used, dependent on non-economic factors such as ownership, environmental impact, reliability, availability, etc.

The schemes presented here all turned out to be relatively highly consumptive of wastewater with the result that water disposal could be accomplished by discharge to the spent shale pile. Excess mine inflow can be reinjected directly into the aquifers from which it came, thus minimizing environmental impact and disposal cost.

CHAPTER 12
IN-SITU SHALE OIL RECOVERY

12.1 APPROACH

The contract calls for the evaluation of true and modified in-situ mining and retorting systems, in addition to the conventional mining and surface retorting schemes examined in the preceding chapters. Mining (if any is required) and retorting for in-situ shale oil recovery are combined into a single chapter, because they are much more dependent upon each other than are conventional mining and retorting systems.

Sources of information pertaining to in-situ oil shale recovery are, in general, less detailed than sources relating to conventional recovery methods, because actual field experience with in-situ methods is limited. Much of the information on in-situ technology is taken from:

i. Technical and Economic Study of the Modified In-Situ Process for Oil Shale, Fenix and Scisson, Inc., 1976.

ii. Oil Shale Tract C-b, Modifications to Detailed Development Plan, C-b Oil Shale Project, Ashland Oil, Inc. and Occidental Oil Shale, Inc., 1977.

iii. In Situ Recovery of Oil Shale, National Science Foundation, 1975.

Numerous U.S. Bureau of Mines (USBM) and Energy Research and Development Administration (ERDA) reports were also used and are listed in the bibliography.

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A brief description of the various true and modified in-situ mining and retorting schemes is presented in this chapter. Water usage during the mining and retorting sequences is also given. Finally, the various parameters influencing mine inflow are considered.

Mine inflow is an extremely important consideration in any in-situ retorting scheme. The amount of water tolerable within the retort zone is not currently known, but significant inflow will retard the retorting front or extinguish the flame front. The allowable inflow will probably also depend upon the retorting method. For instance, retorting by hot-gas injection may be able to withstand more inflow than retorting by an underground combustion process.

12.2 TRUE IN-SITU METHODS

True in-situ mining involves the retorting and recovery of shale oil through bore holes from a permeable oil shale zone. True in-situ methods require no underground mining and only limited surface facilities. A major obstacle encountered in using true in-situ techniques lies in the creation of sufficient permeability to allow retorting and recovery of the oil.

12.2.1 Creating Permeability

Unfractured oil shale generally exhibits very low natural permeabilities, on the order of 10^{-6} to 10^{-9} cm/sec. Various methods of increasing permeability to allow in-situ retorting have been tested or proposed. These include nuclear explosives, conventional explosives, electrolinking, hydraulic fracturing, accoustic fracturing, and solution mining. None of these methods have been tested extensively enough to begin production of shale oil on a commercial scale.

Of the various fracturing techniques proposed, underground nuclear explosives have perhaps the greatest potential to economically fracture a large mass of rock. It also probably has the greatest potential for environmental damage. In view of the current environmental concerns over the consequences of underground nuclear blasts, this technique remains an unlikely method of fracturing oil shale for in-situ retorting.

The Laramie Energy Research Center of the Energy Research and Development Administration has conducted fracturing tests in oil shale using electrolinking, hydraulic fracturing, and explosive fracturing with liquid NG1 (Sohns and Carpenter, 1966; Campbell, et al., 1970; Burwell, et al., 1973; Carpenter in Smith and Atwood (eds.), 1976). The tests were conducted at a site near Rock Springs, Wyoming, in oil shale at depths of less than 200 feet. The increase in permeability resulting from the various fracturing techniques was evaluated qualitatively by measuring air flows between selected wells. Preceding the fracturing experiments, most of the section of oil shale open to the wells was impermeable to air for pressures up to 100-120 psig. Electrolinking was found to have negligible effect upon increasing permeability. Hydraulic fracturing increased permeability, however, with no propping material the fractures healed upon the release of the fracturing pressure. Hydraulic fracturing with sand propping substantially increased permeability by creating horizontal fractures allowing communication between wells. The greatest increase in permeability was achieved by the detonation of liquid explosive implaced in the hydraulically induced fractures.

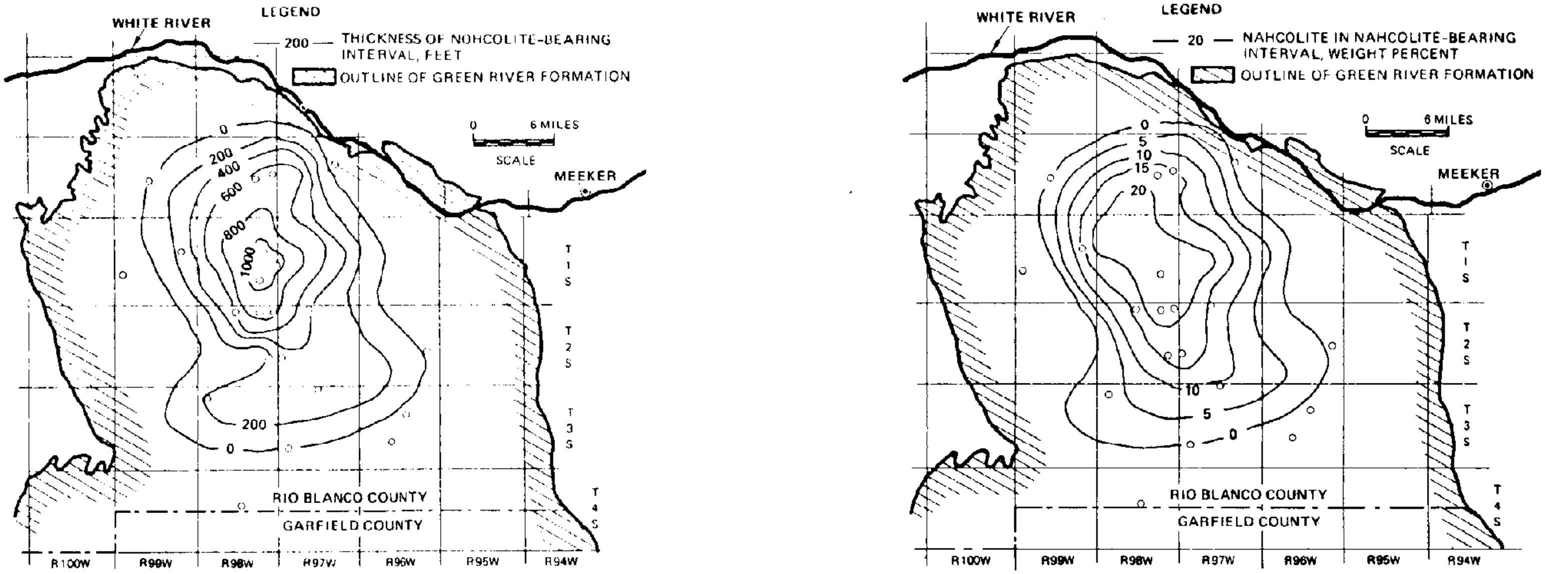
Evidence indicates that fracturing may be much more difficult in deeper wells. Tisot and Sohns (1970) report that induced permeability can be completely lost due to structural deformation of oil shale under high temperature and compressive stress. Depth may not be an important limiting factor with solution injection or in a nuclear chimney, however.

The permeability of the fractured zone will depend upon the porosity and the fracture spacing. Hanson and McKee (1975) give a method of estimating fracture permeability as a function of porosity and fracture distribution. The range of permeabilities necessary for successful in-situ retorting is not currently well defined, but the fractured zone can be expected to have permeabilities at least several orders of magnitude higher than the surrounding unfractured strata.

Much of the oil shale near the central portion of the Piceance Basin contains significant amounts of Nahcolite ($NaHCO_3$) which occurs both as nodules and bedded deposits. The greatest thickness of Nahcolite-bearing strata corresponds to the high resistivity zone extending upward from the Garden Gulch member of the Parachute Creek Formation. Figure 12-1 shows the thickness and weight percent Nahcolite within the Nahcolite-bearing interval. It may be possible to leach and recover the Nahcolite by injecting steam or hot liquid. The permeable zone created by the leaching could then be retorted to recover the shale oil.

12.2.2 Retorting and Recovery

In order to produce shale oil, kerogen in the raw shale must be decomposed into liquid and gaseous hydrocarbons. This can be accomplished by heating the kerogen to temperatures of 700° to $1,000^{\circ}$F. either by underground combustion or the injection of hot gases.


WHITE RIVER
LEGEND
200 THICKNESS OF NAHCOLITE-BEARING INTERVAL, FEET
OUTLINE OF GREEN RIVER FORMATION
0 6 MILES
SCALE
MEEKER
0
200
400
600
800
1000
200
0
T 1 S
T 2 S
T 3 S
T 4 S
RIO BLANCO COUNTY
GARFIELD COUNTY
R100W
R99W
R98W
R97W
R96W
R95W
R94W
WHITE RIVER
LEGEND
20 NAHCOLITE IN NAHCOLITE-BEARING INTERVAL, WEIGHT PERCENT
OUTLINE OF GREEN RIVER FORMATION
0 6 MILES
SCALE
MEEKER
0
5
10
15
20
10
5
0
T 1 S
T 2 S
T 3 S
T 4 S
RIO BLANCO COUNTY
GARFIELD COUNTY
R100W
R99W
R98W
R97W
R96W
R95W
R94W

A. Thickness of nahcolite-bearing interval.

B. Nahcolite content of nahcolite-bearing interval.

Source: Beard and Smith in Smith and Atwood (eds.), 1976. p.35.

Figure 12-1 THICKNESS AND NAHCOLITE CONTENT OF NAHCOLITE-BEARING INTERVAL

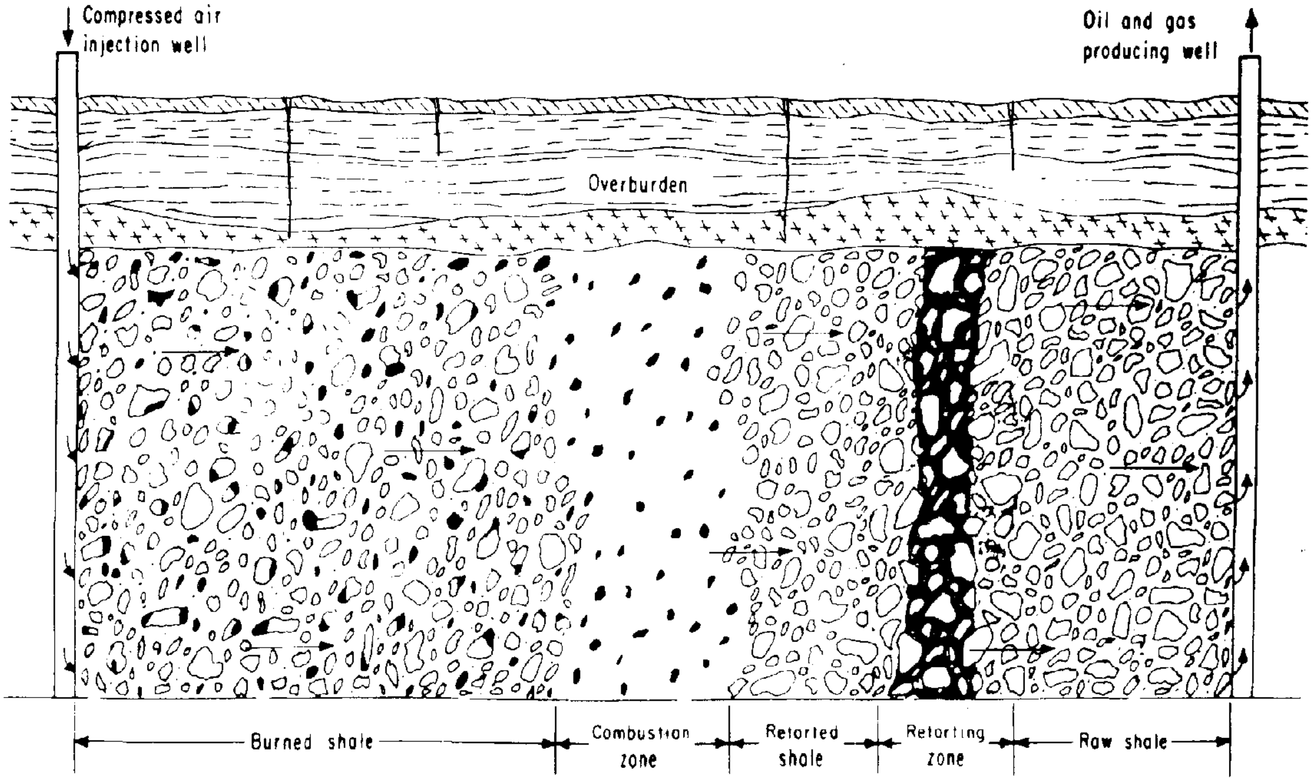
The Laramie Energy Research Center has successfully ignited and maintained an underground flame front at the test site near Rock Springs (Burwell, et al., 1970; Carpenter, et al., 1972; Burwell, et al., 1973). A gas-air mixture was injected into a central well within a five-spot pattern. Oil, water, and off gas was collected at surrounding withdrawal wells. Actual recovery of oil was small due to losses outside of the well pattern into the surrounding formation. The flame front was advanced horizontally cocurrent with the air flow as illustrated in Figure 12-2. Countercurrent air flow is also possible, however, it is less efficient in utilizing the heat generated by the combustion zone, and also consumes valuable light hydrocarbons rather than residual carbon left after the passage of the retort zone.

Schemes using injection of hot gases (up to 1,200° F) to cause retorting produce off gas with a higher BTU content ($\approx$ 750 BTU/ft.^{3}) than schemes using only air injection ($\approx$ 100 BTU/ft.^{3}). The higher BTU gas can be more readily used for additional energy production. The hot gases also help preheat the oil shale in front of the retort zone and allow easier recovery of the oil. Figure 12-3 illustrates a combination of solution mining to create permeability followed by hot gas injection to retort the oil shale.

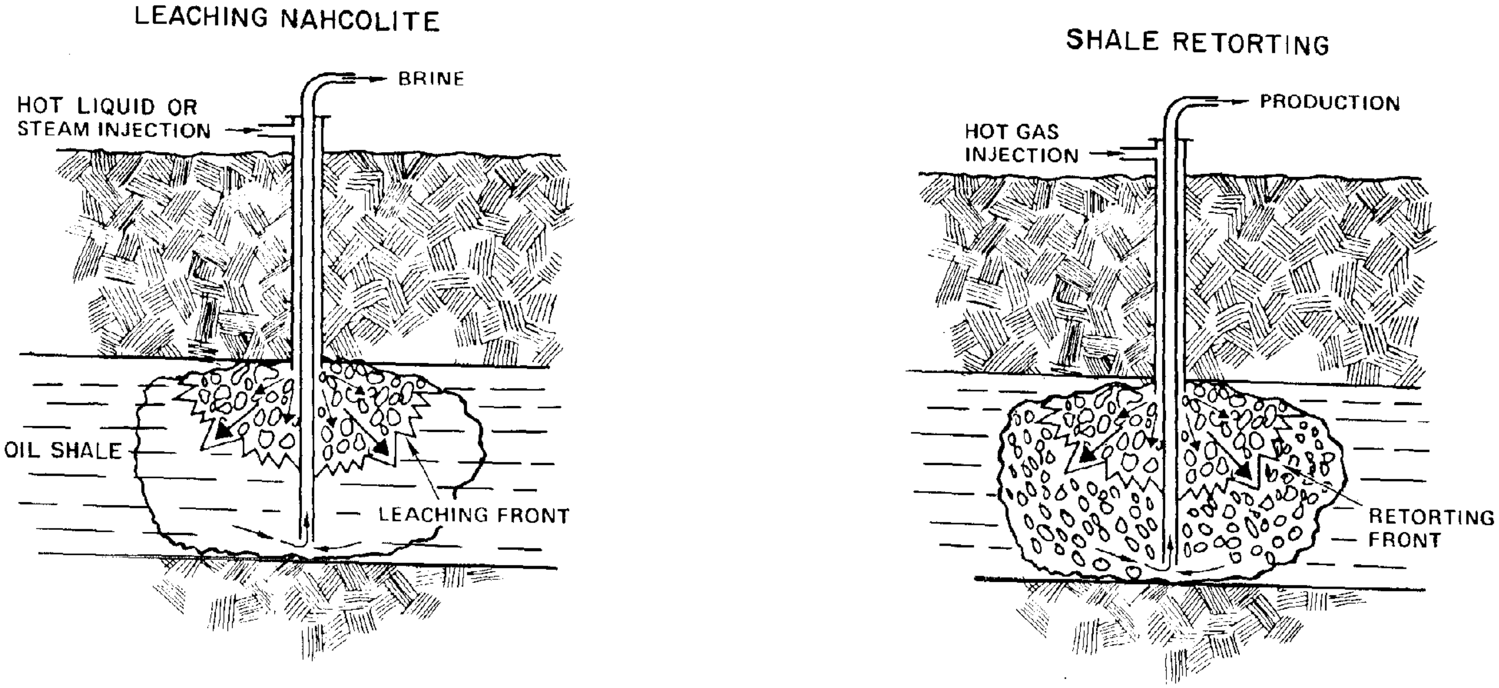
Several additional retorting schemes have been proposed. These include utilizing microwaves or ultrasonics to heat oil shale to retorting temperatures. Bacteria which ingest either the kerogen matrix or the inorganic rock material have also been considered for recovery of shale oil.

The products of oil shale retorting are crude oil, water, and off gas. The properties of the crude oil and the off gases have been studied using products from the Rock Springs site and

Figure 12-2 TRUE IN-SITU MINING WITH COCURRENT AIR FLOW


Compressed air injection well
Oil and gas producing well
Overburden
Burned shale
Combustion zone
Retorted shale
Retorting zone
Raw shale

After: Duvall and Jensen in Gary (ed.), July 1975, p. 188.


LEACHING NAHCOLITE
BRINE
HOT LIQUID OR STEAM INJECTION
OIL SHALE
LEACHING FRONT
SHALE RETORTING
PRODUCTION
HOT GAS INJECTION
RETORTING FRONT

After: Beard and Smith in Smith and Atwood (eds.), 1976, p. 35

Figure 12-3 NAHCOLITE LEACHING AND OIL SHALE RETORTING

the 150-ton retort at Laramie, Wyoming (Burwell, et al., 1969; Dockter and Harak, 1976). Experiments using the 150-ton retort indicate that about one barrel of water will be produced for each barrel of oil shale produced. This water includes the original moisture content of the oil shale plus water chemically made from the combustion process. It is of low quality with total dissolved solids concentrations expected to be in the range of 15,000 to 30,000 mg/l.

12.2.3 Resource Recovery

The percentage of potentially recoverable oil which can actually be recovered with true in-situ mining is not known. Three different efficiencies determine the final resource extraction. They are rubblizing efficiency, retort efficiency, and sweep efficiency. Rubblizing efficiency refers to the percentage of oil shale within the mining zone which is rubblized and available for retorting. It is assumed for this study that a technique is available which will rubblize 100% of the oil shale within the mining zone. The retort efficiency refers to the amount of oil which can be retorted from the rubblized oil shale. The 150-ton Laramie retort indicates that retorting efficiency will be 60-65% of Fischer Assay if favorable retort conditions are maintained. Sweep efficiency will depend upon how uniformly fractured the rubblized zone is and how evenly the active retorting front advances. Dougan, et al. (1970) estimate a sweep efficiency for a horizontal retort of 78%. Assuming 100% rubblization, 60% retorting efficiency, and 78% sweep efficiency yields a total resource extraction of 45%.

12.2.4 Water Usage

Water usage during true in-situ mining is dependent upon the fracturing and retorting method being used. Hydrofracturing requires large volumes of water for injection at high pressures. The injection rate will depend upon the length of the borehole open to the oil shale, the natural permeability, the injection pressure, and the well spacing. Water usage for hydrofracturing in a 30,000 BPD operation is difficult to estimate. Hydrofracturing tests at the Rock Springs site were conducted using injection rates of from 165 to 500 gallons per minute over a time of 10 to 30 minutes. The injection holes were sealed above and below the five-foot interval being injected. The five-spot well pattern at the test site was only 25 feet square, much smaller than a commercial size operation which may require thirty or more five-spot patterns, each about 300 feet square, being developed each year to retort a 200-foot thick oil shale zone. A very rough estimate of water use can be made by assuming that 30 wells per year are developed in a 200-foot thick oil shale zone and that hydrofracturing is done in 5-foot intervals. The injection time used at the Rock Springs site is increased by a factor of $(212 \text{ feet})^2$, the square of the radius of a 300-foot well pattern, divided by $(18 \text{ feet})^2$, the square of the radius of the Rock Springs well pattern. This factor increases the injection time from 30 minutes to 4,160 minutes for each 5-foot interval. Assuming the injection rate is 500 gpm for each interval, it will take approximately 8,050 AFY (5,000 gpm) to fracture a well field producing 30,000 BPD of shale oil. It is assumed that all injected water will be recovered.

Solution mining to create permeability will also require significant quantities of water. Again, the actual water volumes are diffiuclt to estimate. It is assumed that the zone to be leached will have a porosity of about 20% after solution mining of the Nahcolite. If brines reach a concentration of 30,000 mg/l total dissolved solids, it will require approximately 109 gallons of water to leach the

Nahcolite from 1 $ft.^3$ of oil shale or 145,866 AFY (90,600 gpm) to leach a volume of oil shale needed to sustain a 30,000 BPD production rate (50,000 tons/day at 60% retorting efficiency). The leachate will contain 16,300 tons/day of Nahcolite. It is interesting to note that in 1972 the total U.S. consumption of sodium compounds was about 23 million tons per year (U.S. Department of the Interior in Murray (ed.), 1974). Consumption is expected to increase to over 32 million tons per year by the year 2000. A single 30,000 BPD oil shale operation using solution mining to create permeability will produce about 6 million tons per year of Nahcolite or over 25% of the nation's consumption in 1972. The consumptive water use for solution mining will depend upon the maximum concentration attainable within the injected water and the method of removing the dissolved solids from the recovered brine.

No detailed plans for commercial true in-situ mining are currently available. More research into fracturing and retorting methods is needed before commercial production by in-situ methods can be considered feasible.

12.2.5 Water Production

When oil shale is retorted, water is produced from three sources. First, the shale is likely to be wet, even if the rock mass as a whole has been de-saturated. Second, the shale has a significant quantity of water trapped in the kerogen matrix. This can exceed 8% by weight of the shale. Upon retorting, this water is liberated. Third, any direct form of heating involves burning residual carbon (or, in a countercurrent system, product oil and gas) and this produces water of combustion.

On the other hand, the actual retorting reactions can be water consumptive. Under the right conditions the water gas equation

$$CO + H_2O \rightleftarrows CO_2 + H_2$$

can absorb significant quantities of water and improve the quality of the off gas at the same time. This is the reason that most in-situ and conventional direct mode systems inject steam as well as air into the retort chamber.

The net effect of this production and usage can be evaluated by reference to practical retorting experience. In their 150-ton above-ground retort at Laramie, ERDA has found that the relationship between oil and water produced in most of their experiments has been 1:1. That is equal quantities of product oil and water are produced. This evaluation is on the basis of a painstaking mass balance, and includes all water vapor in the off-gas, and all water remaining in the spent shale after retorting. (Dockter and Harak, 1976)

In the C-b Tract Modified DDP, Occidental Oil Company did not directly report a relationship between water and oil produced in the DeBeque retorts. However, back-analysis of the water balances presented suggest that they expect no more than one-half barrel of water per barrel of oil. It seems likely that this evaluation does not include water left in the retort, as it is reported that when the retorts are opened, water is steadily (if slowly) discharged from them. Also, in the trial retorts the off-gas was generally flared, and thus the water contained in this stream is discharged. In a commercial system this energy would be largely utilized, and thus the water would be retained in the processing system.

Conventional retorting systems have generally been reported as producing one-half barrel of water per barrel of oil, under similar open circuit conditions. Thus, for a closed circuit in-situ retort we will assume that one barrel of water is produced per barrel of oil, as this is the result of the only serious attempt to evaluate an actual retort operation.

12.2.6 Retorting Parameters for Dewatering Evaluation

In the absence of any current development plans using true in-situ methods in the Piceance Basin, hypothetical scenarios were considered for each site. In order to evaluate mine inflow, the important mining variables are mining zone height and expansion rates. These are given in Table 12-1 for each site. It is assumed that the same degree of fracturing and retorting efficiency is realized in both the upper and lower zones.

TABLE 12-1

MINE VARIABLES AFFECTING INFLOW FOR TRUE IN-SITU

Variable	Site 1	Site 2	Site 3
Heights (a)			
Zone Mined (ft)	200	140	180
Overall Resource Recovery	47%	47%	47%
Mine Expansion Rate ($mi.^2$/ yr.) for a 30,000 BPD mine (b)	.101	.145	.113

NOTES: (a) Heights based on thickness of Mahogany Zone

(b) The output of a 50,000 TPD convention mine/retort complex is 30,000 BPD assuming 100% efficiency of retorting. Thus, this production rate has been selected for in-situ methods for comparability.

12.3 MODIFIED IN-SITU METHODS

Modified in-situ mining requires limited underground mining to create void space. Subsequent blasting expands the remaining oil shale into the void space forming a mass of rubblized rock which can be retorted either vertically or horizontally. The rock removed to create the void space can be wasted or retorted on the surface.

12.3.1 Creating Permeability

Rubblization within a retort is an important aspect of modified in-situ methods. The uniformity of rubblization and the size of the particles formed directly affect the efficiency of the process. The magnitude of the permeability created by rubblization is a controlling factor in the volume of air or gas which can be circulated through the retort chamber and the ease with which the retorted oil can flow from the active retorting zone. Particle size determines, in part, the amount of residual carbon available to feed a flame front. Various rubblization techniques are considered by Fenix and Scisson (1976) in a study of modified in-situ mining. Occidental Petroleum (C-b Oil Shale Project, 1977) has developed methods for rubblization based upon their experience with actual trial retorts. Mobil Oil Company has also conducted research aimed at modified in-situ oil shale recovery.

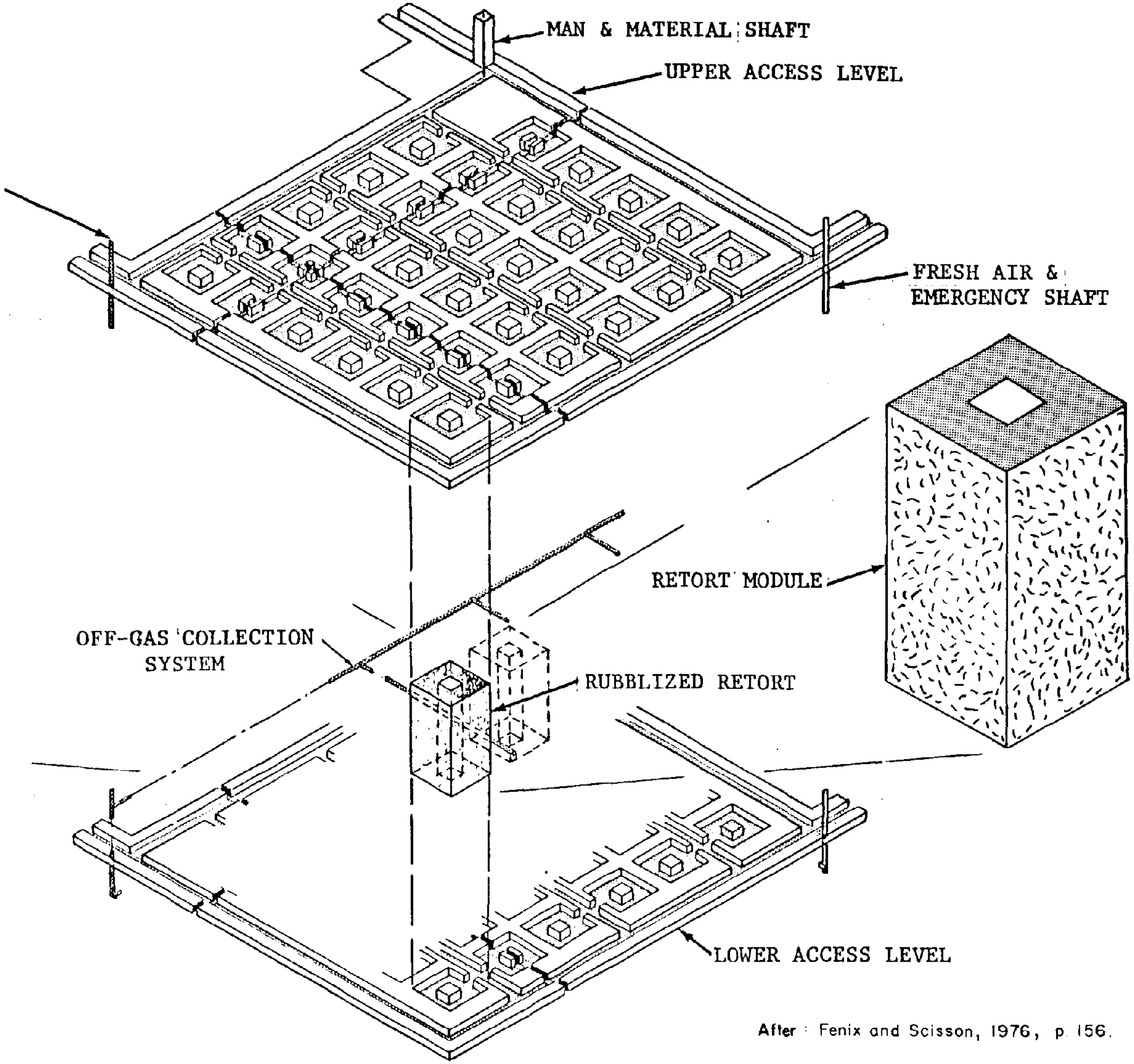
Prior to rubblization some percentage of the rock must be removed from the retort. Estimated values range from 10% to 35% of the retort volume. Mobil researchers estimate 30% to 35% removal may be necessary. Occidental has successfully operated trial in-situ retorts at Logan Wash with 20% to 25% removal to create voids. The rock removed may be either wasted or retorted on the surface, depending among other things upon the grade of the mined rock. Once the desired void space is created, the remaining oil shale is blasted and expanded into the void space to form a rubblized retort chamber. Figure 12-4 is an isometric view of a typical retort using room and pillar mining.

Another possible mining system utilizes tunnel boring and re-stabilization of burned-out retorts (Fenix and Scisson, 1976). An isometric view of this system is shown in Figure 12-5. The advantage to such a system is a greater resource recovery. Practical re-stabilization of burned retorts has not been demonstrated at present.

12.3.2 Retorting and Recovery

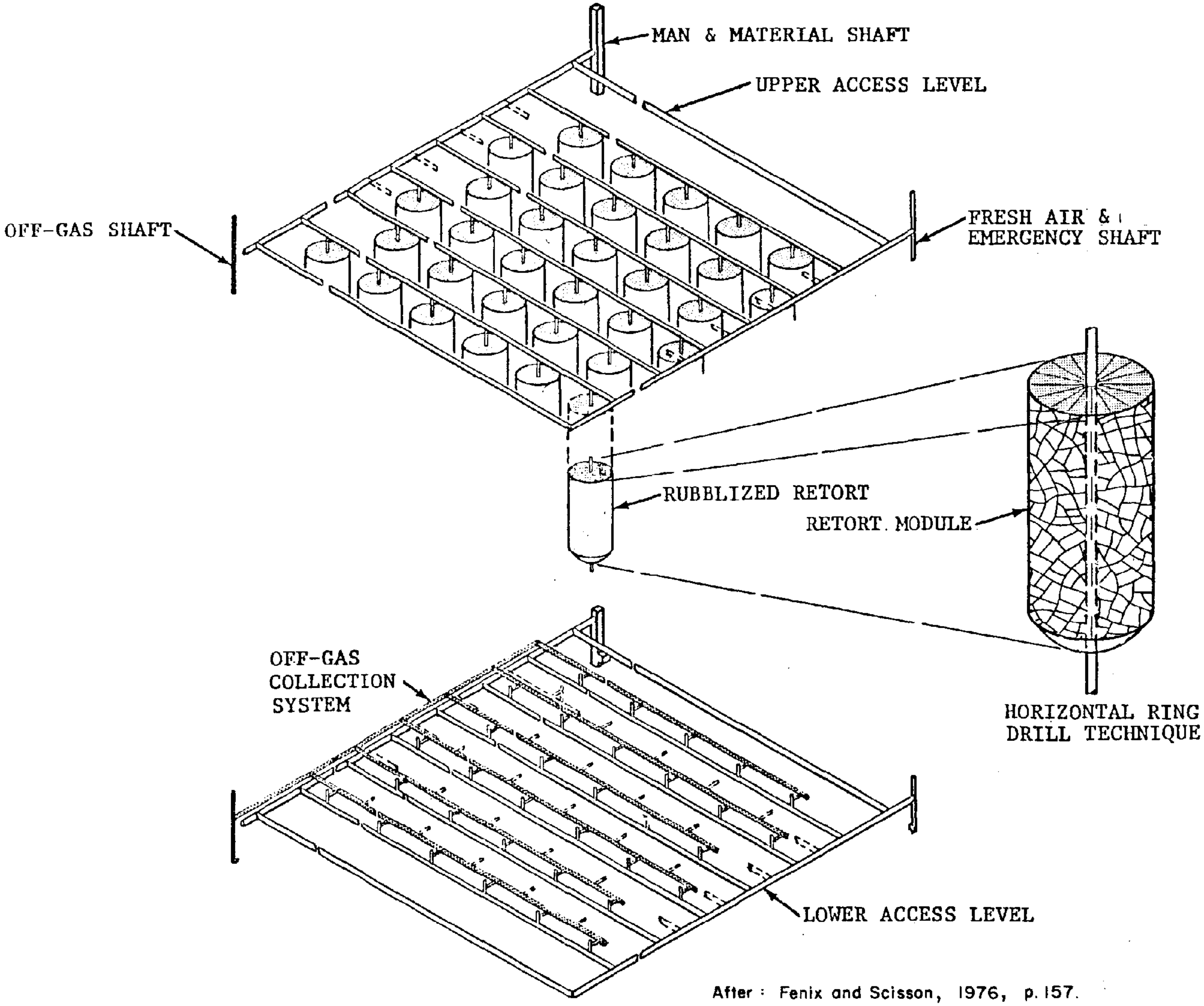
Modified in-situ retorting requires either underground combustion (with cocurrent or countercurrent air flow) or hot gas injection. The retorting front can progress vertically or horizontally, depending upon the retort design. Occidental, in their modified DDP (C-b Oil Shale Project, 1977) for Tract C-b, proposes vertical retorts with cocurrent air flow. The retorts are 200 x 200 feet square and 310 feet high. Steam is injected as a diluent with the air to improve the BTU quality of the off gas. Figure 12-6 illustrates a typical modified in-situ mining operation with cocurrent air flow and underground combustion. The system remains essentially the same for hot-gas injection with the exception that air is replaced by hot gas and a facility for producing the hot gas must be added.

In any retort, gas and the liquid product must be collected at an outlet. The gas can be treated and discharged into the atmosphere, flared, recycled back into the retort to control oxygen levels or used to fire low BTU boilers for steam and


MAN & MATERIAL SHAFT
UPPER ACCESS LEVEL
OFF-GAS SHAFT
FRESH AIR & EMERGENCY SHAFT
RETORT MODULE
OFF-GAS COLLECTION SYSTEM
RUBBLIZED RETORT
LOWER ACCESS LEVEL

After : Fenix and Scisson, 1976, p 156.

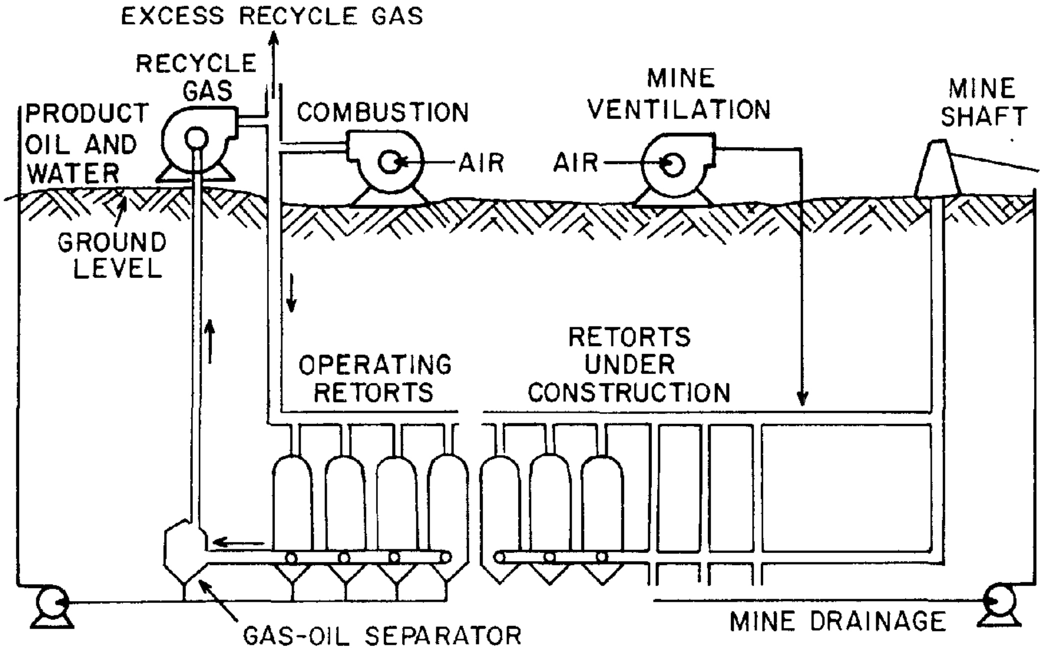
Figure 12-4 EXPLODED ISOMETRIC VIEW - ROOM & PILLAR MINING SYSTEM


MAN & MATERIAL SHAFT
UPPER ACCESS LEVEL
OFF-GAS SHAFT
FRESH AIR &
EMERGENCY SHAFT
RUBBLIZED RETORT
RETORT MODULE
HORIZONTAL RING
DRILL TECHNIQUE
OFF-GAS
COLLECTION
SYSTEM
LOWER ACCESS LEVEL

After: Fenix and Scisson, 1976, p. 157.

Figure 12-5 **EXPLODED ISOMETRIC VIEW – TUNNEL BORING MINING SYSTEM**

Figure 12-6 MODIFIED IN-SITU RETORTING SCHEME


EXCESS RECYCLE GAS
RECYCLE GAS
PRODUCT OIL AND WATER
COMBUSTION
AIR
AIR
MINE VENTILATION
MINE SHAFT
GROUND LEVEL
OPERATING RETORTS
RETORTS UNDER CONSTRUCTION
GAS-OIL SEPARATOR
MINE DRAINAGE

Source: Murray in Penner (ed.), 1974, p.281

power generation. The liquid product consists of oil and water which is pumped to the surface and separated.

Current information indicates that retorting must be conducted under relatively dry conditions, since excessive water inflow will extinguish the flame. This may not be true for hot-gas injection techniques. Data is not available on the maximum amount of water tolerable within an active retort chamber. This study assumes that the retort chamber must be desaturated and all inflow intercepted. Modified in-situ mining produces a highly permeable mass of spent shale containing large quantities of soluble solids. The range of permeabilities expected in the retort chamber during and after retorting is effectively infinite compared to the permeability of undisturbed oil shale. Surface retorting of the rock mined to create the void space is possible if the ore is of sufficient grade. Surface retorting can be accomplished by any of the methods described previously in this report.

12.3.3 Resource Recovery

Resource recovery from modified in-situ mining depends upon the size of the retorts, the thickness of the pillars separating retorts, and the retort efficiency. Exact retort dimensions are site-specific and must be developed using rock strength parameters and the thickness of the zone to be retorted.

The percentage of oil shale which is left in pillars or wasted determines the total resource recovery. Fenix and Scisson (1976) estimate that a mine utilizing small retorts (120 ft. square by 200 ft. high) will require 47% of the oil shale left as barrier pillars or wasted. Large retorts (180 ft. square by 500 ft. high) require 42% of the oil shale left or wasted. That is, 53% of the oil shale for small retorts and 58% for large retorts is available for retorting. They estimate this can be raised to 87% areal extraction if tunnel boring and re-stabilization techniques are used. Occidental (C-b Oil Shale Project, 1977) estimates an areal extraction of about 67% on Site 3 (C-b Tract).

Retorting efficiency is expected to be about 60% of Fischer Assay. Occidental has obtained efficiencies ranging from 30% to 50% in their trial retorts. It is assumed that a 60% efficiency is obtainable for large commercial size retorts. Assuming a 67% areal extraction and a 60% retorting efficiency gives a resource recovery of 40%, which is the value used by Occidental. Resource recovery can be improved if the rock mined to create the voids can be retorted. Occidental predicts resource recovery can be raised from 40% to 55% with surface retorting. The resource recoveries given by Occidental and Fenix and Scisson do not include the oil shale resource left as sill pillars. The overall resource recovery given by Fenix and Scisson will be reduced from 32% to 27% for small retorts and from 35% to 31% for large retorts. Occidental overall recovery would be 34% assuming 50-foot sill pillars.

Multi-level mining is possible using modified in-situ methods if a sufficient sill pillar is left between layers. Re-stabilization of burned-out retorts will also be helpful if not necessary for multi-level mining. Fenix and Scisson estimate needing a 40-foot sill pillar separating 200-foot high retorts and a 60-foot pillar separating 500-foot high retort chambers.

12.3.4 Water Usage

12.3.4.1 Mine Usage

Water usage can occur during both the mining-rubblization phase and the retorting phase. Room and pillar mining to create void space will essentially have the same water requirements presented in Chapter 7 scaled down to the smaller mining rate. Water requirements for a 30,000 BPD operation removing 28,000 tons/day of raw shale are shown in Table 12-2. The values shown in Table 15-2 were found by scaling water usage for a 50,000 TPD room and pillar mine (Table 7-1) to 28,000 TPD and increasing the water usage for drilling until the total water usage agreed with Oxy's estimate. The increase in drilling water usage is the result of the greater drilling capacity needed to rubblize the in-situ retorts.

TABLE 12-2

WATER USAGE IN A 30,000 BPD MODIFIED IN-SITU MINE USING ROOM & PILLAR METHODS

Ore Handling	90 AFY	(56 gpm)
Drilling	370 AFY	(229 gpm)
Bolting	24 AFY	(15 gpm)
Crushing	6 AFY	(4 gpm)
Miscellaneous	4 AFY	(3 gpm)
TOTAL	494 AFY	(307 gpm)

12.3.4.2 Retort Usage

Little or no water is needed for an underground combustion process using injection of air and/or recycled off gas. Schemes using dry heated gas will also require no water during retorting. Water is produced during the retorting process and is collected along with the oil product. Retort water is derived from two sources; interstitial water in the rubblized shale and chemically-made water from combustion. The quality of the retort water will be low averaging from 20,000 to 30,000 mg/l total dissolved solids. Data from the experimental 150-ton Laramie retort indicate that approximately one barrel of water is produced for each barrel of shale oil. In a commercial retort some portion of the water may be carried away with the off gas as vapor, thus reducing the volume of foul water which must be separated from the oil.

If all of the water produced during the retorting process is considered, that is liquid and gas, there will be an output of 1,409 AFY (875 gpm) of foul water in a 30,000 BPD operation. A non-combustion process will produce about 25% less retort water or about 1,057 AFY (656 gpm). These figures are very approximate due to the lack of data from actual in-situ operations.

Occidental's modified in-situ process uses steam injection to improve the BTU quality of the off gas. Oxy's water usage for a 30,000 BPD operation (from 57,000 BPD) results in 1,591 AFY (988 gpm) of water for retort steam and 188 AFY (117 gpm) of water for general facilities. The latter usage includes heating and process requirements. Oxy indicates that about 254 AFY (158 gpm) of water can be returned to the system as condensate although the exact source of this water is somewhat unclear. Presumably most of the 188 AFY used for general facilities can be returned with the additional 66 AFY coming from other sources. An additional water usage in Oxy's process is blowdown water for the steam generation plant. This will result in 85 AFY (53 gpm) of low quality water assuming a 30,000 BPD production.

12.3.5 Water Production

The comments made in Section 12.2.5 on water production during retorting also apply to the modified in-situ method. It is thus assumed that equal quantities of foul water and oil are produced by the system.

12.3.6 Mine Inflow Parameters

The only available development plan for modified in-situ mining is in the modified DDP for Tract C-b (C-b Shale Oil Project, 1977). The mining heights and expected resource extraction from this development plan are used for the Site 3 mining scenarios presented in this report. Fenix and Scisson (1976) is used as the source of mining parameters for Sites 1 and 2. The important mining parameters are shown in Table 12-3.

TABLE 12-3

MINE VARIABLES AFFECTING INFLOW FOR MODIFIED IN-SITU

Variable	Site 1 (a)		Site 2		Site 3 (c)
	Small Retort	Large Retort	Small Retort(a)	Large Retort(b)	
Heights					
Retort height(ft)	200	500	200	700	310
Pillar height(ft)	40	60	40	60(d)	50 (d)
Overall Resource Recovery	27%	31%	27%	22%	34%
Mine Expansion Rate (mi^2/yr) for a 30,000 BPD mine	.189	.068	.189	.056	.096

NOTES:
(a) From Fenix and Scisson, 1976.
(b) From Rio Blanco Oil Shale (Private Communication)
(c) From C-b Shale Oil Project, 1977.
(d) Estimated
(e) The comments made in Table 15-1 also apply to the above table

12.4 SUMMARY

A summary of the water usage and production within a true or modified in-situ mine is shown in Table 12-4. It is assumed that the retorting process will result in one barrel of foul water for each barrel of oil produced. Mine inflow is not considered.

TABLE 12-4

WATER PRODUCTION AND USE IN MINING AND RETORTING FOR A 30,000 BPD OPERATION (ACRE-FEET PER YEAR)

	True In-Situ (a)		Modified In-Situ (b)	
	Production	Use	Production	Use
Mining	-0-	2000	-0-	494
Retorting	1409	-0-	1409	-0-
Retorting with Steam Injection	1409	1864	1409	1864

NOTES: (a) Hydrofracturing followed by underground combustion.
(b) Room and Pillar mining followed by underground combustion.

CHAPTER 13
DEWATERING FLOWS FOR IN-SITU RETORTS

13.1 APPROACH

The evaluation of inflow to the in-situ retort is similar to that for conventional mining. For this reason, the rubblized retort and any ancillary workings or development will, in this chapter, be referred to as a "mine", despite the fact that (particularly) the true in-situ development has little in common with developments normally considered to be mines.

13.1.1 True In-Situ

The particular method of true in-situ mining chosen for the purpose of inflow analyses is fracturing by non-nuclear methods followed by retorting using underground combustion. This is the only scheme for which field data exists, being the scheme that ERDA is testing at Rock Springs, Wyoming. However, inflow of water to the fractured zone should be similar for all of the various fracturing methods. It is assumed that the retort zone must be dewatered before underground retorting can be initiated. Inflow is calculated by assuming that the entire fractured zone is at atmospheric pressure. The inflow to the fractured zone will be less than calculated if air or gas is injected into the zone at pressures greater than atmospheric due to lower pressure gradients in the surrounding rock mass.

13.1.2 Modified In-Situ

Inflow to a modified in-situ mine will be approximately the same as inflow to a conventional mine of similar dimensions.

Therefore, the method of analysis used in Chapter 8 is also used for modified in-situ mines. In this approach the rock around the proposed mine is divided into three zones, with different flow patterns typifying each:

i. Zone 1 is defined as all the material above the elevation of the mine roof. Flow is horizontal in this zone until the mine area is approached, whereupon the water increasingly moves downward toward the mine. In this zone, most of the water originates in desaturating the strata comprising the zone.

ii. Zone 2 is the material opposite the mine opening. Flow from this zone is horizontally toward the mine.

iii. Zone 3 is all the material beneath the elevation of the floor of the mine. Flow is horizontal until the mine is approached, and then gradually turns upward into the floor of the mine. Water comes primarily from the specific storage of the rock.

The actual modified in-situ mining schemes analyzed are patterned after those proposed for the various sites within the Piceance Basin.

13.2 INFLOW ANALYSES - SITE 1

13.2.1 Analyses Performed

The contract calls for the consideration of true and modified in-situ mining within the upper and lower oil shale zones. The various factors considered in developing meaningful mining scenarios are:

- a. Mining Types
    - i. True In-Situ
    - ii. Modified In-Situ
- b. Mine Location
    - i. Mahogany Zone
    - ii. R-4 Zone
    - iii. Multilevel from Mahogany to Blue Marker
- c. Subsidence
    - i. None
    - ii. Full (not considered for true in-situ)
- d. Production Rates
    - i. 30,000 BPD (Equivalent to 50,000 TPD conventional)
    - ii. 60,000 BPD (Equivalent to 100,000 TPD conventional)

Note that the production rates are given in terms of barrels of oil per day. A 30,000 BPD rate corresponds to conventionally retorting 50,000 tons/day of 25 GPD oil shale at 100% recovery. The actual tonnage of in-place oil shale which must be retorted by in-situ methods to yield 30,000 BPD is greater because retorting efficiency is only about 60%. The inflow to a true in-situ mine is comparable to a modified in-situ mine with similar dimensions and expansion rate. For this reason the results discussed below relate to both types of mining.

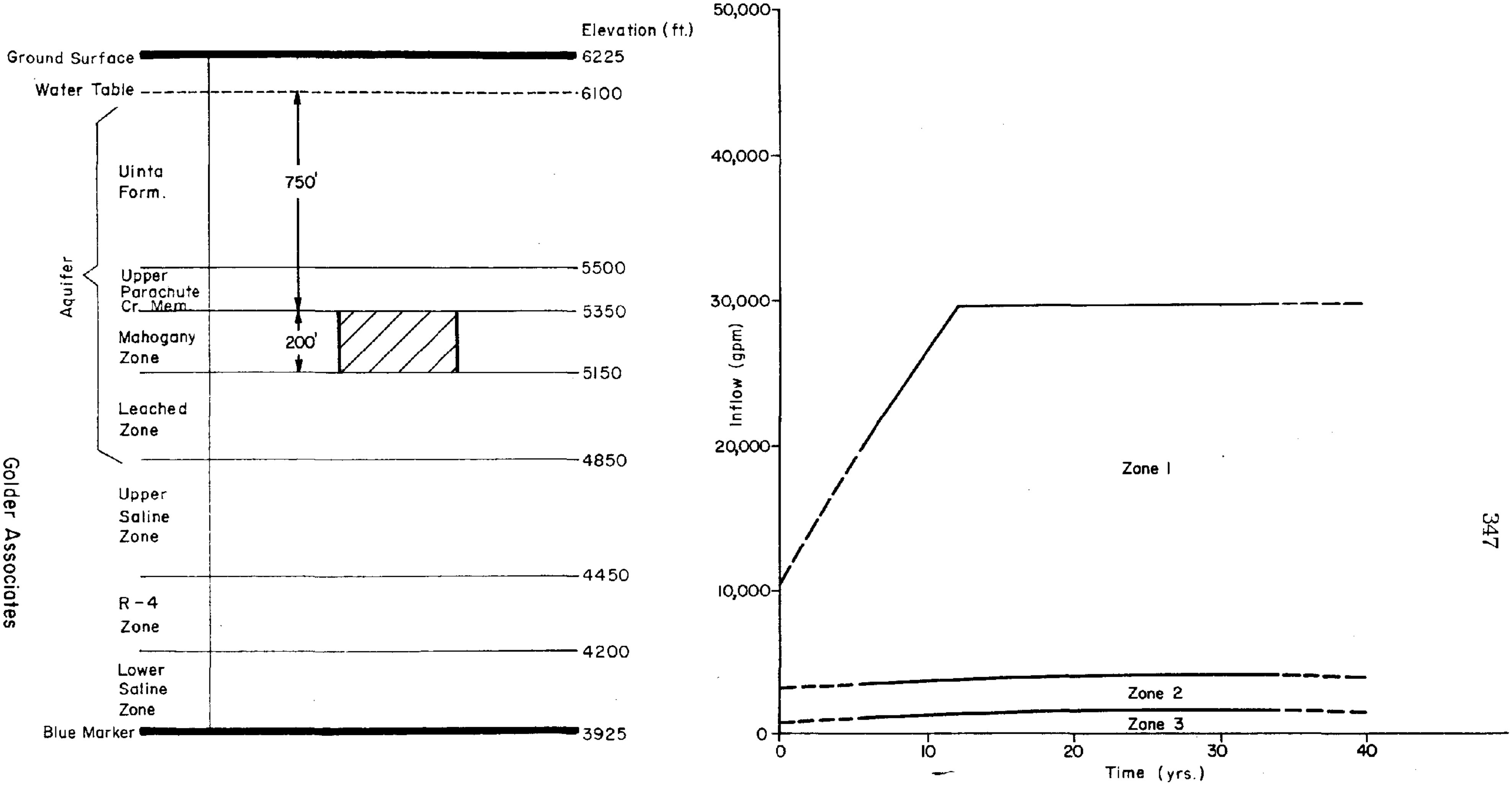
13.2.2 Results

Mine inflows were calculated for eighteen various mining scenarios on Site 1. Complete results are given in Appendix D. The geologic and hydrologic parameters in Figure 8-5 and the mine variables in Table 12-1 were used in the inflow computations. Four representative scenarios for development rates of 30,000 BPD are discussed below.

a. No Subsidence Single Pass Mining in the Mahogany Zone. Figure 13-1 gives a typical mine inflow for this scenario. Flow from Zone 1 increases rapidly as the mine expands until the water table drops to the roof of the mine, at which point flow becomes relatively steady. Zone 2 inflow remains constant over the entire 30-year mine life. Zone 3 inflow increases as the mine expands; however, its contribution to total inflow remains small.

b. No Subsidence Single Pass Mining in the R-4 Zone. Flows calculated for this case are the smallest of the four scenarios considered. Zone 1 flow increases with the expanding mine radius but remains very small due to low vertical permeabilities of the rock immediately overlying the mine. Zones 2 and 3 remain relatively constant throughout the 30-year mine life. The average inflow for thirty years is only two percent of that calculated in case a.

c. No Subsidence Multiple Pass. Although a greater interval of the aquifer is exposed, flows resulting from mining the entire interval between the Mahogany and the R-4 are reduced from the first case because of a much slower mine expansion rate. Zone 1 inflow increases as the mine expands while Zone 2 again remains constant. Inflow from Zone 3 is assumed to be zero since the mine floor is located on functionally impervious strata. The thirty year average inflow is approximately 42% of that for case a.



Time - yrs.	Radius - ft.	MINE INFLOW (gpm) Zone 1	(drain) Zone 1	Zone 2	Zone 3	Total
5	2896	15,192	-	2444	1131	18,770
10	4095	22,576	-	2444	1355	26,380
20	5792	25,311	-	2444	1503	29,260
30	7093	25,311	-	2444	1561	29,320

DESCRIPTION:

Mining Method Modified In-Situ, No Subsidence

Number of Passes 1

Location Mahogany

Mining Height 200 ft

Expansion Rate .189 mi^2/yr

Initial Radius 0

Mining Rate 50,000 ton/day

Figure 13-1 MINE INFLOW - SITE 1

d. Full Subsidence Single Pass in R-4 Zone. This case represents the maximum inflow rate. The mine and the caved rock overlying it become essentially a large radius well. Inflow for a caved mine in the R-4 zone is 60 times the inflow for the uncaved mine in the same location.

The inflow to a 60,000 BPD single-pass, no-subsidence mine located in the Mahogany Zone substantially increases from that of a 30,000 BPD mine due to the faster mine expansion rate. The water table will also drop to the roof of the mine at an earlier time with the higher mining rate.

Table 13-1 gives 30-year average inflows for all eighteen scenarios considered on Site 1.

TABLE 13-1

AVERAGE INFLOWS FOR 30 YEARS OF MINING - SITE 1

(ACRE-FEET PER YEAR)

Location	Rate*	Subsidence	True In-Situ	Modified In-Situ
Single Pass in Mahogany Zone	30,000 BPD	None	20,300	25,400
		Full	-	29,100
	60,000 BPD	None	25,300	37,500
		Full	-	41,700
Single Pass in R-4 Zone	30,000 BPD	None	100	500
		Full	-	30,000
	60,000 BPD	None	100	1,000
		Full	-	43,100
Multiple Pass for Maximum Extraction	30,000 BPD	None	11,600	10,600
		Full	-	15,700
	60,000 BPD	None	13,000	15,300
		Full	-	19,000

* 30,000 BPD is equivalent to 50,000 TPD assuming 25 GPT and 100% retorting efficiency.

13.3 INFLOW ANALYSES - SITE 2

13.3.1 Analyses Performed

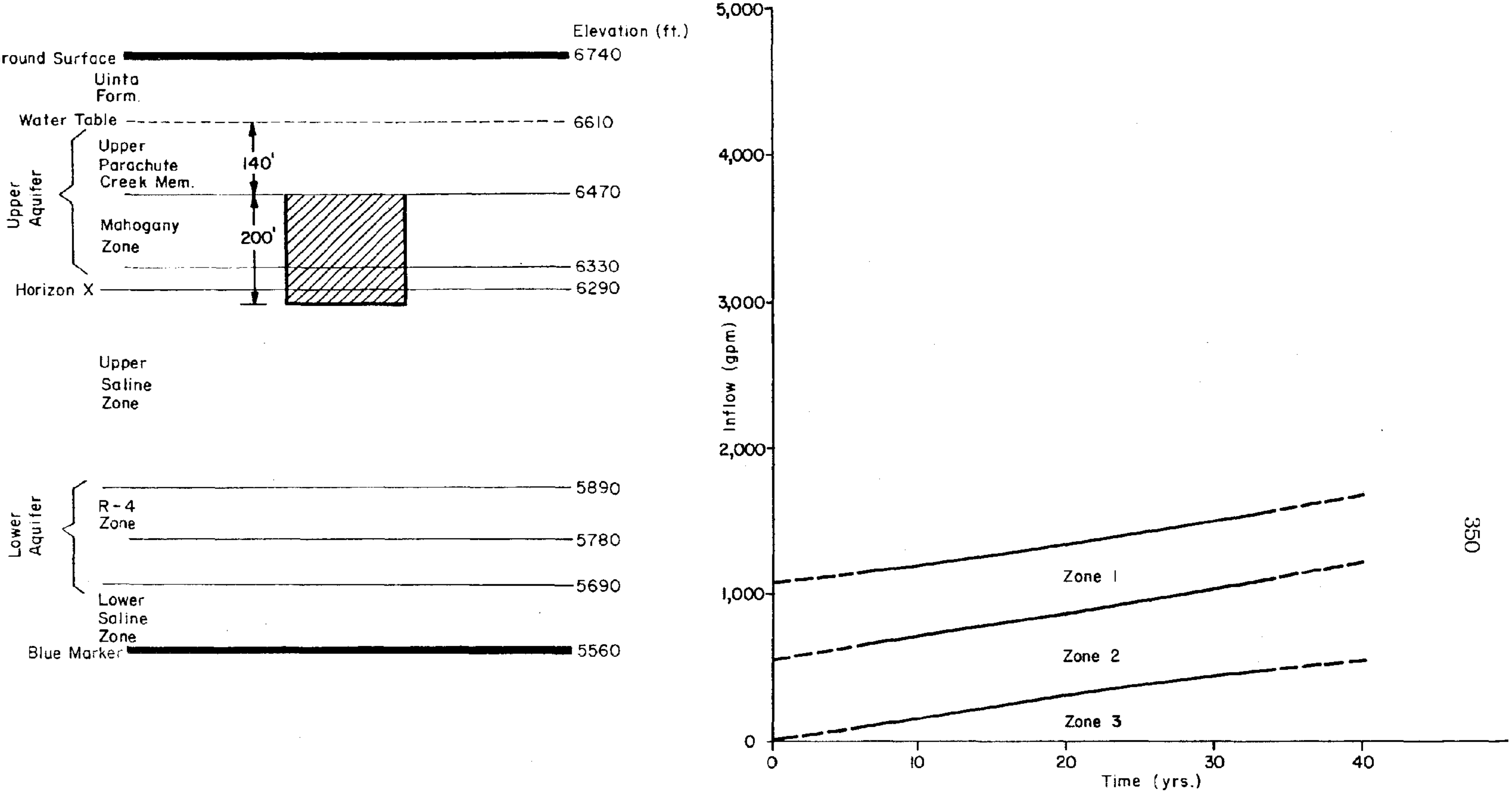
The contract called for consideration of true and modified in-situ mining in the upper and lower oil shale zones on Site 2. The following factors were considered in developing the mining scenarios.

- a. Mining Types
  - i. True In-Situ
  - ii. Modified In-Situ
- b. Mine Location
  - i. Mahogany Zone
  - ii. R-4 Zone
  - iii. Multi-level from Mahogany to Blue Marker
- c. Subsidence
  - i. None
  - ii. Full (not considered for true in-situ)
- d. Production Rates
  - i. 30,000 BPD (Equivalent to 50,000 TPD conventional)
  - ii. 60,000 BPD (Equivalent to 100,000 TPD conventional)

13.3.2 Results

Mine inflows were calculated for eighteen mine scenarios on Site 2. Complete results are found in Appendix D. Four representative cases for 30,000 BPD mines are discussed below. Figure 8-7 gives the geologic and hydrologic setting.

a. No Subsidence Single Pass Mining in the Mahogany Zone. Inflow to a mine within the Mahogany Zone is lower on Site 2 than on either Sites 1 or 3. A typical result is shown in Figure 13-2. The relatively small inflows occur because the Mahogany Zone is overlain by



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MINE INFLOW (gpm)

Time - yrs	Radius - ft.	Zone I	(drain) Zone I	Zone 2	Zone 3	Total
5	2896	481	-	564	78	1120
10	4095	481	-	564	156	1200
20	5792	481	-	564	311	1360
30	7093	481	-	564	467	1510

DESCRIPTION:

Mining Method Modified In-Situ, No Subsidence

Number of Passes 1

Location Mahogany

Mining Height 200 ft

Expansion Rate .189 mi^2/yr

Initial Radius 0

Mining Rate 50,000 ton/day

Figure 13-2 MINE INFLOW - SITE 2

a much thinner aquifer layer than at the other two sites. The Uinta sandstone is located above the water table over much of Site 2 and, therefore, does not contribute large volumes of stored water to mine inflow. The water table of the overlying aquifer reaches the roof of the mine a few years after mining commences.

b. No Subsidence Single Pass in the R-4 Zone. The R-4 zone on Site 2 is located within a very permeable aquifer zone confined above and below by relatively impermeable strata. Zone 1 inflow is low throughout the 30-year life of the mine. Inflow from Zone 2 forms the major portion of mine water. The Zone 3 contribution is, as usual, relatively small. Inflow for this case is almost seven times larger than for the Mahogany Zone mine in the preceding case.

c. No Subsidence Multiple Pass. Flows resulting from mining the entire resource interval are reduced from the previous case because the mine expansion rate is much slower. Zone 1 flow remains relatively constant after the water table reaches the mine roof, again only a short time after mining begins. Zone 2 contributes the greatest volume of inflow with Zone 3 assumed to be impervious and, therefore, contributing no inflow.

d. Full Subsidence Single Pass in the R-4 Zone. This case represents the highest inflow rate, however, the inflow is only about 9% greater than the case of non-subsidence mining in the R-4 zone. This increase is the result of greater inflow from Zone 1 due to caving. Zones 2 and 3 remain unchanged from the no-subsidence case.

Doubling the mining capacity from 30,000 to 60,000 BPD results in only a 16% increase in mine inflow. (Based upon a no-subsidence mine in the R-4 zone.)

Mine inflows averaged over 30 years are given in Table 13-2. These values represent all eighteen scenarios considered on Site 2.

TABLE 13-2

AVERAGE INFLOWS FOR 30 YEARS OF MINING - SITE 2

(ACRE-FEET PER YEAR)

Location	Rate*	Subsidence	True In-Situ	Modified In-Situ
Single Pass in Mahogany Zone	30,000 BPD	None	2,100	2,100
		Full	-	2,100
	60,000 BPD	None	2,700	2,700
		Full	-	2,700
Single Pass in R-4 Zone	30,000 BPD	None	13,000	14,200
		Full	-	16,400
	60,000 BPD	None	14,000	15,500
		Full	-	18,500
Multiple Pass for Maximum Extraction	30,000 BPD	None	12,600	13,400
		Full	-	13,400
	60,000 BPD	None	13,500	14,500
		Full	-	14,500

13.4 INFLOW ANALYSES - SITE 3

13.4.1 Analyses Performed

Site 3 is the final specific area to be considered for true and modified in-situ mining as called for in the contract. The following factors were considered in developing the appropriate mining scenarios.

a. Mining Types
    i. True In-Situ
    ii. Modified In-Situ
b. Mine Location
    i. Mahogany Zone
c. Subsidence
    i. None
    ii. Full (not considered for true in-situ)
d. Mining Rates
    i. 30,000 BPD (Equivalent to 50,000 TPD conventional)
    ii. 60,000 BPD (Equivalent to 100,000 TPD conventional)

13.4.2 Results

A total of six mining scenarios were considered on Site 3. Full results are given in Appendix D. Two representative cases are discussed below. They are again based upon modified in-situ mines with a capacity of 30,000 BPD. Figure 8-8 gives the important geologic and hydrologic parameters used to compute mine inflow.

a. No Subsidence Single Pass in the Mahogany Zone. Mine inflow calculated for this case is shown in Figure 13-3. Flow from Zone 1 comprises the majority of inflow, however, it remains relatively small due to low vertical permeabilities of the overlying strata. Flow from Zone 2 remains constant and Zone 3 increases slightly with continued expansion of the mine.

b. Full Subsidence Single Pass in the Mahogany Zone. Full subsidence results in an increase of 250% in mine inflow over the no-subsidence case above.

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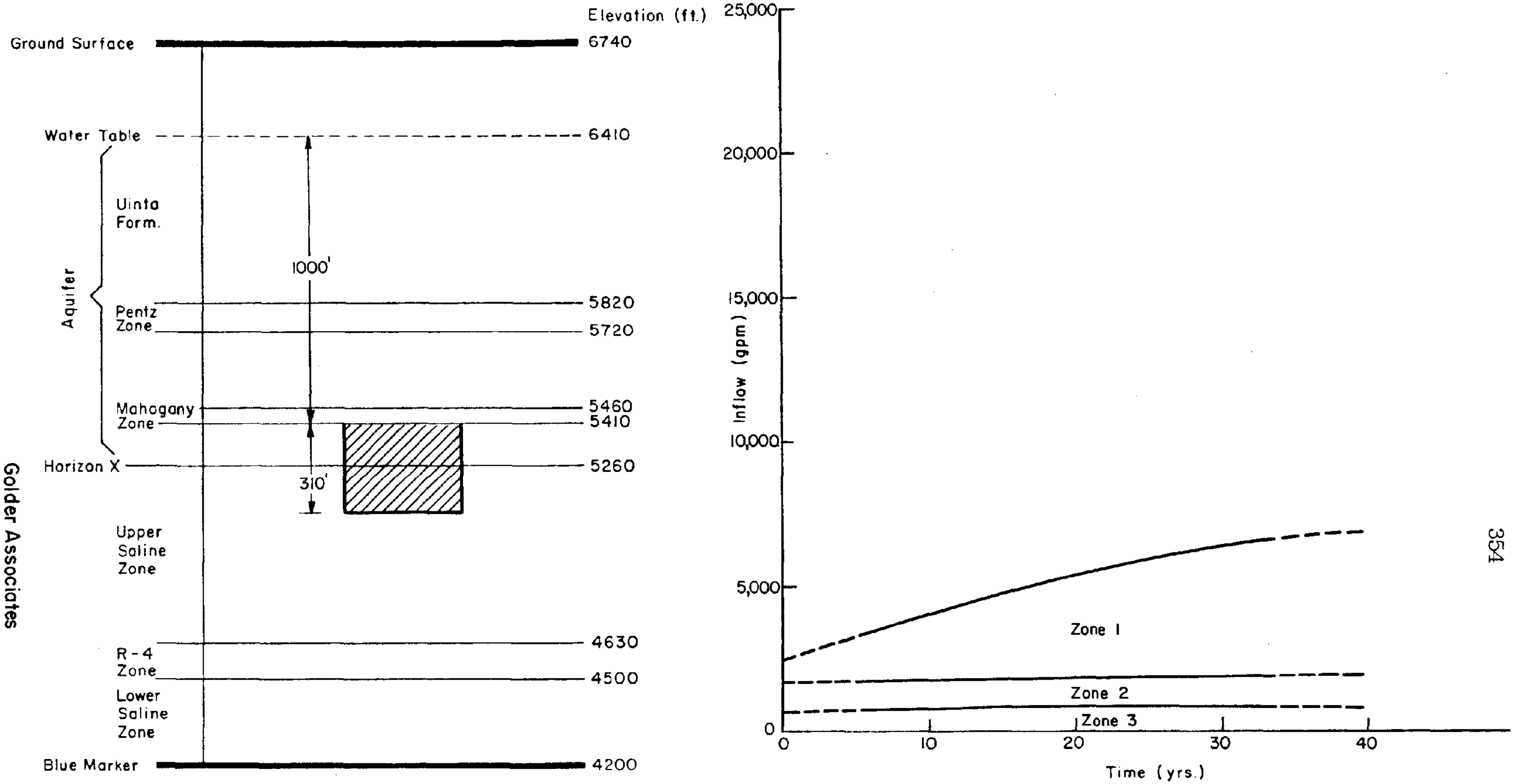


		MINE INFLOW (gpm)				
Time - yrs	Radius-ft.	Zone 1	(drain) Zone 1	Zone 2	Zone 3	Total
5	2064	1502	-	1038	729	3270
10	2919	2225	-	1038	841	4100
20	4128	3448	-	1038	911	5400
30	5055	4504	-	1038	937	6480

Figure 13-3 MINE INFLOW - SITE 3

DESCRIPTION:

Mining Method Modified In-Situ, No Subsidence

Number of Passes 1

Location Mahogany

Mining Height 310 ft

Expansion Rate .096 mi^2/yr

Initial Radius 0

Mining Rate 50,000 ton/day

> The increase is entirely due to flow from Zone 1 which is greatly enhanced by caving. Flow from Zones 2 and 3 remains unchanged from the uncaved case.

Doubling the mine capacity to 60,000 BPD increases inflow to an uncaved mine by about 40%. The majority of the increased flow comes from Zone 1 which is supplied by the extensive aquifer in the Uinta Formation.

Table 13-3 lists the 30-year average inflows for the six cases considered on Site 3.

TABLE 13-3

AVERAGE INFLOW FOR 30 YEARS OF MINING - SITE 3

(ACRE-FEET PER YEAR)

Location	Rate	Subsidence	True In-Situ	Modified In-Situ
Single Pass in Mahogany Zone	30,000 BPD	None	17,100	7,600
		Full	-	18,800
	60,000 BPD	None	29,100	10,500
		Full	-	34,300

CHAPTER 14

WATER MANAGEMENT SYSTEMS FOR IN-SITU SHALE OIL INDUSTRIES

This chapter complements Chapter 11, which presented water management systems for conventional developments. The logic of presentation is similar. First the elements of the entire process are reviewed to determine net water use, broken down by required water quality. Then the system which best meets the net water needs is developed. This involves optimizing water supply, treatment, and disposal choices. Finally, the role of mine inflow is evaluated, in the light of water demand for the entire system.

14.1 WATER USAGE

14.1.1 True In-Situ Methods

In order to evaluate true in-situ methods, we have selected the only technique which has been demonstrated to be technically feasible: the method developed by the Laramie Energy Research Center. As described in Chapter 12, this process involves drilling a network of holes, hydrofracturing and blasting the formation, and igniting from a central hole. Oil, gas, and water are collected from outer holes. Very few details are available for water, power, and other variables which might be applicable to a commerical scale plant. However, we have scaled up to this size as well as possible at this stage, and the resulting water use table for a 30,000 BPD operation is shown as Table 14-1. This table may be directly scaled to other production rates.

Two cases are presented. The base case is the water use and production in the simplest conceivable industry: where power is provided from off-site sources, and steam is not

TABLE 14-1
WATER USE - TRUE IN-SITU CASES
(IN ACRE-FEET PER YEAR FOR A 30,000 BPD OPERATION)

Use	Input				Output	Net
	Boiler	Service	Waste	Total		
Base Case						
Site Development	-	57	-	57	-	57
Retorting	-	-	-	-	1,409	(1,409)
Upgrading	81	-	-	81	81	0
Miscellaneous	-	254	-	254	-	254
BASE CASE TOTAL	81	311	-	392	1,490	(1,098)
Increments to Base Case						
Steam Injection to Retorts	1,779	-	-	1,779	-	1,779
On-Site Power Generation	570	1,020	-	1,590	-	1,590
TOTALS WITH BOTH INCREMENTS	2,430	1,331	-	3,761	1,490	2,271

NOTE: Much of the material in this table is estimated. It should only be used in conjunction with the material presented in the text.

injected into the retorts to upgrade the off-gas. (Note that there are no published proposals to use steam injection for this purpose in true in-situ systems). The base case actually produces water at the rate of 1,098 AFY (682 gpm) because of the water liberated from the oil shale during retorting. This is equivalent to production of 0.8 barrels of water per barrel of oil. The quality of the water thus gained is assumed to be very low.

The second case is a maximum water consumption case for this style of mining. On-site power generation is assumed, and steam is injected into the retorts in order to upgrade the off-gas and thus allow its use for power production. It must be appreciated that the power required and the steam input necessary to produce higher quality gas have both been estimated, based on very indirect information. In this maximum use case, there is a relatively small net water demand of 2,271 AFY (1,412 gpm), or 1.6 barrels of water per barrel of oil produced.

Note that in both cases the water use for hydrofracturing the rock has been ignored. It is assumed that the retorts will be dewatered either during or after hydrofracturing. Thus this water will be collected by the dewatering system, and effectively recycled without consumptive use.

14.1.2 Modified In-Situ Method

The modified in-situ method water use is similar to the true in-situ usage, with the addition of mining and rock disposal water uses. The data upon which the evaluation is based is somewhat better than for the true in-situ case, as it has been partly taken from actual experience in the Basin. The results of the use evaluation are presented on Table 14-2.

TABLE 14-2

WATER USE - MODIFIED IN-SITU CASES

(IN ACRE-FEET PER YEAR FOR A 30,000 BPD OPERATION)

Use	Input				Output	Net
	Boiler	Service	Waste	Total		
Base Case						
Site Development	-	57	-	57	-	57
In-Mine Use	-	398	96	494	-	494
Rock Transport	-	153	-	153	-	153
Retorting	-	-	-	-	1,409	(1,409)
Upgrading	81	-	-	81	81	-
Revegetation	-	61	-	61	-	61
Miscellaneous	-	254	-	254	-	254
BASE CASE TOTAL	81	923	96	1,100	1,490	(390)
Increments to Base Case						
Steam Injection to Retorts	1,779	-	-	1,779	-	1,779
On-Site Power Generation	570	1,020	-	1,590	-	1,590
TOTALS WITH BOTH INCREMENTS	2,430	1,943	96	4,469	1,490	2,979

NOTE: Much of the material in this table is estimated. It should only be used in conjunction with the material presented in the text.

The base case is a minimum water usage condition, and produces a net water surplus of 390 AFY (242 gpm). This is equivalent to the production of 0.3 barrels of water per barrel of oil. Quality of this water will be very low. The maximum usage, which would appear to be the method most likely to be used in a commerical operation, consumes a net quantity of 2,979 AFY (1,850 gpm) of water. This is equivalent to the use of 2.1 barrels of water per barrel of oil produced.

14.2 WATER ACQUISITION AND TREATMENT

The usage quantities in the maximum use situations above are relatively small. Even for a 120,000 BPD operation, the largest to be considered under this contract, the net use is about 12,000 AFY or 7,400 gpm. It is expected that this quantity of water can be extracted from the groundwater system at any site (Chapter 5). As shown in Chapter 11, this is the least expensive form of water acquisition, and so it will be used here.

The cost of groundwater was evaluated in Chapter 5. Mine inflow water has no cost as a water supply, for it must be pumped out of the retort in any case. Groundwater pumped from a well system will cost $30 per acre-foot at Sites 1 and 2, and $90 per acre-foot at Site 3 (1974 dollars).

The cost of treatment of water is a more significant question. For the treatment technique selected (reverse osmosis), it is necessary to distinquish between input quantity and output quantity, as there is a certain amount of water removed in the concentrate. Table 14-3 presents the quantity relationships and costs for treatment of water to the required use standards.

TABLE 14-3
TREATMENT OF WATER TO VARIOUS USE STANDARDS

Source of Water	Groundwater		Wastewater	
Proposed Use	Boiler	Service	Boiler	Service
Input Quantity (AF)	1.000	1.000	1.000	1.000
Filtrate Output (AF)	0.816	0.864	0.637	0.657
Concentrate (AF)	0.184	0.136	0.363	0.343
Cost Per AF of Input (1974 dollars)	$228	$163	$532	$474
Cost Per AF of Output (1974 dollars)	$280	$189	$836	$721

14.3 WATER DISPOSAL

Unlike the conventional processing situation, in in-situ processing there is no spent shale pile in which to dispose of low quality wastewater. We do not expect that the relevent regulatory agencies will allow wastewater re-injection into spent retorts or wastewater disposal on or in waste rock piles. In both cases it is almost certain that leaching would occur, finally resulting in degradation of surface and subsurface water supplies.

Further, as shown in Section 14.1 above, there is little requirement for wastewater in the process, so that a large quantity of generated foul water must be treated before it can be disposed of or reused.

Purification to discharge standards is discussed in Chapter 6. In summary, purification of 1 AF of input water produces 0.715 AF of drinking standard water, and 0.285 AF of very high TDS concentrate (estimated at 87,000 mg/l). The cost per acre-foot of input water is $586 in 1974 dollars.

In order to dispose of the concentrate, the most economical technique appears to be evaporation and solid disposal of the salts. As shown in Chapter 6, evaporation costs about $690 per acre-foot. It is assumed that the salts could be sold for at least enough to cover transport costs, and so no cost is included for salt disposal.

In the event of an excess of purified water, it could be directly discharged. However, as legal title to the water is vested in the company developing it, this water could be sold, perhaps for the equivalent of the cost of drinking water in the Basin. This cost can be estimated by evaluating the cost of obtaining and purifying groundwater, which is $310 at Sites 1 and 2, and $370 at Site 3 per acre-foot of water supplied. Accordingly, the value of drinking water has been set in this study at $300/AF (1974 dollars). This is equivalent to $0.92 per 1,000 gallons, which is in line with water supply prices in the region.

14.4 WATER MANAGEMENT SYSTEMS

Four use cases have been considered in the evaluation of overall water management systems:

i. True in-situ processing, minimum water demand.
ii. True in-situ processing, maximum water demand.
iii. Modified in-situ processing, minimum water demand.
iv. Modified in-situ processing, maximum water demand.

The systems presented have assumed that any water input required will be obtained from groundwater resources. It has also been assumed that the costs of processing waste water to drinking water, boiler water, and service water are the same. This does not do significant violence to the data presented in Sections 14.2 and 14.3 above. Note that in all cases a 30,000 BPD industry is assumed. All results in this section are directly scalable.

14.4.1 True In-Situ Processing, Minimum Water Demand

The water management system for true in-situ processing with minimum water demand is shown in Figure 14-1. The system is self sufficient in water, actually producing a small pure water output of 651 AFY (404 gpm). This is equivalent to the production of 0.5 barrels of water per barrel of oil.

The cost of the water-related activities in the figure is as follows (1974 dollars):

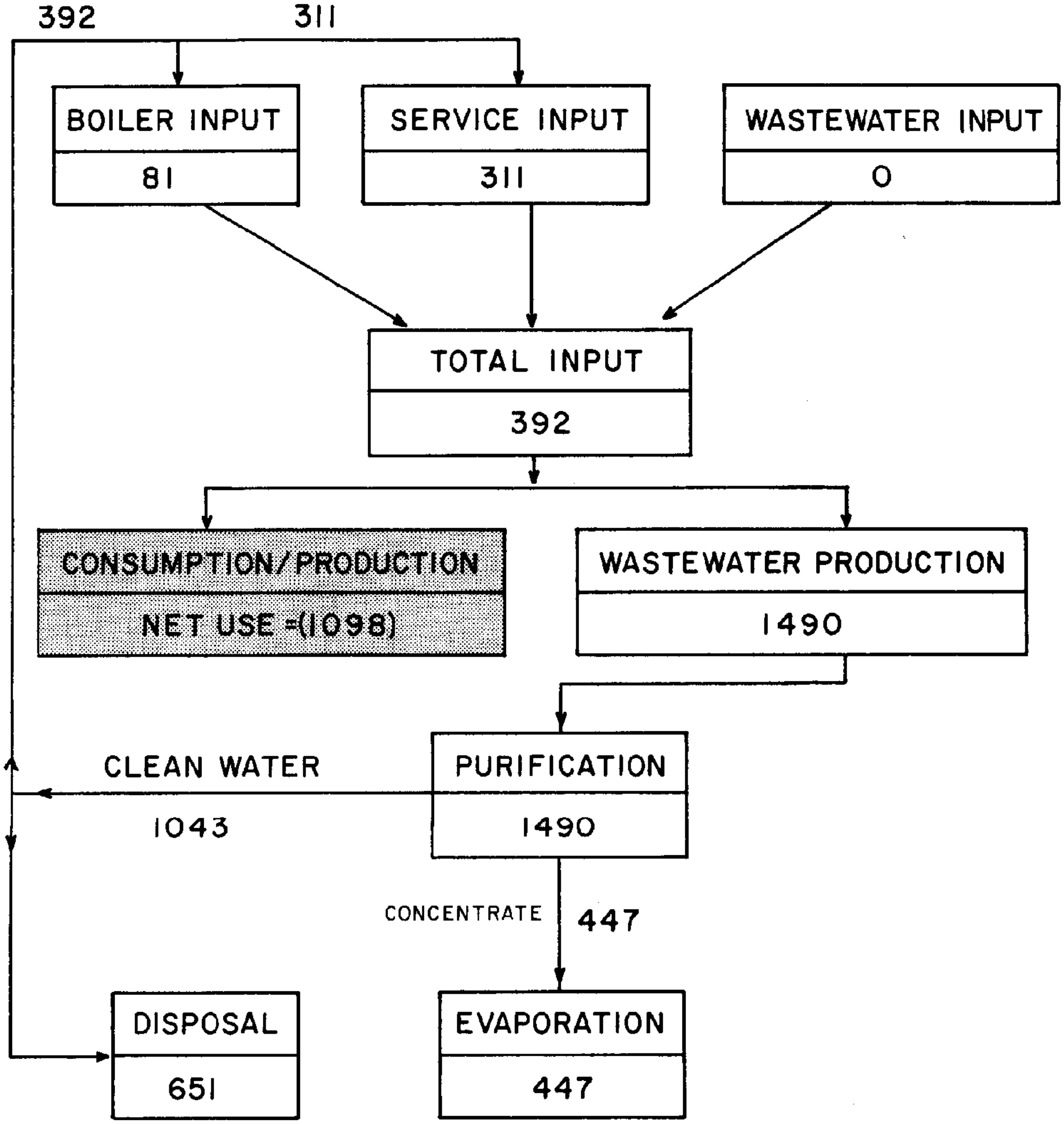
Purification	1,490 AFY @ $586/AF =	$873,000/yr.
Evaporation	447 AFY @ $690/AF =	$308,000/yr.
Disposal	651 AFY @ $(300)/AF =	$(195,000)/yr.
TOTAL WATER-RELATED COST FOR 30,000 BPD	=	$ 986,000/yr.
Cost per barrel of oil	=	$ 0.09/BBL

The figures are the minimum which the developer could realize under the assumptions made in the study above. It must be noted, however, that there would be significant water usage external to the project to generate power. Additionally, the off-gas generated in the project would probably have to be flared, with considerable loss of hydrocarbon resource.

14.4.2 True In-Situ Processing, Maximum Water Demand

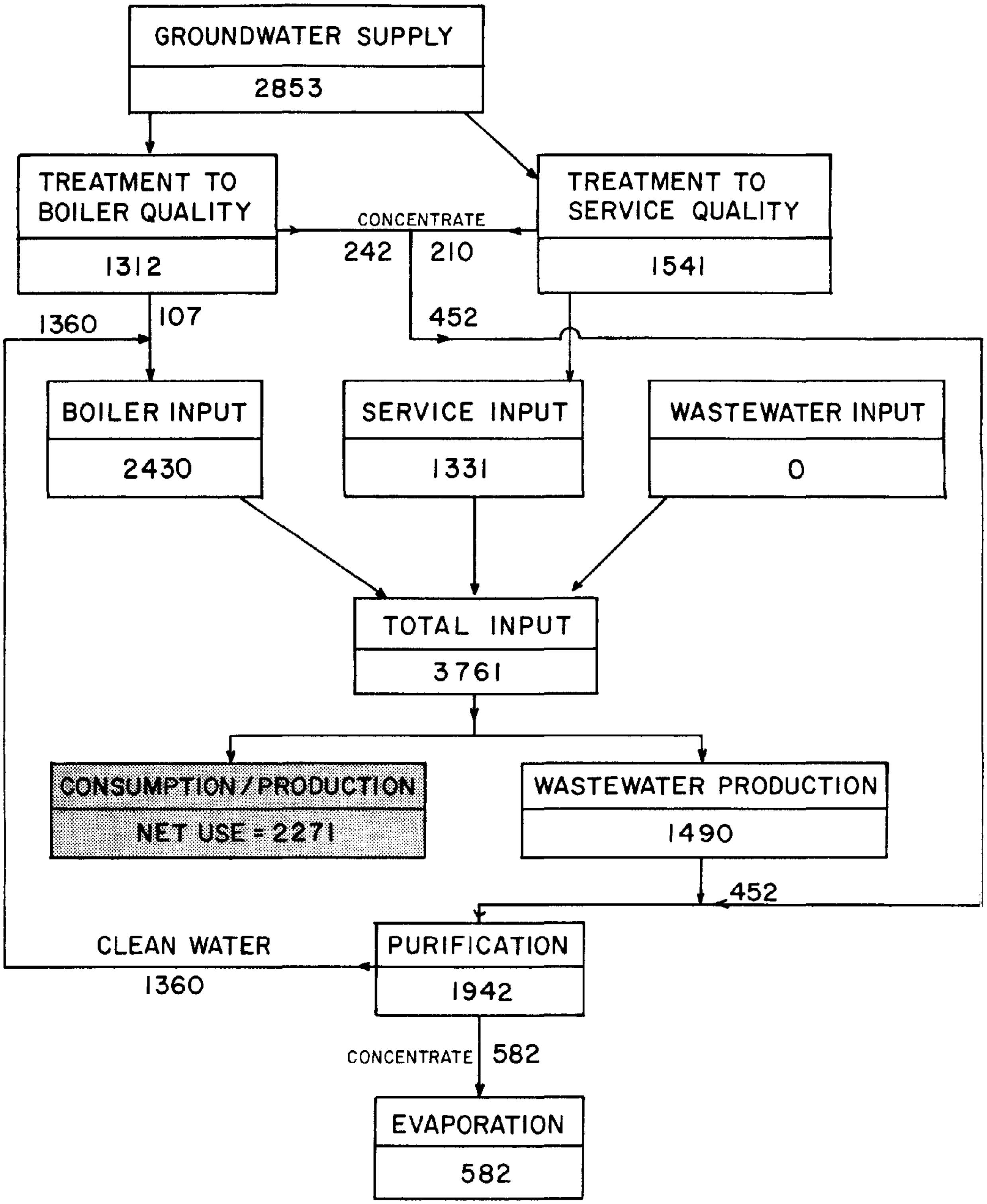
The water management system for true in-situ processing with maximum water demand is shown in Figure 14-2. The system is moderately consumptive of water, requiring the input of 2,853 AFY (1,767 gpm) of water. This is equivalent to 2.0 barrels of water per barrel of oil produced.

Figure 14-1 WATER MANAGEMENT SYSTEM FOR TRUE IN-SITU PROCESSING – MINIMUM WATER DEMAND


392
311
BOILER INPUT
81
SERVICE INPUT
311
WASTEWATER INPUT
0
TOTAL INPUT
392
CONSUMPTION/PRODUCTION
NET USE =(1098)
WASTEWATER PRODUCTION
1490
CLEAN WATER
1043
PURIFICATION
1490
CONCENTRATE
447
DISPOSAL
651
EVAPORATION
447

Notes:
i. All flows are in acre-feet/year.
ii. Flows are for a 50,000 TPD/30,000 BPD operation.

Figure 14-2 WATER MANAGEMENT SYSTEM FOR TRUE IN-SITU PROCESSING-MAXIMUM WATER DEMAND


GROUNDWATER SUPPLY
2853
TREATMENT TO BOILER QUALITY
1312
TREATMENT TO SERVICE QUALITY
1541
CONCENTRATE
242
210
452
1360
107
BOILER INPUT
2430
SERVICE INPUT
1331
WASTEWATER INPUT
0
TOTAL INPUT
3761
CONSUMPTION / PRODUCTION
NET USE = 2271
WASTEWATER PRODUCTION
1490
452
CLEAN WATER
1360
PURIFICATION
1942
CONCENTRATE
582
EVAPORATION
582

Notes: i. All flows are in acre-feet/year.
ii. Flows are for a 50,000 TPD/30,000 BPD operation.

The cost of the water-related activities in the figure is as follows (1974 dollars):

Treatment to boiler quality	1,312 AFY	@ $228/AF	= $ 300,000/yr.
Treatment to service quality	1,541 AFY	@ $163/AF	= $ 251,000/yr.
Purification of waste water	1,942 AFY	@ $586/AFY	= $1,138,000/yr.
Evaporation of condensate	582 AFY	@ $690/AF	= $ 402,000/yr.
TOTAL WATER-RELATED COSTS FOR 30,000 BPD			= $2,091,000/yr.
Water-related cost per barrel of oil			= $ 0.19/BBL

In addition to the above there may be some costs of groundwater acquisition. This question is determined by reference to the mine water inflow (see Section 14.5 below).

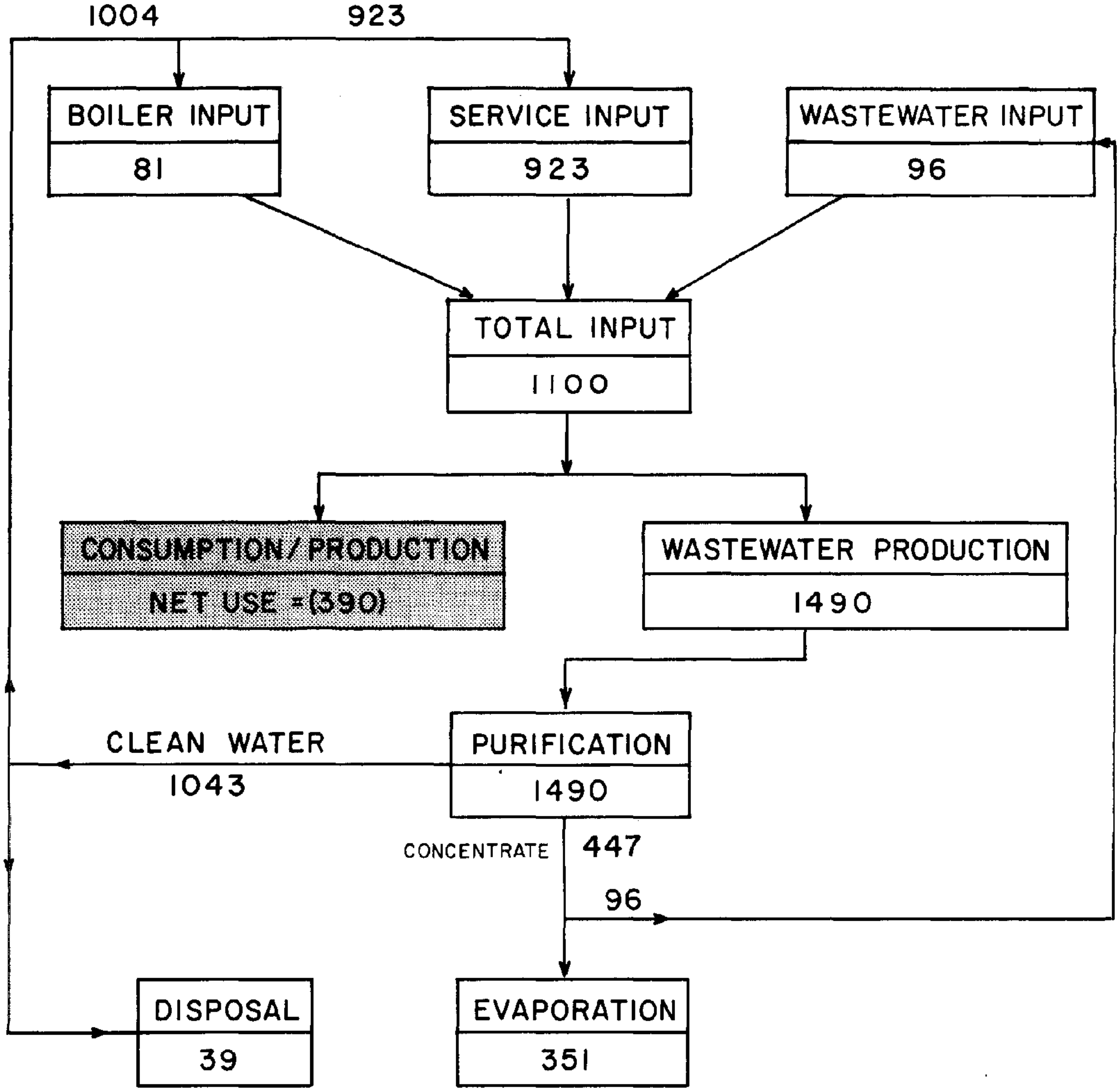
It is expected that the system on which the above evaluation is based will be close to that which would actually be utilized in a true in-situ development. This is because on-site power production using retort off-gas is almost certain to be very attractive.

14.4.3 Modified In-Situ Processing, Minimum Water Demand

The water management system for modified in-situ processing with minimum water demand is shown in Figure 14-3. This system is similar to the minimum true in-situ condition, except that water usage is higher due to mining activities and rock disposal. Despite this the system produces a slight output of pure water which is available for disposal.

The cost of the water-related activities in the figure is as follows:

Figure 14-3 WATER MANAGEMENT SYSTEM FOR MODIFIED IN-SITU PROCESSING – MINIMUM WATER DEMAND


1004
923
BOILER INPUT
81
SERVICE INPUT
923
WASTEWATER INPUT
96
TOTAL INPUT
1100
CONSUMPTION/PRODUCTION
NET USE =(390)
WASTEWATER PRODUCTION
1490
CLEAN WATER
1043
PURIFICATION
1490
CONCENTRATE
447
96
DISPOSAL
39
EVAPORATION
351

Notes: i. All flows are in acre-feet/year.
ii. Flows are for a 50,000 TPD/30,000 BPD operation.

Purification 1,490 AFY @ $586/AF = $ 873,000/yr.
Evaporation 351 AFY @ $690/AF = $ 242,000/yr.
Disposal 39 AFY @ $(300)/AF = $(12,000)/yr.
TOTAL WATER-RELATED COST FOR 30,000 BPD = $1,104,000/yr.
Water-related cost per barrel of oil = $ 0.10/BBL

As in the minimum true in-situ case, this is the minimum water use situation which a developer could expect.

14.4.4 Modified In-Situ Processing, Maximum Water Demand

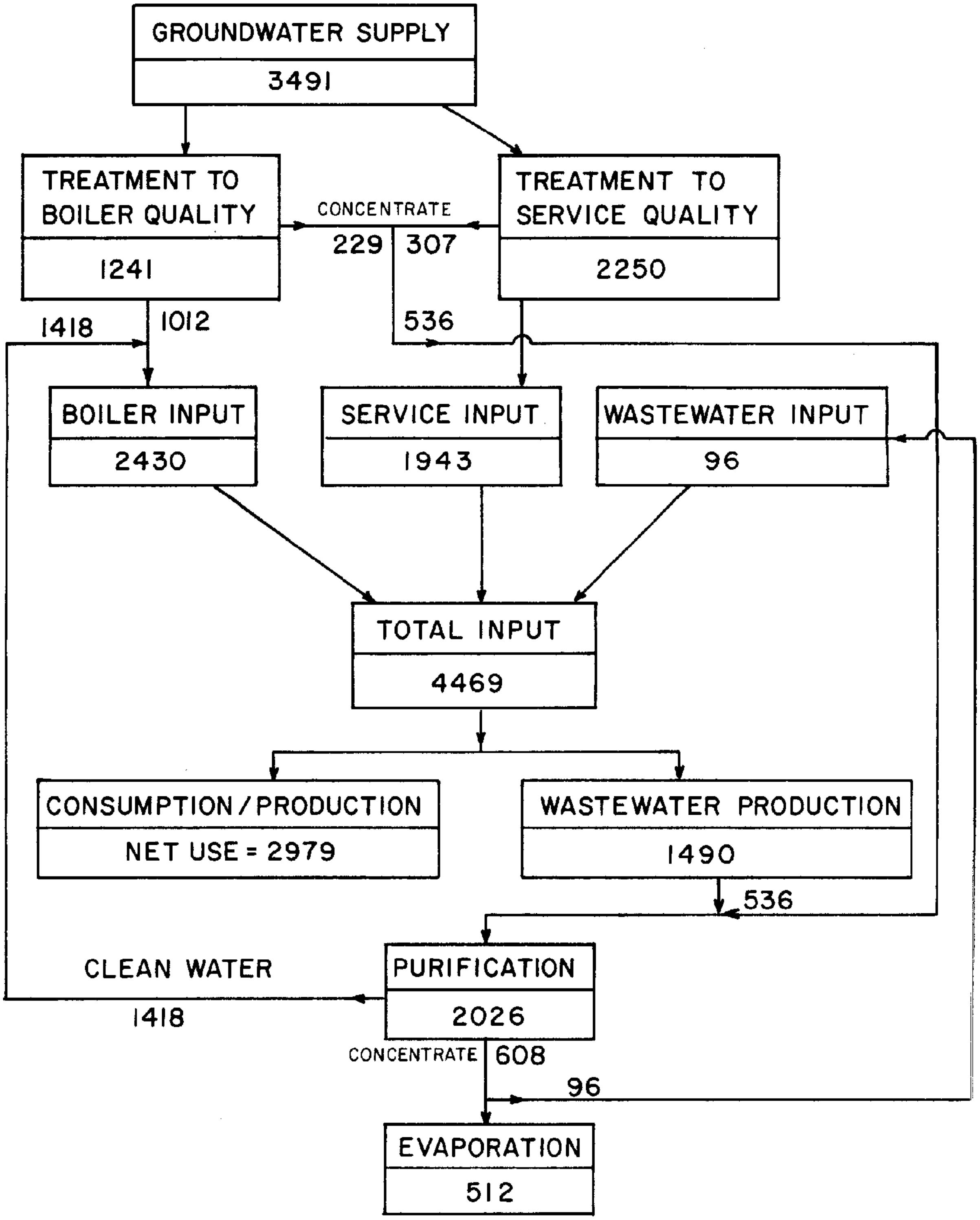
The water management system for modified in-situ processing with maximum water demand is shown in Figure 14-4. This is the most water consumptive of the in-situ systems evaluated, and requires input of 3,491 AFY (2,168 gpm) of water. This is equivalent to 2.5 barrels of water per barrel of oil produced.

The cost of the water-related activities in the figure is as follows:

Treatment to boiler quality 1,241 AFY @ $228/AF = $ 283,000/yr.
Treatment to service quality 2,250 AFY @ $163/AF = $ 337,000/yr.
Purification of waste water 2,026 AFY @ $586/AF = $1,187,000/yr.
Evaporation of condensate 512 AFY @ $690/AF = $ 353,000/yr.
TOTAL WATER-RELATED COSTS FOR 30,000 BPD PRODUCTION = $2,190,000/yr.
Water-related cost per barrel of oil = $ 0.20/BBL

In addition to the above there may be some costs of groundwater acquisition (see Section 14.5 below). It is expected that the maximum water demand system will be used in a commercial development of this type to optimize power production costs and off-gas use.

Figure 14-4 WATER MANAGEMENT SYSTEM FOR MODIFIED IN-SITU PROCESSING – MAXIMUM WATER DEMAND


GROUNDWATER SUPPLY
3491
TREATMENT TO BOILER QUALITY
1241
TREATMENT TO SERVICE QUALITY
2250
CONCENTRATE
229
307
536
1418
1012
BOILER INPUT
2430
SERVICE INPUT
1943
WASTEWATER INPUT
96
TOTAL INPUT
4469
CONSUMPTION / PRODUCTION
NET USE = 2979
WASTEWATER PRODUCTION
1490
536
CLEAN WATER
1418
PURIFICATION
2026
CONCENTRATE
608
96
EVAPORATION
512

Notes: i. All flows are in acre-feet / year.
ii. Flows are for a 50,000 TPD / 30,000 BPD operation.

14.5 MINE INFLOW CONSIDERATIONS

14.5.1 Quantity and Quality of Inflow

Mine inflow depends primarily upon the location, height, expansion rate, and degree of subsidence for a particular mine. Thus, the inflow to a conventional or an in-situ mine can be approximately equal if the above parameters are similar in both mines. Inflow rates from the 42 analyses of in-situ mines (see Chapter 13) are shown in Figure 14-5. Most inflow rates fall in three categories.

i. Category A. Inflows in the range 0-4,000 AFY (0-2,500 gpm). These flows occur in deep single pass mines on Site 2.

ii. Category B. Inflows in the range 12,000-36,000 AFY (7,400-22,400 gpm). This category contains the majority of calculated inflows.

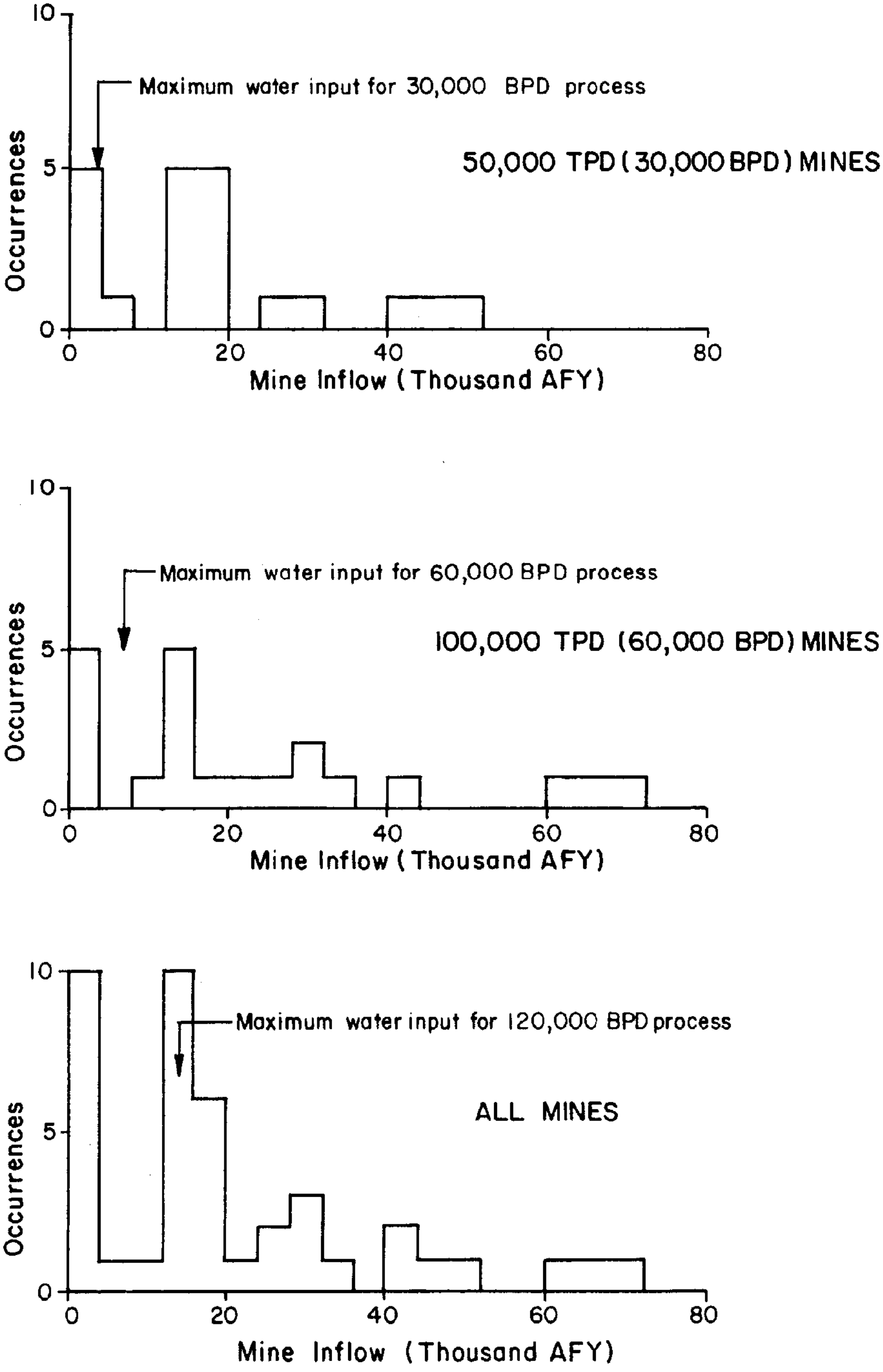
iii. Category C. Inflows in the range 40,000-72,000 AFY (24,800-44,700 gpm). This category includes rapidly expanding, single pass mine on Site 1 located in the Mahogany Zone, with and without subsidence, and similar mines in the R-4 Zone with subsidence.

Quality of mine inflow will be the same for conventional or in-situ mining schemes. The quality of most inflow will range from 800 mg/l to 3,000 mg/l total dissolved solids with a flow weighted average of about 1,500 mg/l.

14.5.2 Mine Water Inflow Management

The greatest water requirement for an in-situ industry is 2.5 barrels of water per barrel of oil, for modified in-situ processing

Figure 14-5 SUMMARY OF INFLOW RATES FOR IN-SITU MINES



NOTE: Occurrences is defined as the number of times a particular mine inflow rate was obtained in our analyses.

Golder Associates

with on-site power generation. This requires 3,500 AFY for a 30,000 BPD industry, 7,000 AFY for a 60,000 BPD industry, and 14,000 AFY for a 120,000 BPD industry. As shown on Figure 14-5, most of the mine inflow conditions exceed these rates.

In the case where mine inflow exceeds the usage rate, the obvious disposal technique is re-injection into the stratum from which the water percolated. The cost of this procedure has been explored in Chapter 6, and is $60/AF at Sites 1 and 2, and $150/AF at Site 3. As before, this is considerably less expensive than treating the groundwater to discharge standards and releasing it on the surface, and also minimizes the impact of groundwater withdrawal upon the rest of the Basin. Re-injection would be by wells, probably several miles distant from the mine location.

In the cases where mine inflow is inadequate to supply the process water needs, additional groundwater would be obtained by wells drilled from the surface (or from the mine in the case of modified in-situ). The cost and feasibility of doing this have been evaluated in Chapter 5.

14.6 WATER AVAILABILITY CONSIDERATIONS

The availability of water to oil shale operations in the Basin has been presented in Chapter 11. It is of interest to evaluate the limitations in production by in-situ methods which the limited availability of water in the region imply. Only the two maximum water demand cases will be evaluated, as the minimum water demand cases both produce, rather than consume, water.

14.6.1 In-Basin Water Supply

The in-Basin water supply comes from three sources: surface runoff, infiltration, and stored groundwater. Using the material presented in Chapter 11 (Table 11-5) and the water input requirements developed in this chapter, the limitations on oil shale production by in-situ means using in-Basin water supplies have been evaluated (Table 14-4).

Table 14-4

LIMITATIONS ON SHALE OIL PRODUCTION BY IN-SITU MEANS USING IN-BASIN WATER SUPPLIES

In-Basin Water Source	Available Flow (AFY)	Maximum Size of Industry which can be Sustained by Nominated Water Source (In Barrels of Oil/Day)	
		True In-situ	Modified In-situ
Recharge	24,000	250,000 BPD	200,000 BPD
Recharge + Runoff	44,500	500,000 BPD	400,000 BPD
Recharge + Runoff + Storage Used in 100 Years	133,000	1,400,000 BPD	1,200,000 BPD
Recharge + Runoff + Storage Used in 30 Years	340,000	3,600,000 BPD	2,900,000 BPD

NOTE: Assumes maximum water usage.

Based on this table, it seems likely that an industry of 1 million barrels of oil per day could be sustained by the in-Basin water supply alone. However, it must be appreciated that this involves mining the groundwater of the Basin along with the oil shale.

14.6.2 Extra-Basin Water Supply

As presented in Section 11.8.2 above, it is likely that substantial extra-Basin water is available to an oil shale industry. Using the data presented, and usage rates developed above, the limitations which extra-Basin supply impose on shale oil production by in-situ means are presented in Table 14-5.

TABLE 14-5

LIMITATIONS ON SHALE OIL PRODUCTION BY IN-SITU MEANS USING EXTRA-BASIN WATER SUPPLIES

Extra-Basin Water Source	Available Flow (AFY)	Maximum Size of Industry which can be Sustained by Nominated Water Source (in Barrels of Oil/Day) True In-Situ	Modified In-Situ
Estimated Available Water from Colorado Basin (2000 AD)	200,000	2,100,000 BPD	1,700,000 BPD
Present Available Water from Colorado Basin	800,000	8,400,000 BPD	7,000,000 BPD

Thus this water supply appears capable of supporting an industry of the order of 2 million barrels per day capacity.

14.6.3 Combined Water Supply

From the above it appears that for in-situ processing techniques, the limitation on production of shale oil implied by water availability is of the order of 3 million barrels per day of pipelineable oil. Note that this does not include the water consumption required for refining. At this rate of extraction, the oil shale in the Basin would last some 300 years.

14.7 OTHER IN-SITU TECHNIQUES

The water management aspects of other in-situ techniques have not been more than superficially addressed. Some of them appear so esoteric that commercial development to the size considered in this report seems likely to take several decades or more.

Others, for example nahcolite leaching to create voids, are so water consumptive and produce so much highly saline water that they do not appear at all attractive with the presently available water purification techniques. Based on the computations presented in Chapter 6 on cost of water purification, the salt removal from this dissolution process alone would add $15 per barrel of oil to the process cost (1974 dollars), thus making it clearly unattractive at present. Again, the lead time required to develop an improved water purification technology for this purpose is likely to be very long. The process would also consume some water, on the order of a barrel per barrel of oil over and above the consumption in retorting. This makes it even less attractive.

In summary, we have evaluated the techniques which appear at this time to have some economic promise. Future technological change will hopefully improve the attractiveness of other extraction techniques, at which time the building blocks presented in this report can be used to evaluate the water management aspects of the schemes.

CHAPTER 15
BASIN-WIDE CONSIDERATIONS

For the purposes of this contract, the primary reason for evaluating Basin-wide geohydrology during mining is to establish the maximum groundwater flow which can be obtained at each of the study sites. In order to perform this task a computer model of the Basin hydrology and geohydrology was constructed, and groundwater withdrawals of the magnitude anticipated in this study were made at each site.

Although the evaluation of the impact of oil shale development on the hydrology of the Basin is to some extent beyond the scope of this contract, we have examined several dimensions of the likely impact because of their obvious importance to the viability of the proposed schemes.

During mining, the major concern relates to the reduction of piezometric pressures in the Basin, and the possible reduction or elimination of streamflow in Piceance and Yellow Creeks.

After mining or retorting ceases, the primary concern relates to the impact of the mine structure or retort on the geohydrology and hydrology of the Basin. Two impacts are likely: impacts on water quality due to connection of water-bearing zones via the abandoned mine structure, and impacts on water quality due to leaching of mine backfill or spent retorts.

This chapter sets out the results of these evaluations and, where appropriate, attempts to evaluate the economic feasibility of mitigation strategies.

15.1 EFFECTS OF GROUNDWATER WITHDRAWAL

In order to establish the effects of groundwater withdrawal and consumptive use we have analyzed a series of situations which covers the likely range of use alternatives presented in this study. The geohydrology model used has been presented in Chapter 4, and is a single-layer aquifer model with directly coupled surface streams. The solution technique uses the Golder Associates version of the University of California-Berkeley's Finite Element Method fluid flow program. This is a very powerful tool for layered aquifer modelling (although the multi-layer feature was not, in fact, finally used for this project). The details of operation of the program, and some references on the solution algorithm are presented in Appendix E.

The approach used is to solve the unmined, steady state situation, and to compare it to measured piezometric and streamflow data. Once a reasonable match between observed and computed data is achieved (by adjusting the permeabilities used, if necessary), then the resulting analysis forms the base case against which all following analyses are compared.

At each site analyses are performed to establish whether groundwater can sustain a 30-year industry of the sizes nominated in the contract. Then the worst case of impact effect is evaluated by computing the steady-state condition under maximum sustained flow withdrawal. Because the maximum water use demands occur for conventional mining/retorting complexes, these are considered in the main evaluation. The conditions for in-situ retorting are then considered in a separate section (Section 15.1.5).

15.1.1 Baseline Condition

The baseline condition analysis results are shown on Figure 15-1. When the results are contrasted with the observed creek flows and piezometric levels the agreement is relatively good, especially considering the simplicity of the model and the crudity of some of the data.

Computed and observed creek flows are tabulated in Table 15-1.

TABLE 15-1

COMPUTED AND OBSERVED STREAMFLOWS

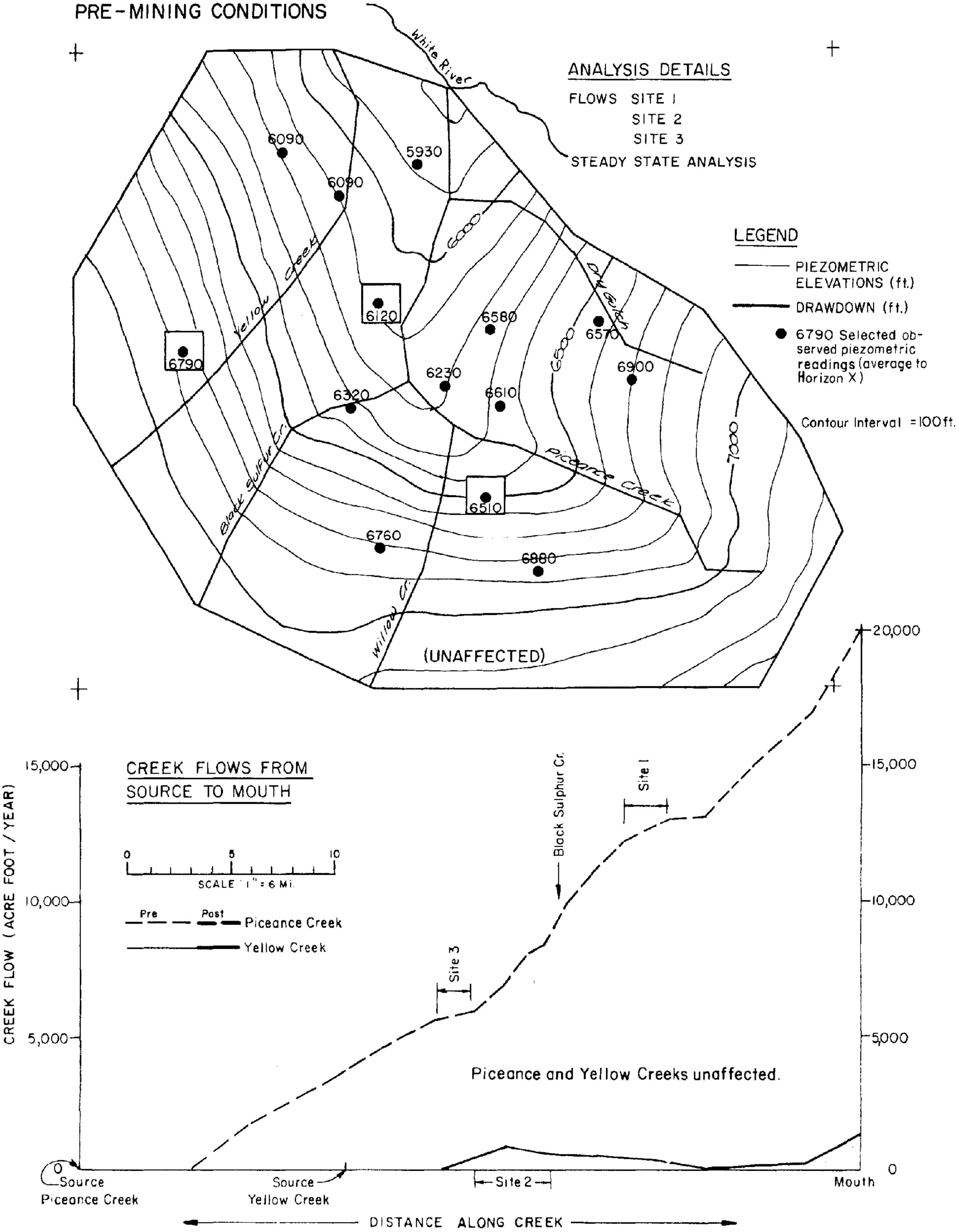
Gage Point	Flows (AFY) Computed	Observed	% Error
Piceance Creek at White River	20,000	17,400	+15
Piceance Creek below Ryan Gulch	12,000	14,000	-14
Yellow Creek at White River	1,200	1,270	- 6

NOTE: For streamflows, refer to Chapter 3. Values used are corrected mean annual flows.

Piezometric elevations observed in the aquifer system above Horizon X are plotted on Figure 15-1 to serve as a comparison. (Information supplied by Mr. J. Weeks, USGS, Denver). The agreement between computed and observed elevations is tolerable, except in the northeast section of the Basin. The lack of agreement in this area may reflect the total lack of reliable permeability data for the quadrant. In addition, the topography near Piceance Creek is steep, with much of the area above 7,000 feet. The resulting recharge may well create a piezometric condition which is considerably less than hydrostatic. The single layer model which was used is incapable of reflecting this vertical head gradient, and thus may err

BASIN-WIDE ANALYSIS RESULTS
PRE-MINING CONDITIONS

FIGURE 15-1


White River
ANALYSIS DETAILS
FLOWS SITE 1
SITE 2
SITE 3
STEADY STATE ANALYSIS
LEGEND
PIEZOMETRIC ELEVATIONS (ft.)
DRAWDOWN (ft.)
● 6790 Selected observed piezometric readings (average to Horizon X)
Contour Interval =100ft.
6090
5930
6090
6000
Yellow Creek
Dry Gulch
6120
6580
6570
6790
6500
6900
6230
6320
6610
7000
Piceance Creek
Black Sulfur Cr.
6510
6760
6880
Willow Cr.
(UNAFFECTED)
CREEK FLOWS FROM SOURCE TO MOUTH
CREEK FLOW (ACRE FOOT / YEAR)
15,000
10,000
5,000
0
20,000
15,000
10,000
5,000
0
0 5 10
SCALE 1" = 6 Mi.
Pre
Post
Piceance Creek
Yellow Creek
Black Sulphur Cr.
Site 1
Site 3
Site 2
Piceance and Yellow Creeks unaffected.
Source Piceance Creek
Source Yellow Creek
Mouth
DISTANCE ALONG CREEK

in giving too low values. In any case, as none of the study sites are on the northeast side of Piceance Creek, the lack of good agreement there was regarded as of little significance to this project.

The piezometric conditions and creek flows shown in Figure 15-1 are the basis against which all computed mining-induced changes are evaluated. It is interesting to note that neither Willow Creek to the south or Dry Gulch to the north are flowing in our base case. In both instances the groundwater levels are below the creeks. As evidence exists which suggests that Willow Creek depresses the piezometric conditions on Tract C-b, it seems likely that there is significant subsurface recharge in the areas below 7,000 feet elevation (see Chapter 4, Section 4.5.6).

15.1.2 Site 1 Analyses

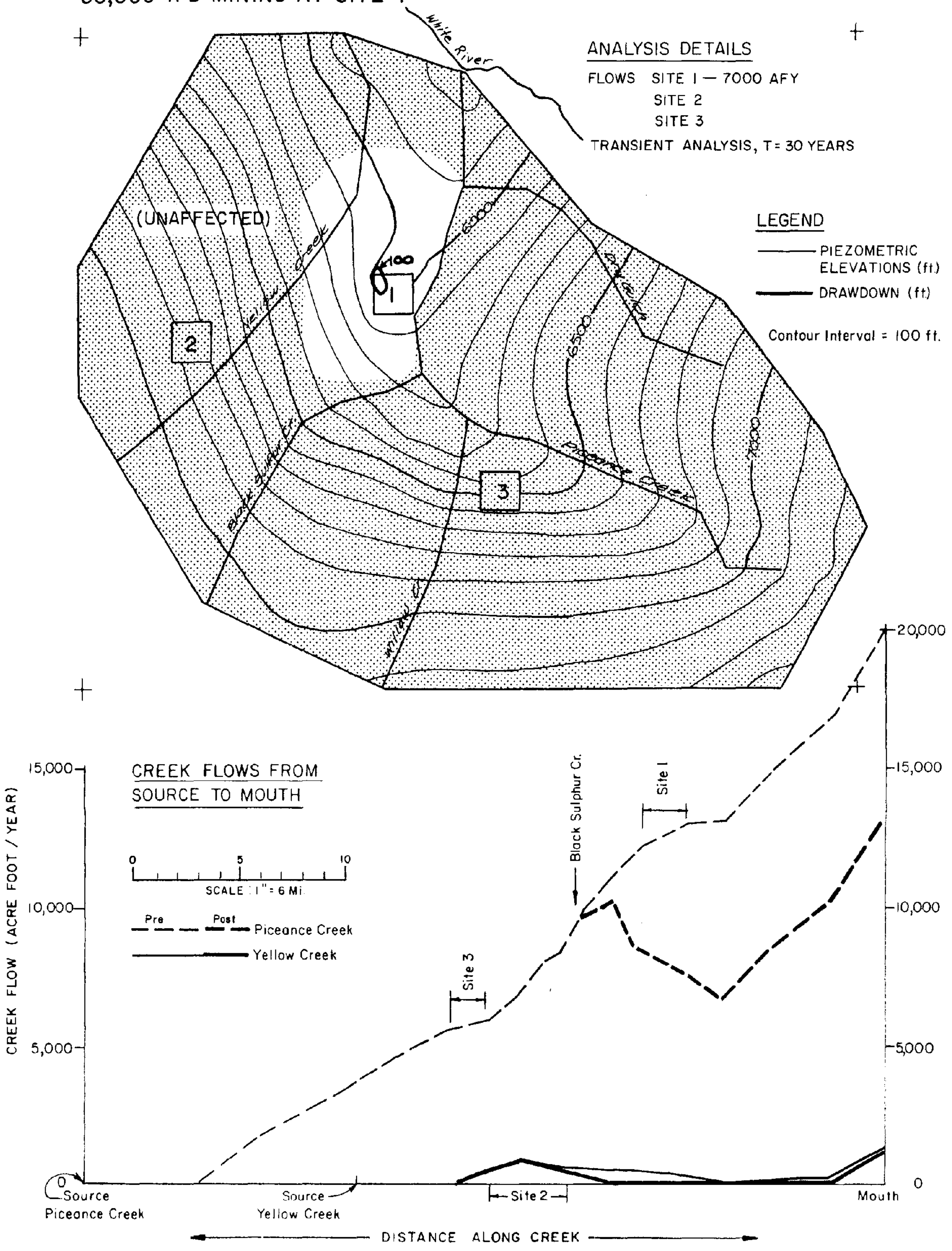
15.1.2.1 Transient Analyses

As shown in Chapter 11, conventional shale oil recovery requires water inflow at the rate of about 7,000 AFY per 50,000 TPD/ 30,000 BPD industry module. The contract calls for evaluation of conventional processes at Site 1 of 50,000 and 100,000 TPD extraction rates, and the results of the appropriate transient analyses are discussed below.

i. 50,000 TPD Mining. This evaluation calls for the steady withdrawal of 7,000 AFY (4,400 gpm) of water from a four square mile area at Site 1. The extraction is continued for 30 years, which is the nominal mine life. The results of the analysis are shown in Figure 15-2. The upper part of the figure shows a plan view of the Basin, with

BASIN-WIDE ANALYSIS RESULTS
50,000 TPD MINING AT SITE 1

FIGURE 15-2


White River
ANALYSIS DETAILS
FLOWS SITE 1 — 7000 AFY
SITE 2
SITE 3
TRANSIENT ANALYSIS, T = 30 YEARS
LEGEND
PIEZOMETRIC ELEVATIONS (ft)
DRAWDOWN (ft)
Contour Interval = 100 ft.
(UNAFFECTED)
Yellow Creek
Black Sulphur Cr.
Piceance Creek
Willow Cr.
Stewart Gulch
6500
6500
7000
100
1
2
3
CREEK FLOWS FROM SOURCE TO MOUTH
0 5 10
SCALE: 1" = 6 Mi.
Pre Post Piceance Creek
Yellow Creek
CREEK FLOW (ACRE FOOT / YEAR)
15,000
10,000
5,000
0
20,000
15,000
10,000
5,000
0
Black Sulphur Cr.
Site 1
Site 3
Site 2
Source Piceance Creek
Source Yellow Creek
Mouth
DISTANCE ALONG CREEK

contours of piezometric elevations. Superimposed on these contours are contours of drawdown due to the withdrawal (compared with the no-mining case). The lower part of the figure compares the post-mining creek flows with those which were computed in the pre-mining analysis.

The drawdown impact is relatively small. The average drawdown across Site 1 is 90 feet, and this is primarily limited by the close proximity of Piceance Creek, which remains flowing despite the nearby withdrawal of groundwater. The slight groundwater drawdown is enough, however, to dry up a few miles of the middle reach of Yellow Creek. At the end of 30 years, the sources of water for the mine are given in Table 15-2.

TABLE 15-2

WATER BALANCE - 50,000 TPD MINING AT SITE 1

		Flows (AFY)	
Source	Pre-Mining	Post Mining	Differences
Piceance Creek	18,400	12,377	6,023
Yellow Creek	1,200	1,094	106
Mining	-	7,000	-7,000
TOTAL	19,600	20,471	- 871

The 871 AFY is being drawn from storage, which indicates that the water table is still falling, although the conditions are close to steady state.

ii. 100,000 TPD Mining. This rate of mining calls for 14,000 AFY of water. The conditions which would occur after 30 years of groundwater extraction at this rate are shown in Figure 15-3. The drawdown influences a somewhat wider area of the Basin and causes the middle reach of Yellow Creek to dry up. Piceance Creek very nearly dries up in the reach adjacent to the Site. The water balance for this analysis is given in Table 15-3.

TABLE 15-3

WATER BALANCE-100,000 TPD MINING AT SITE 1

Source	Pre-Mining	Flows (AFY) Post Mining	Differences
Piceance Creek	18,400	6,346	12,054
Yellow Creek	1,200	1,062	138
Mining	-	14,000	-14,000
TOTAL	19,600	21,408	- 1,808

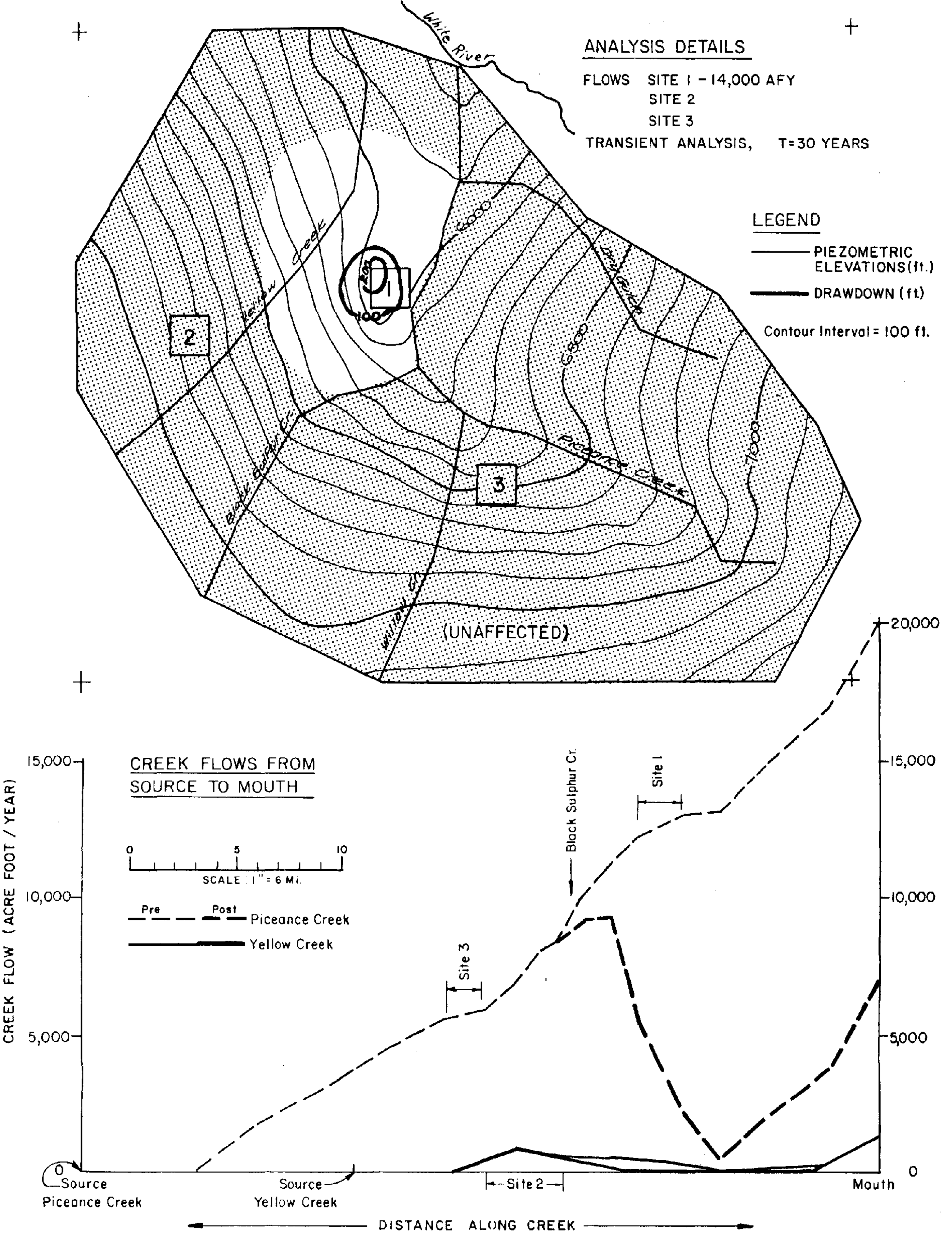
Once again, the 1,808 AFY missing in the water balance is being drawn from storage, suggesting that the drawdown is within 13% of equilibrium.

15.1.2.2 Steady State Analysis

The maximum drawdown impact occurs when the mine area is kept dry, and after infinite time has elapsed. This analysis was attempted for Site 1, and the results are presented in Figure 15-4. The flow which is generated is 17,740 AFY. Because of the limited capability of a single-layer model to realistically analogue the near-mine condition for this case, this analysis should be taken as providing only an indication of the maximum steady state flow to the mine. It is, however, 90% of the recharge to the aquifer, which indicates that Site 1 is an excellent location from which to drain the Basin. Of the 19,600 AFY recharge, 17,740 AFY goes to the mine, 1,310 AFY exists in Piceance Creek and 550 AFY exists in Yellow Creek.

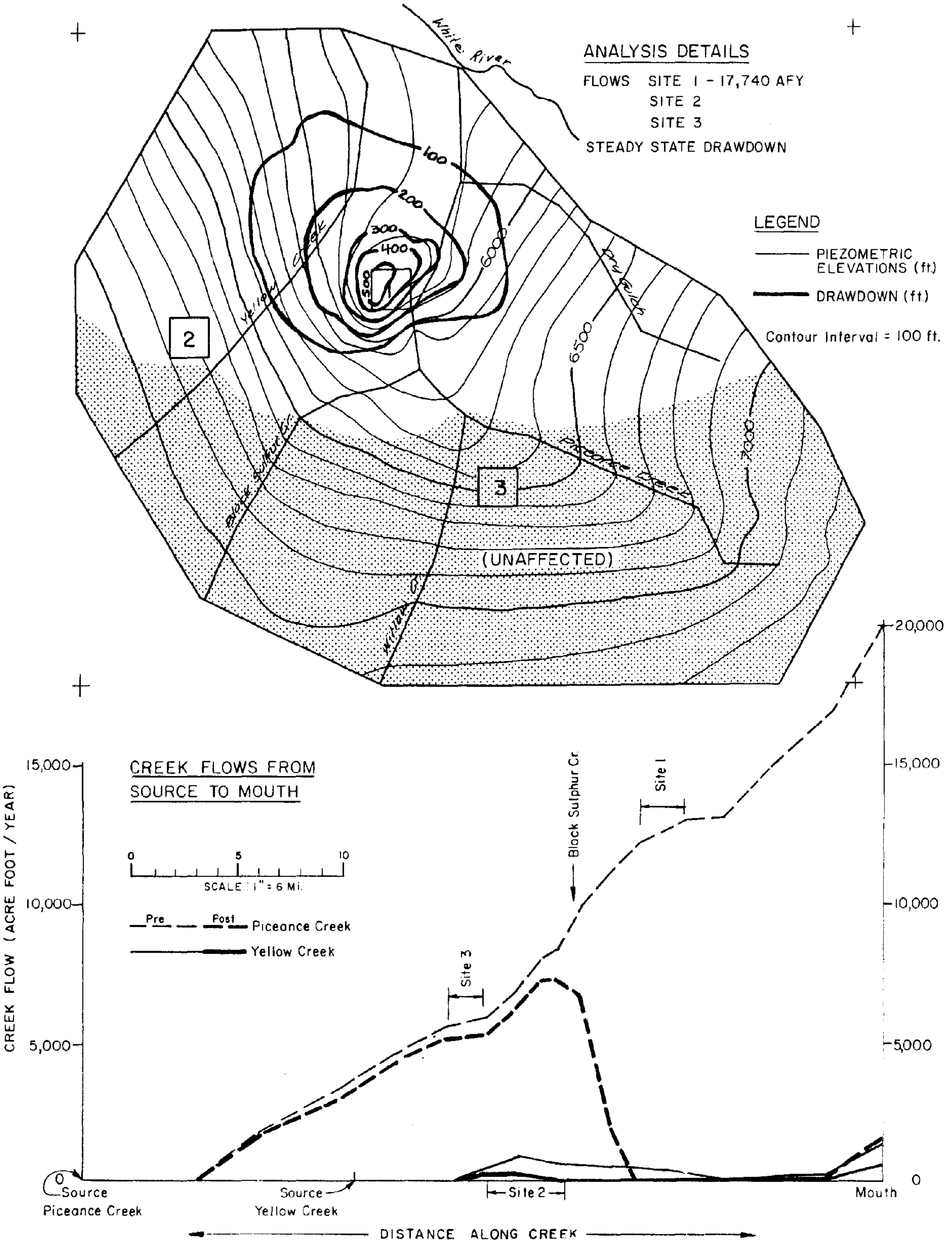
BASIN-WIDE ANALYSIS RESULTS 100,000 TPD MINING AT SITE 1

FIGURE 15-3


White River
ANALYSIS DETAILS
FLOWS SITE 1 - 14,000 AFY
SITE 2
SITE 3
TRANSIENT ANALYSIS, T=30 YEARS
LEGEND
PIEZOMETRIC ELEVATIONS (ft.)
DRAWDOWN (ft.)
Contour Interval = 100 ft.
Yellow Creek
Dry Gulch
Piceance Creek
Black Sulphur Cr.
Willow Cr.
6000
6800
7000
200
100
1
2
3
(UNAFFECTED)
CREEK FLOWS FROM SOURCE TO MOUTH
0 5 10
SCALE : 1" = 6 Mi.
Pre
Post
Piceance Creek
Yellow Creek
CREEK FLOW (ACRE FOOT / YEAR)
15,000
10,000
5,000
0
20,000
15,000
10,000
5,000
0
Black Sulphur Cr.
Site 1
Site 3
Site 2
Source Piceance Creek
Source Yellow Creek
Mouth
DISTANCE ALONG CREEK

BASIN-WIDE ANALYSIS RESULTS
MAXIMUM IMPACT DUE TO SITE I

FIGURE 15-4


White River
ANALYSIS DETAILS
FLOWS SITE I - 17,740 AFY
SITE 2
SITE 3
STEADY STATE DRAWDOWN
LEGEND
PIEZOMETRIC ELEVATIONS (ft.)
DRAWDOWN (ft.)
Contour Interval = 100 ft.
100
200
300
400
500
6000
6500
7000
0
Yellow Creek
Dry Gulch
Piceance Creek
Black Sulphur Cr.
Willow Cr.
2
3
(UNAFFECTED)
CREEK FLOWS FROM SOURCE TO MOUTH
0
5
10
SCALE : 1" = 6 Mi.
Pre
Post
Piceance Creek
Yellow Creek
CREEK FLOW (ACRE FOOT / YEAR)
15,000
10,000
5,000
0
20,000
15,000
10,000
5,000
0
Black Sulphur Cr.
Site I
Site 3
Site 2
Source Piceance Creek
Source Yellow Creek
Mouth
DISTANCE ALONG CREEK

The drawdown cone is steep, and influences more than half the Basin. The northeastern region of the Basin is drawn down because the protection of Piceance Creek is removed. Drawdown at the Site is about 500 feet. As the original saturated section at Site 1 was computed to be 1,240 feet thick, it is likely that an even greater effect could have been obtained by drawing a larger flow rate from the mine. However, the relatively major impact of the quantity withdrawn indicates the likely effect of major groundwater exploitation at this Site.

15.1.3 Site 2 Analyses

As noted in Chapter 4, Site 2 has a deep, highly permeable aquifer which does not appear to have significant connection with the recharge areas above it. Accordingly, all the analyses in this section are for the relatively thin permeable zone above Horizon X. The saturated thickness of this zone is about 570 feet at the mine site.

15.1.3.1 Transient Analyses

The contract calls for analyses at 50,000, 100,000, and 200,000 TPD mine rates. If these industries are to be supplied with groundwater, then the limited capacity of the upper permeable layer may become an important limitation.

The analysis of the Site for an extraction of 7,000 AFY for 30 years was completed without running out of water. The results are shown in Figure 15-5. As can be seen, only a relatively small part of the Basin is influenced by the extraction, with the result that most of the water being drawn from the groundwater regime is coming from storage, even after 30 years. This is shown in Table 15-4.

BASIN-WIDE ANALYSIS RESULTS
50,000 TPD MINING AT SITE 2

FIGURE 15-5

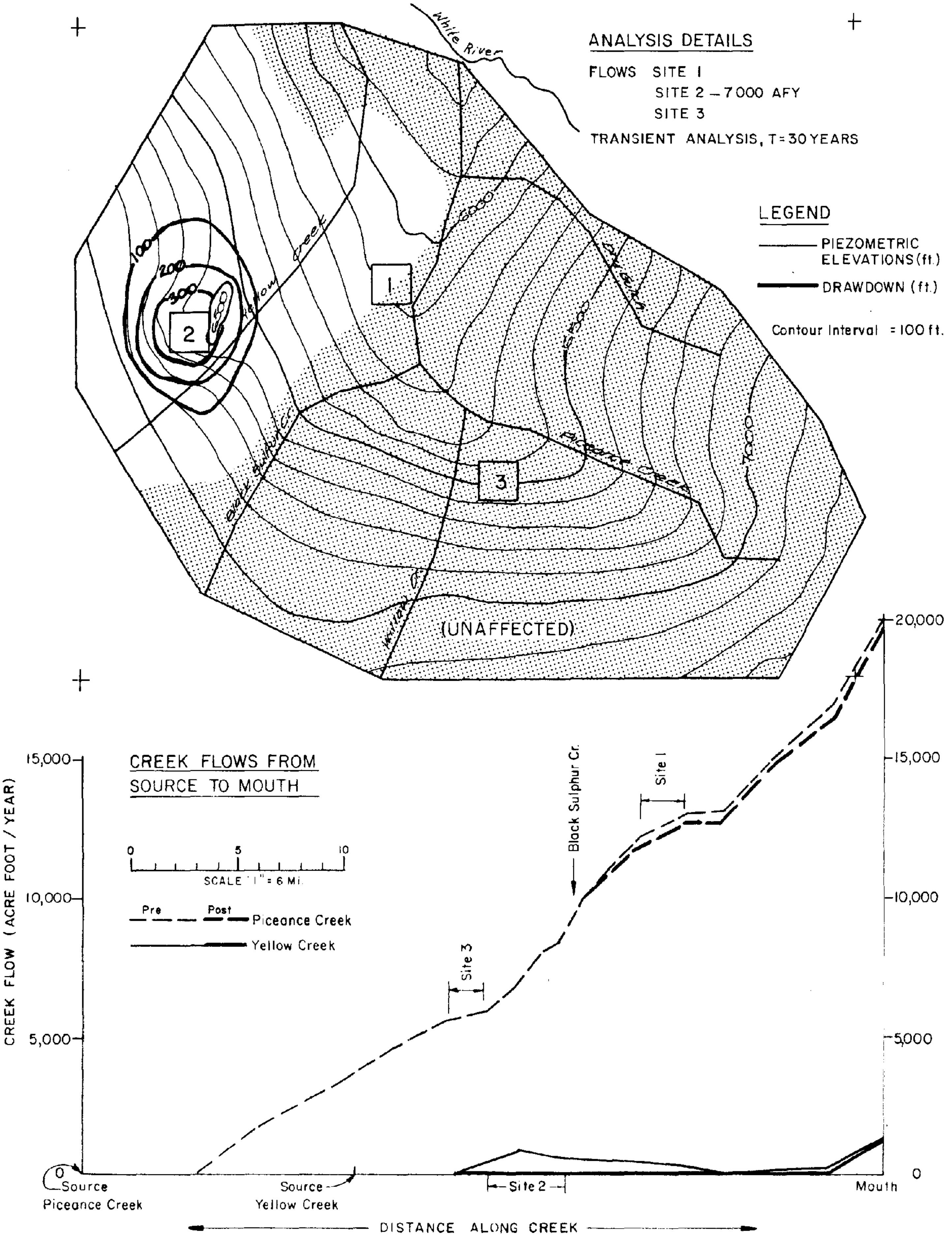

White River
ANALYSIS DETAILS
FLOWS SITE 1
SITE 2 – 7000 AFY
SITE 3
TRANSIENT ANALYSIS, T = 30 YEARS
LEGEND
PIEZOMETRIC ELEVATIONS (ft.)
DRAWDOWN (ft.)
Contour Interval = 100 ft.
Yellow Creek
100
200
300
500
1
2
3
6000
6500
7000
Piceance Creek
Black Sulphur Cr.
Willow Cr.
(UNAFFECTED)
CREEK FLOWS FROM SOURCE TO MOUTH
0
5
10
SCALE 1" = 6 Mi.
Pre
Post
Piceance Creek
Yellow Creek
CREEK FLOW (ACRE FOOT / YEAR)
15,000
10,000
5,000
0
20,000
Black Sulphur Cr.
Site 1
Site 3
Site 2
Source Piceance Creek
Source Yellow Creek
Mouth
DISTANCE ALONG CREEK

TABLE 15-4

WATER BALANCE - 50,000 TPD MINING AT SITE 2

	Flows (AFY)		
Source	Pre-Mining	Post Mining	Difference
Piceance Creek	18,400	18,163	237
Yellow Creek	1,200	1,096	104
Mining	-	7,000	-7,000
TOTALS	19,600	26,259	-6,659

This means that the water table will drop continuously, as long as the mining of both the oil shale and the groundwater continue. After 30 years, the water table has dropped some 270 feet, which is close to half the original saturated thickness. It is clear that this is the maximum size industry which can be supported at Site 2 by groundwater alone, unless our assessment of the productivity of the lower permeable zone is incorrect.

15.1.3.2 Steady State Analysis

The steady state, maximum flow analysis for Site 2 is presented in Figure 15-6. At steady state, almost half the Basin is influenced by the withdrawal at Site 2. The steady state flow is only 1,600 AFY, well short of the needs of a large industry. Drawdown at the Site was about 210 feet, somewhat less than half the original saturated thickness of the stratum at the mine location. Yellow Creek is substantially dewatered by the extraction, but the bulk of the water actually results from a reduction in the flow of Piceance Creek. Because of the low flow rate extracted, head changes are in general small.

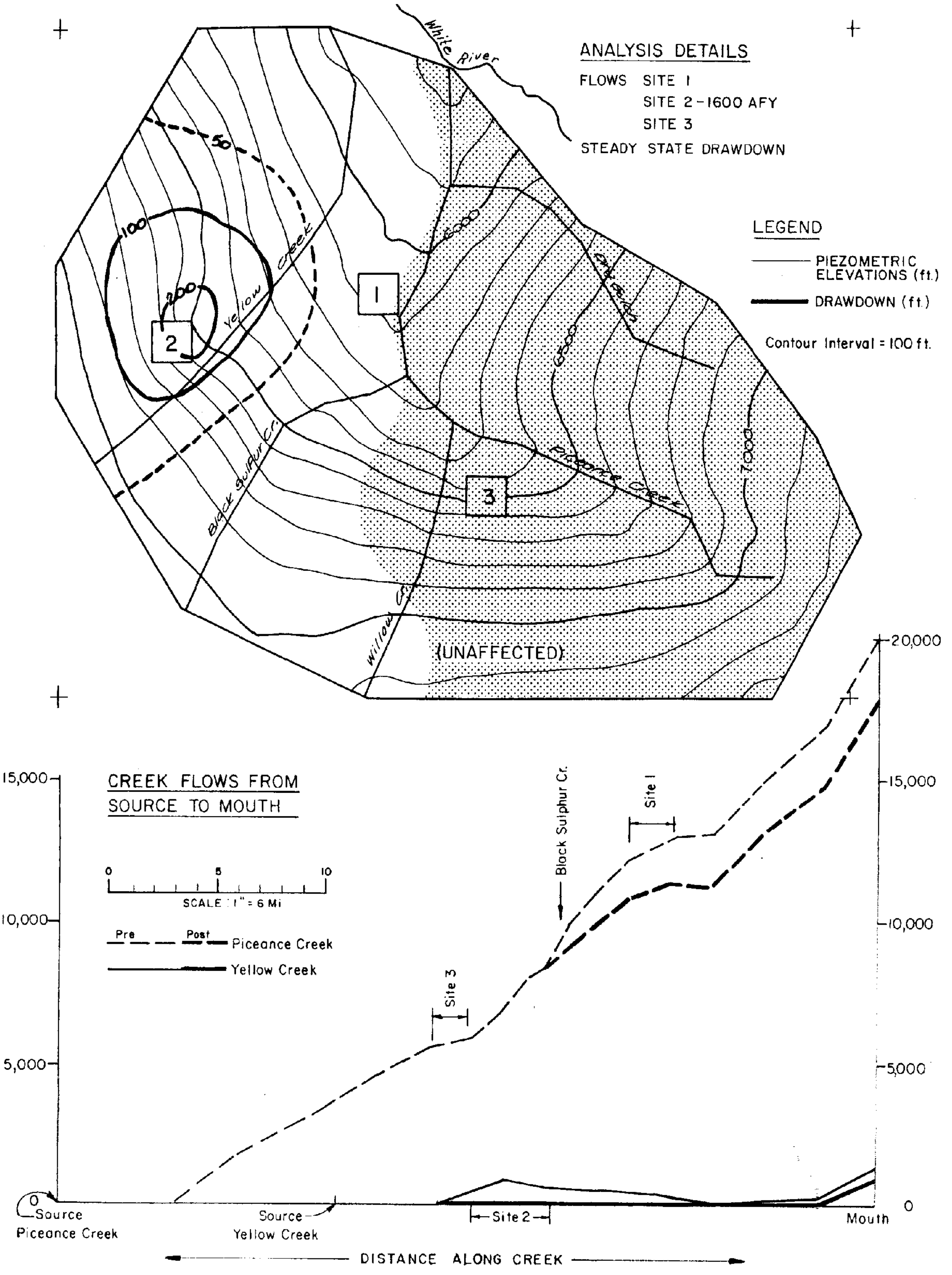
15.1.4 Site 3 Analyses

15.1.4.1 Transient Analyses

The contract only calls for one mining rate at Site 3 - 50,000 TPD. Figure 15-7 shows the result of the anaysis for a 50,000 TPD

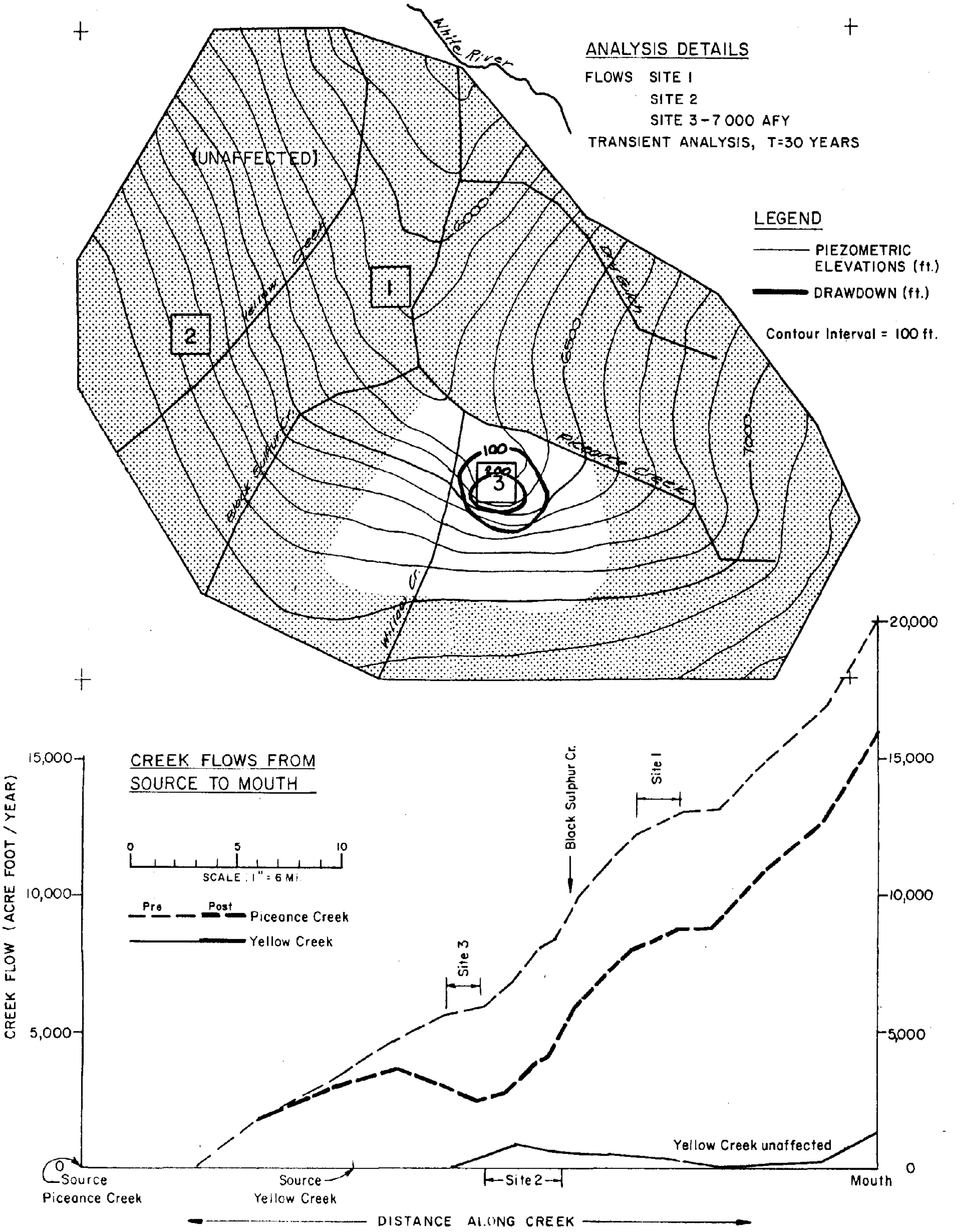
BASIN-WIDE ANALYSIS RESULTS
MAXIMUM IMPACT DUE TO SITE 2

FIGURE 15-6


White River
ANALYSIS DETAILS
FLOWS SITE 1
SITE 2 - 1600 AFY
SITE 3
STEADY STATE DRAWDOWN
LEGEND
PIEZOMETRIC ELEVATIONS (ft.)
DRAWDOWN (ft.)
Contour Interval = 100 ft.
50
100
200
1
2
3
Yellow Creek
Black Sulphur Cr.
Willow Cr.
Piceance Creek
Dry Fork
6000
6500
7000
(UNAFFECTED)
CREEK FLOWS FROM SOURCE TO MOUTH
0
5
10
SCALE 1" = 6 Mi
Pre
Post
Piceance Creek
Yellow Creek
CREEK FLOW (ACRE FOOT / YEAR)
15,000
10,000
5,000
0
20,000
15,000
10,000
5,000
0
Black Sulphur Cr.
Site 1
Site 3
Site 2
Source Piceance Creek
Source Yellow Creek
Mouth
DISTANCE ALONG CREEK

BASIN-WIDE ANALYSIS RESULTS
50,000 TPD MINING AT SITE 3

FIGURE 15-7



mining/retorting complex supplied with groundwater for 30 years. Impact is limited, as is drawdown (210 feet at the mine in a saturated section of 1,050 feet).

The water drawn from the formation is supplied as shown in Table 15-5.

TABLE 15-5
WATER BALANCE - 50,000 TPD MINING AT SITE 3

	Flow (AFY)		
Source	Pre-Mining	Post Mining	Difference
Piceance Creek	18,400	14,590	3,810
Yellow Creek	1,200	1,200	-
Mining	-	7,000	-7,000
TOTALS	19,600	22,790	-3,190

This indicates that after 30 years about half the water flowing to the project is still provided by storage in the rock matrix, and that the groundwater regime is by no means at equilibrium.

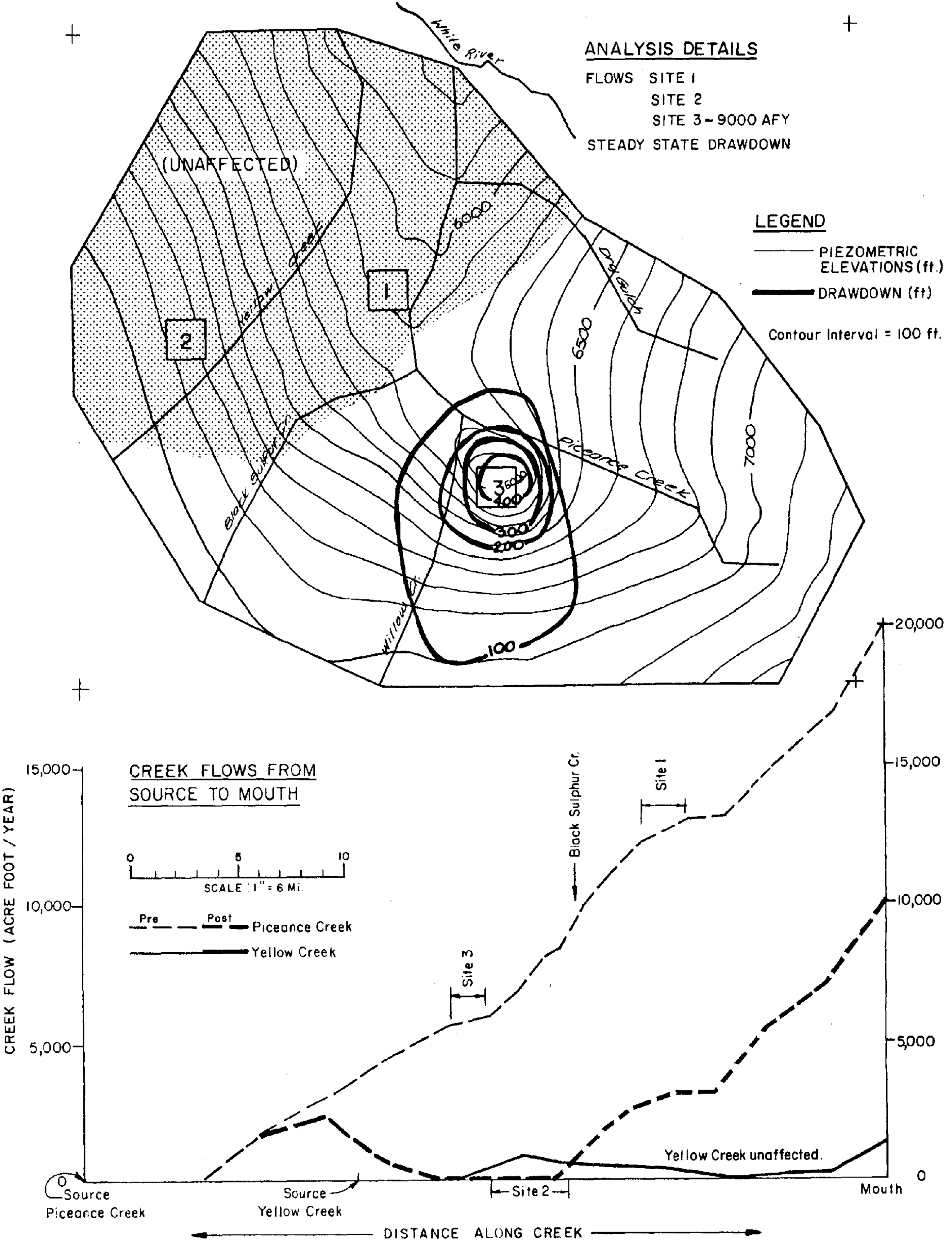
Impact on Piceance Creek is as might be expected. A portion of the early flow is removed and never made up. There is a substantial decrease in the flow of the creek adjacent to the Site. Yellow Creek is not influenced.

15.1.4.2 Steady State Analysis

The maximum impact case for Site 3 is shown on Figure 15-8. The steady state flow to the mine under a drawdown of 420 feet was 9,000 AFY. This came entirely from the catchment of Piceance Creek. Yellow Creek was not significantly affected. About 3 miles of the reach of Piceance Creek adjacent to Site 3 dried up under this condition.

BASIN-WIDE ANALYSIS RESULTS
MAXIMUM IMPACT DUE TO SITE 3

FIGURE 15-8


White River
ANALYSIS DETAILS
FLOWS SITE 1
SITE 2
SITE 3 - 9000 AFY
STEADY STATE DRAWDOWN
LEGEND
PIEZOMETRIC ELEVATIONS (ft.)
DRAWDOWN (ft)
Contour Interval = 100 ft.
(UNAFFECTED)
Yellow Creek
Black Sulphur Cr.
Dry Gulch
Piceance Creek
Willow Cr.
1
2
3
6000
6500
7000
6500
400
300
200
100
CREEK FLOWS FROM SOURCE TO MOUTH
0
5
10
SCALE 1" = 6 Mi.
Pre
Post
Piceance Creek
Yellow Creek
CREEK FLOW (ACRE FOOT / YEAR)
15,000
10,000
5,000
0
20,000
15,000
10,000
5,000
0
Black Sulphur Cr.
Site 1
Site 3
Site 2
Yellow Creek unaffected.
Source Piceance Creek
Source Yellow Creek
Mouth
DISTANCE ALONG CREEK

As the original saturated section at Site 3 was some 1,050 feet thick, a somewhat greater "maximum" flow could have been extracted from the area, perhaps on the order of 12,000 AFY. This is the likely maximum steady state flow which is available from this loaction.

15.1.5 In-Situ Retorting Considerations

In-situ mining/retorting systems in general require that the rock to be retorted be unsaturated. As a result, all schemes must dewater the zones which are to be retorted. As evaluated in Chapter 13, the "mine" inflows produced by this activity are generally high, of the order of 10,000 AFY or more. In order to minimize the impacts of this groundwater withdrawal, and to dispose of the resulting excess water, most of the water will be re-injected into the formations from which it was taken (Figure 15-9).

As presented in Chapter 14, in-situ processes either produce some water (of the order of 1,000 AFY maximum for a 30,000 BPD operation) or they use some water (of the order of 3,500 AFY maximum for a 30,000 BPD operation). Which use value is chosen depends upon whether or not the developer intends to generate power on-site. Presuming that the latter is the economically rational approach, in-situ retorting will consume 3,500 AFY of water per 30,000 BPD operation. This is about half the water flow for conventional systems of the same oil production capacity.

If all of the required water supply is to be provided by groundwater, then the analyses of impacts presented above are also valid for in-situ developments. Figure 15-2 shows the impact of a 60,000 BPD operation at Site 1, and Figure 15-3 shows the impact of a 120,000 BPD operation. Figure 15-5 shows the impact of a 60,000 BPD operation at Site 2. This is about the maximum

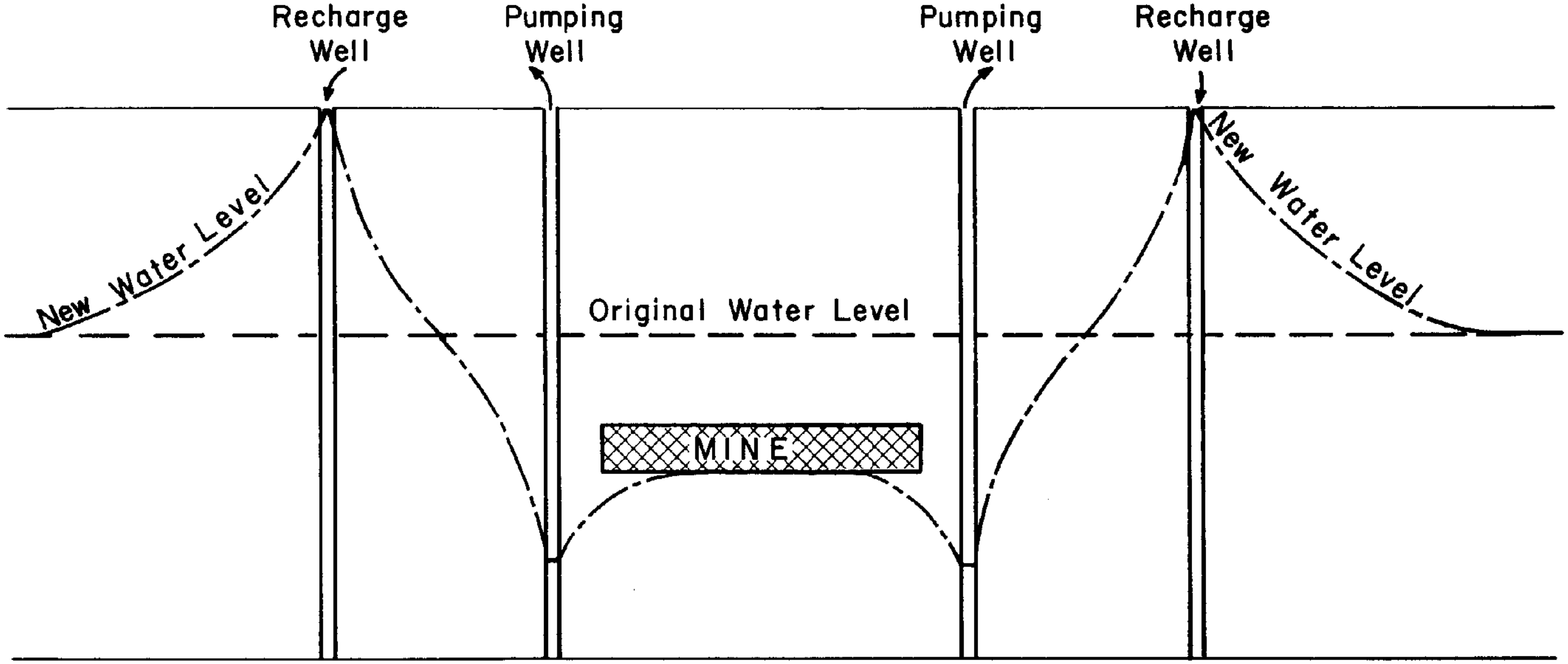

Recharge Well
Pumping Well
Pumping Well
Recharge Well
New Water Level
New Water Level
Original Water Level
MINE

Figure 15-9 SCHEMATIC OF POSSIBLE DEWATERING SYSTEM USING REINJECTION
(Not to scale)

size operation which can be supplied locally with groundwater at Site 2. Figure 15-7 shows the impact of a 60,000 BPD operation at Site 3. It is probably that a 120,000 BPD operation could be run at Site 3 using locally-acquired groundwater only, but this would be at the limit of the productive capacity of the area.

In the case where the shale oil production does not require any water, re-injection of mine inflow will limit environmental impact to the region within the re-injection well ring. Mines located below a zone of very low vertical permeability may not require dewatering of the overlying aquifers. The results of the inflow analyses in Chapter 13 indicate that mines located in the R-4 zone on Sites 1 and 3 will have very low inflows. The overlying aquifers are effectively isolated from the mine in the uncaved case and will probably not require dewatering. A mine within the R-4 zone on Site 2 will also be isolated from above but will require dewatering of the surrounding R-4 zone which is, itself, an aquifer at this Site.

15.1.6 Relationship Between Groundwater Pressure Lowering and Creek Flows

In the above analyses it is assumed that water can move from the creek into the groundwater system without hindrance. This assumption is important in the case where the groundwater level is depleted by withdrawal and consumptive use, because the analysis performed simply extracts enough water from the creeks nearby to keep the water table at creek level. If so much water is extracted that the creek dries up, then the water table is allowed to fall below creek level. Thus the creek flow results are very strongly dependent on the validity of the assumption of good connection between groundwater and creek.

In order to check the assumption an analysis was made of the amount of water which the creek could lose per unit of creek length if the water pressure in the rock immediately beneath the alluvium dropped to zero (i.e. gravity drainage of the creek plus alluvium into the rock was analyzed). Based on the permeability data for the three sites, and assuming that the permeability of the alluvium is substantially greater than that of the rock, the creeks would lose between 300 and 3,000 AFY of water per mile of their length.

This limit on the rate of depletion of the creeks would be significant only at Site 1, where the depletion rates shown on Figures 15-3 and 15-4 are in excess of the upper value. In this case the total depletion from the creek would be somewhat reduced, but the reach of the creek influenced would be somewhat larger, extending upstream for several miles further than shown.

This matter is very important to evaluations of surface water impact of mining, and the analysis above is not intended to resolve the problem. Both field and analytical investigation to establish the real degree of interconnection are needed, and suggestions for further work are included in Chapter 16. However, it does seem clear that the stream depletions shown in this chapter are not in general unreasonable.

15.1.7 Summary of Groundwater Use Effects

Any development in the Basin which uses groundwater as a primary source of process water will make a significant impact on the surrounding groundwater regime, and upon the surface water regime which depends upon the groundwater.

Site 1 developments tend to have a marked impact on Yellow Creek, primarily because Yellow Creek only flows as a result of a delicate balance between infiltration above it, and underdrainage by the topographically lower Piceance Creek.

As Site 1 is in the center of the Basin, very large groundwater withdrawals from it have the potential to dramatically affect all of the Basin. Should central groundwater extraction, treatment, and reticulation ever be considered in the Basin, this would be a good location for the plant.

Site 2 developments have little water supply optential, but on the other hand do not have a dramatic impact on Basin hydrology. Only the slight flow in Yellow Creek suffers any significant impact from developments on Site 2.

Site 3 is intermediate between the above tow cases. Water gathering potential is moderate, and long-term supplies are obtainable. Impact of groundwater at this site on the Basin can be major, especially if withdrawals cause Piceance Creek to dry up. Under these circumstances drawdown impacts are felt on the northeast side of the creek, which is unaffected by most other developments.

Thus the Basin is seen as a sensitive geohydrologic structure. Changes in one location can influence much of the rest of the Basin. This is of paramount importance in water rights determinations, and in water supply planning. These matters are addressed in a more general context elsewhere in this report.

15.2 EFFECTS OF AQUIFER COMMUNICATION

As discussed in Section 3.3.5, the quality of waters in the Piceance Basin varies with location and with depth. Particularly, the water in the material between the water table and the top of the relatively impermeable saline zone has been divided into two subzones by Weeks, et al. (1974). The material from the water table to the Mahogany Zone is believed to have relatively high quality groundwater, while the material from the Mahogany Zone to the top of the saline zone is believed to have lower quality water, with the quality deteriorating rapidly to the north of the Basin. These variations have already been presented in Figures 3-11 and 3-12 in Chapter 3.

The data obtained in pumping tests at the three study sites do not, however, show any marked variation of water quality above and below the Mahogany Zone. Water qualities at all sites are in the range 1,000 to 2,000 mg/l TDS above Horizon X, and perhaps 3,000 mg/l TDS in the lower aquifer at Site 2. Thus, inter-aquifer communication does not seem to be a significant water quality consideration. It should be noted, however, that this may not be true at other locations in the Basin, particularly to the north of the study sites. Two conditions are necessary before the creation of intercommunication of aquifers is detrimental to groundwater quality:

i. The presence of marked quality variations between aquifers.

ii. The presence of a driving head to cause mixing of good quality water with low quality water.

For the purposes of any water quality degradation evaluation, it is conservative to assume that all water in the saturated rock above Horizon X will be polluted by a pollution source at any level in that zone. This assumption will be made in the balance of this chapter.

15.3 EFFECTS OF LEACHING OF SPENT RETORTS

The mine zone must be kept dewatered during the actual mining activity in order to maintain the combustion front and provide safe underground working conditions. It will probably not be physically and economically possible to continue to dewater the mining zone after mining has ceased. The environmental impact of re-saturating the retort zones will depend upon the hydrologic and chemical characteristics of the burned retorts.

15.3.1 Retort Characteristics

Very little data is publicly available relating to the physical and chemical characteristics of a burned-out in-situ retort. We understand that work is currently in progress on material obtained from Occidental's DA property retorts, but results were not available at the time of preparation of this report. As a consequence, all of the remainder of this section is based upon the leachability of surface retorted shale. It is likely that in-situ retorted shale will contain less leachable saline minerals than conventional spent shale.

Examination of retorted oil shale from the 150-ton Laramie retort indicates that the burned retort will contain a very permeable rock mass. Chemical investigations of spent shale from the various surface retorting processes indicate that large quantities of soluble solids are mobilized within the spent shale. Leaching tests conducted on TOSCO II spent shale show initial TDS concentrations of leachates as high as 55,000 mg/l (Metcalf and Eddy, October 1975).

The burned retort chamber will probably have permeabilities which are at least several orders of magnitude greater than the oil shale surrounding the chamber. It is possible that some sealing of the retort walls will result from heat penetrating the barrier pillars and causing plastic deformation at temperatures lower than those necessary for retorting. More data is needed concerning burned retorts to determine their important characteristics relating to water quality hydrology. For this study it is assumed that the retorts have no vertical resistance to flow, and that the net horizontal permeability of the retorted material plus the (presumably) somewhat sealed walls is equal to the original horizontal permeability of the rock.

It is also necessary to make some evaluation of the quantity of leachable salts which remain in the spent retorts after processing. The TOSCO II studies mentioned above suggest that about 1% by weight of the original oil shale is made leachable by the retorting process. This assumes that retorting is not performed in the saline zone in the center of the Basin. In this case, leachable salt content may reach as high as 20% of total weight.

15.3.2 Passive Projection of Post-Mining Impact

The impact on the streams and groundwater in the Basin of the leaching of retorts which were simply abandoned at the end of oil recovery will be examined here. This is a "passive" evaluation, in the sense that no mitigating activities are assumed.

The post-mining history of the retorts would be that they would gradually re-fill with water after the dewatering of the region ceased (at the end of the recovery phase). The time taken to refill the retorts to a point where groundwater would flow through them, rather than only towards them, depends on the geohydrology, the method of prior dewatering, and the degree of prior consumptive use of the groundwater. In most cases flow through the retorts begins between 10 and 100 years after abandonment. The groundwater then flows slowly through the burned retorts, dissolving the salts in the retort until saturation of the groundwater is achieved, or the salts are exhausted. The groundwater then flows downdip to the creeks of the Basin and out into the White River. In the process, the salinity of these streams is increased.

In order to indicate the potential magnitude of these effects, a 30,000 BPD industry with a 30-year productive life was assumed for each site. The steady-state groundwater flow through each retort was computed on the assumption that the average horizontal permeability of the retorts was equal to the pre-mining rock permeability. The volume of groundwater flow through each complex was computed, and the impact of this polluted flow on the creeks of the Basin was determined.

The results of this evaluation are presented in Table 15-6. While the assumptions are relatively crude, it is clear that there will be significant impact due to additional salt leaching in the Basin, and that the salinity of Piceance Creek will increase by between 1,500 and 6,500 mg/l in the long term. (Interestingly Yellow Creek is losing water to the subsurface aquifer at the point adjacent to Site 2, and so suffers no degradation, at least according to our computer model.) If all three sites were developed at the 30,000 BPD rate, then after abandonment Piceance Creek would suffer a salinity increase of about 10,000 mg/l.

As well as the impact on the creeks, there will be a major degradation of groundwater quality over a significant portion of the Basin. Figure 15-10 shows the minimum plume sizes of polluted groundwater emanating from 4-square mile developments at the three study sites. Groundwater quality in these plumes would be of the order of 25,000-50,000 mg/l of TDS, with very considerable hydrocarbon content.

TABLE 15-6

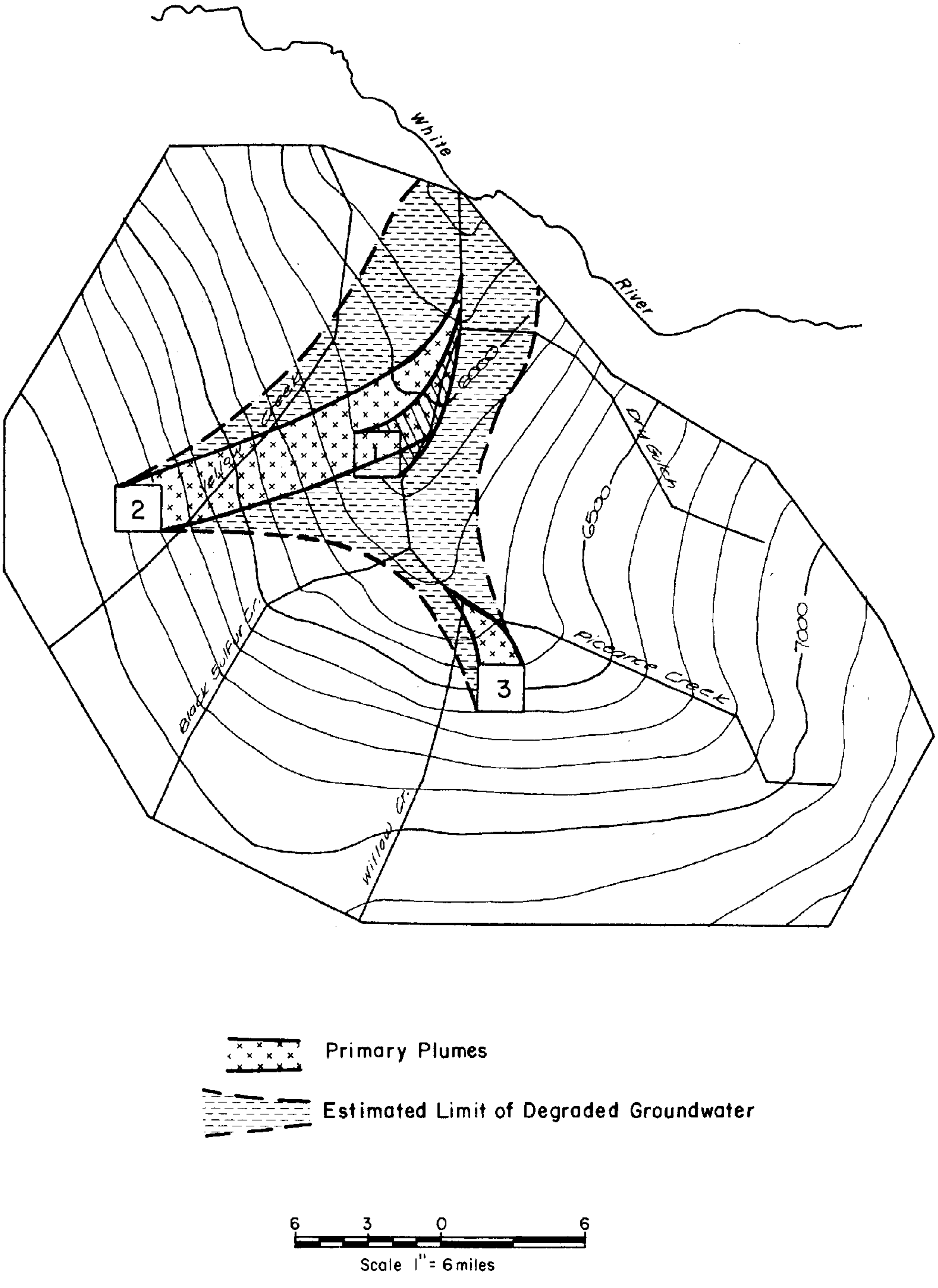
POLLUTION POTENTIAL OF BURNED-OUT IN-SITU RETORTS (30-YEAR, 30,000 BPD PROJECT)

ITEM	SITE 1	SITE 2	SITE 3
Total Salt Mobilized (Ton) (1)	9,000,000	9,000,000	9,000,000
Groundwater Flow Through Retorts (AFY) (2)	2,350	665	533
Rate of Salt Leaching (Tons/Day) (3)	980	273	222
Increase of Salinity at Mouth of Piceance Creek (MG/L) (4)	6,400	1,780	1,450
Minimum Duration of Leaching (Years) (5)	25	90	115

NOTES:

(1) Assumes 1% mobilized salt by weight.
(2) Assumes steady-state conditions.
(3) Assumes leachate at 50,000 mg/l.
(4) All leach flow will appear in Piceance Creek, even from Site 2.
(5) Assumes leachate at 50,000 mg/l until all salt removed. Actual times will be longer. Leaching will start between 10 and 100 years after abandonment of mine.
(6) Ignores dispersion and adsorption - see text.
(7) Leachate will take between 300 and 1,500 years to reach streams.

Figure 15-10 ESTIMATED PLUMES OF POLLUTED GROUNDWATER FROM IN-SITU RETORTS AT SITES 1, 2, AND 3


White River
Yellow Creek
6000
Dry Gulch
6500
7000
2
1
3
Black Sulfur Cr.
Piceance Creek
Willow Cr.
Primary Plumes
Estimated Limit of Degraded Groundwater
6 3 0 6
Scale 1" = 6 miles

#144 - 76628

This diagram ignores two effects which will serve to spread the plumes over a much wider portion of the Basin. First, the likely much higher permeability of the retorted area when compared with the host rock causes a spread-out of the resulting pollutant plume (McWhorter and Rowe, 1976). Figure 15-11 shows the effect for both low permeability and high permeability retorts. This effect could as much as triple the area over which polluted water would spread out. Second, dispersion will serve to further diffuse the saline plume from each of the study sites. Figure 15-10 includes an estimate of the total area of the Basin which could be impacted in this way by retort leaching.

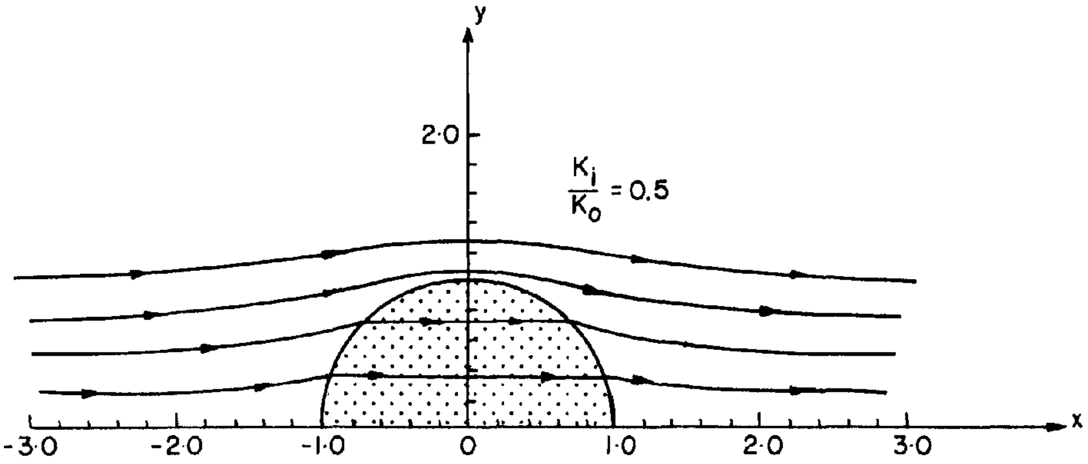
It is important to note that the time scale for these effects is large. It would require between 300 and 1,500 years for the polluted groundwater plume to reach the creeks, at which time the concentration of the plume might well be much attenuated by dispersion and retarded by adsorption. The effect of adsorption has been ignored in this crude evaluation because the saline facies in the rock mass and the history of deposition of the Basin rock strongly suggest that most adsorption sites will already be occupied by saline ions. However this assumption is highly conjectural.

The above evaluation is intended to indicate the possible magnitude of post-retorting impacts. One of the recommendations arising from this study is that a much more extensive study of this problem be performed as a matter of considerable urgency.

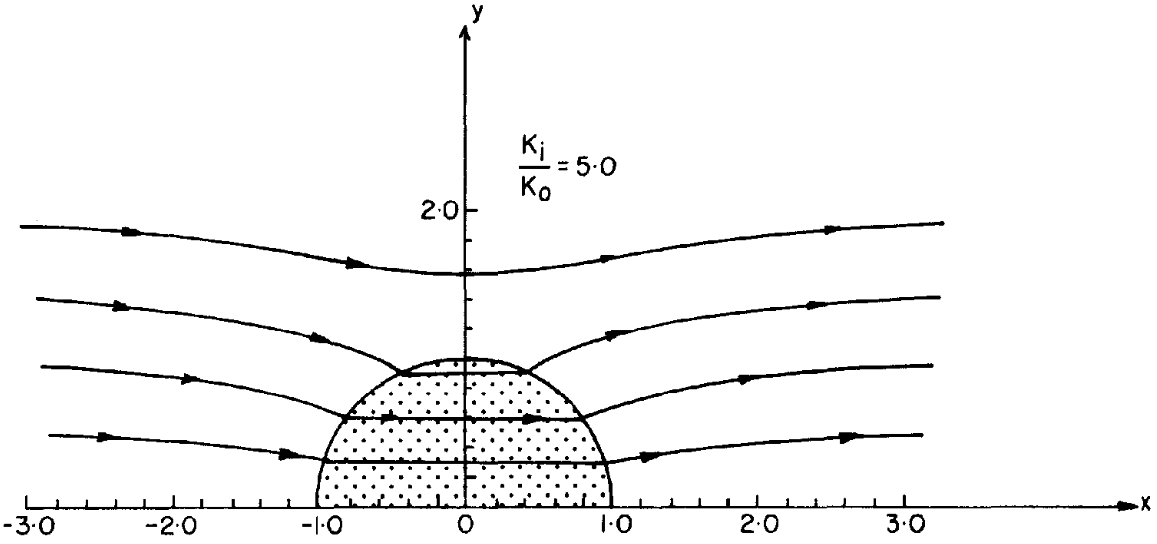
15.3.3 Possible Mitigation Measures

There are two main classes of mitigation measures available, if it is presumed that the above impacts are unacceptable.

Figure 15-11 PLAN VIEW OF A MINE IN UNIFORM FLOW


y
2·0
$\frac{K_i}{K_o} = 0.5$
x
-3·0
-2·0
-1·0
0
1·0
2·0
3·0

A. Flow pattern of streamlines in mined area, $K_i / K_O = 0.5$.


y
$\frac{K_i}{K_o} = 5{\cdot}0$
2·0
x
-3·0
-2·0
-1·0
0
1·0
2·0
3·0

B. Flow pattern of streamlines in mined area, $K_i / K_O = 5.0$.

Source: Mc Whorter and Rowe, 1976, p.4.

i. Immobilization. If the salts can be immobilized within the retort, then the pollution potential disappears. Several methods have been suggested. In order for this strategy to be effective, the average permeability of the retort zone would have to be reduced to about two orders of magnitude less than the original host rock permeability. This implies a post-treatment permeability of less than 0.01 ft/day (3 x 10^{-6} cm/sec or less). This would reduce incremental salt loading in Piceance Creek to less than 100 mg/l per 30,000 BPD industry.

Two methods have been suggested. The simplest is self-cementation of the retorts by the re-injection of foul water during the cooling phase. Although no data is known to exist, it seems highly unlikely that the required permeability goals can be met. The more promising approach is post-grouting of the retort. However, a conservative check of the cost of this measure using Portland cement grout and 10% retort void volume indicates that it would load the cost of the project by $15 (1974 dollars) per barrel of oil produced and is thus very unattractive. Grouting around the periphery of the project might be attractive, but any future tectonic activity would probably destroy the seal, liberating the mobilized salts.

ii. Leaching of Spent Retorts. This system would involve flooding the retort after combustion and pumping out the water until the salinity was at an acceptable level. The cost loading of processing the saline water thus generated would be of the order

> of $0.20 per barrel of oil produced, and the ancillary hardware might add a further $0.30 per barrel, for a total leaching cost of $0.50 per barrel of oil produced. This excludes the cost and impact of importing extra water for the considerable power requirement needed for the water handling and purification system. For a 30,000 BPD industry this activity would consumptively use 100 AFY of water for evaporation of the condensate, and would produce 300,000 tons of mixed bicarbonate salt per year. This is a substantial proportion of U.S. demand for this commodity, so disposal might prove difficult.

Based on the above, leached extraction of salts from the retorts would appear to be an economically viable approach to mitigation of the likely impacts of spent retort leaching. If this or a similar mitigation method is used there is no reason to expect that in-situ retorting will not be acceptable from the point of view of water management-related environmental impact.

15.4 EFFECTS OF LEACHING OF MINES BACKFILLED WITH SPENT SHALE

The effects of the leaching of mines backfilled with spent shale are similar to the effects presented above for leaching of spent in-situ retorts. There are, however, several important differences.

First, the permeability of the backfilled spent shale is likely to be considerably lower than the permeability of the rock mass into which it would be placed, and thus leaching would occur at a much slower rate than would be the case in the more permeable spent in-situ retort. This would have the effect of reducing the concentration of pollutants in the groundwater plume, reducing the concentration increase in the surface streams, and increasing the time of arrival of the peak concentration at the streams.

Second, the backfill will be placed in stable mines, so that only a relatively small vertical section of the total rock mass would be subject to pollution at the source. Depending on mine location, it might be possible to select backfill locations where leaching would not occur at a significant rate, due to low host-rock permeability.

Third, mitigation is virtually impossible. Pre-abandonment leaching would take an unacceptably large period of time. Further, the geometry of mine backfill situations does not lend itself to economical leaching systems.

As a consequence, it seems likely that backfilling of mines with spent shale is only environmentally acceptable where it can be shown that the mobile salts are effectively permanently sealed in the host rock, or where it can be shown that the permeability of the backfill itself is low enough to prevent significant salt release. Clearly further evaluation of this area is required before more definite conclusions can be reached.

CHAPTER 16
RECOMMENDATIONS

The recommendations presented below have been generated from areas identified in the study as important to the water-related aspects of oil shale development, and in which a presently inadequate level of knowledge exists.

We have attempted to outline the need and the reason that it is important, and the areas in which the present level of knowledge is inadequate. We have presented a suggested program of investigation to fill the need, and where appropriate have tried to estimate the level of effort required to perform the investigation.

The recommendations have in general been generated without regard to existing programs. Parts of several of the recommended activities are to our knowledge already underway. However, we have chosen to present a list of recommendations which we believe fill gaps in presently available data or study results.

16.1 DATA ASSEMBLY

> Recommendation: That a data and information bank be set up to make material related to oil shale more readily available.

The volume of information available to investigators in the oil shale industry is enormous. Particularly in geology, hydrology, shale properties, processing, disposal, and reclamation, there is a vast literature and data base. There is a need to assemble this data in one location, to rationalize it, to standardize the format in which it is stored, and to make it accessible.

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The approach which seems reasonable is to:

i. Decide on scope and format of information collection, storage, and retrieval.

ii. Select a site for the collection.

iii. Collect the existing data and information.

iv. Assemble and cross reference the collection.

v. Develop an updating system.

The estimated effort involved is 10 man-years to set up the collection, and perhaps 2 man-years per year to maintain it.

16.2 MINE INFLOW STUDY

Recommendation: That a methodology for predicting inflow in oil shale mines be developed and validated, and estimates of inflow generated for different sites in the Basin.

Mine inflow is important in evaluating mining economics, water disposal costs, mine safety, and designing mine drainage systems. Presently no proven technology for predicting mine inflow exists; nor does any established technology exist for evaluating two of the most critical parameters: vertical permeability and porosity.

The recommended program involves three steps:

i. Develop a test methodology by pre-analysis of proposed approaches of measuring the major parameters.

ii. Perform a prototype test program at a site in the Basin where an actual mine development is proposed.

iii. Instrument the actual test mine to determine the accuracy of the test predictions both with respect to inflow, and to pressure distribution around the mine.

The proposed USBM Demonstration Minesite would seem an appropriate locality at which to perform this program.

The estimated total effort involved in such a program is 3 man-years. Significant drilling, instrumentation, testing, and computer analysis would also be involved.

16.3 IN-SITU RETORTING STUDY

Recommendation: That a study of the water-related aspects of in-situ retorting be conducted.

Due to the lack of publicly available information on commercial size in-situ retort operations, it is very difficult to develop meaningful estimates of water consumption for in-situ retorting, post-retorting permeabilities in and near the retort chamber, post-retorting mobilizable salt concentrations, and the leachability of spent retorts. In order for regulatory agencies to evaluate the merits of proposed retort operations with respect to water management and abandonment, it is necessary to have independently obtained information on these parameters.

The recommended program could be performed in conjunction with either or both of the proposed prototype retorting operations on Federal Tracts C-a and C-b. The general dimensions of the program could be:

i. Development of a proposed investigation methodology.

ii. Installation of appropriate test equipment prior to retort firing.

iii. Evaluation of results and presentation of fundamental behavioral parameters.

iv. Re-evaluation of the water management and environmental aspects of in-situ processing presented in Chapters 14 and 15 of this report.

The effort involved in such a program is strongly dependent on the degree of cooperation received from the Tract leasees. A median figure of 7 man-years seems appropriate, with considerable drilling, instrumentation, and computational support.

16.4 BASIN-WIDE IMPACT EVALUATION

> Recommendation: That a more detailed evaluation of Basin-wide impacts of large-scale development be conducted, especially with respect to aquifer interconnection, post-mining retort and backfill leaching, and evaluation of the adequacy of the present Basin geohydrology data.

This report has presented simple evaluations of Basin-wide impacts due to aquifer interconnections and spent retort or backfill leaching. Although these studies help define the extent of the problem, many important questions remain unanswered, for example:

i. What are the probable aquifer interconnection problems in the northern end of the Basin?

ii. What are the effects of dispersion and adsorption on post-mining pollutant transport?

iii. What are the effects of mining in the northern end of the Basin upon the section of the Basin to the south of the Piceance Creek drainage area?

In order to evaluate these questions a more detailed Basin-wide study is needed.

The recommended program would involve a research study as follows:

i. Collection of data additional to that collected for the study reported in this report.

ii. Analysis of impacts using a computer code capable of modeling transient pollutant transport phenomena as well as Basin hydraulics.

iii. Development of mitigation strategies, and analysis of the effectiveness of these strategies using the above computer code.

This study is estimated to require 2 man-years, and significant computer time.

16.5 GEOHYDROLOGY DATA COLLECTION METHODOLOGY

Recommendation: That a program to develop an effective, simple, relatively inexpensive methodology for determining mining-related geohydrology data be performed, and tested in the field.

Most of the data presently available for geohydrology and water quality evaluations in the Basin is considerably too gross in scale for the evaluation of mining-related geohydrology. Methodology exists which could be modified to suit the conditions of the Basin to allow rapid, appropriate, inexpensive testing of Basin rock sequence permeability, completion of piezometers, and groundwater sampling. The proposed U.S.B.M. demonstration mine area would be an appropriate site to develop and test the recommended methodologies. The methods developed could later be used to provide infill data in parts of the Basin where information is lacking or inadequate.

The procedure envisaged for this research project would be:

i. A thorough review of existing oil field and geohydrology testing and completion techniques.

ii. Development of prototype equipment.

iii. Testing and evaluation.

iv. Presentation of findings including cost information, and equipment and technique specifications.

It is anticipated that a program to develop permeability test equipment, piezometric completion methods, and groundwater sampling installations might require 5 man-years of effort and substantial equipment, drilling, and site support.

16.6 STUDY OF STREAM/GROUNDWATER INTERACTION

Recommendation: That a study be performed to determine the relationship between streamflow and groundwater piezometric pressures, particularly with respect to:

i. streamflow depletion due to groundwater pressure reduction
ii. origin of springs and stream baseflow.

One of the primary environmental questions relating to water management in oil shale mining is the relationship between streamflow and groundwater. The recommended project would be designed to evaluate this relationship both theoretically and by field test, and to develop a standard test methodology for use in impact studies for proposed developments.

A recommended approach would be:

i. Perform analyses of stream/groundwater interaction to illuminate critical parameters and to develop a field testing protocol.

ii. Perform a field test to develop interaction parameters at a site where mining is likely to occur.

iii. Develop predictions of interaction.

iv. Monitor actual interaction as mining develops and modify testing approach if necessary.

An appropriate site for this evaluation would be the U.S.B.M's proposed demonstration mine site or Tract C-b, due to their proximity to Piceance Creek.

We estimate that the first three steps in the above approach might involve 2 man-years of effort, with the second step requiring substantial drilling and equipment support, and the first and third steps involving some computer analysis time.

16.7 WATER MANAGEMENT STUDY FOR TOTAL BASIN DEVELOPMENT

> Recommendation: That a study of the water management aspects of total development of the Basin resources be made.

The present study has evaluated the water management aspects of the development of relatively small-scale oil industries in three specific Basin localities. However, it seems likely that there is much to be gained from the synergistic effects of simultaneously developing a large portion of the Basin, especially in terms of water usage. For example, if groundwater were centrally collected, treated, and reticulated to several retorting sites, this might result in considerable economies of scale. Likewise, the overall Colorado Basin might well benefit from consumptive use of all of the surface run-off from Piceance Basin, as its salinity significantly degrades downstream water quality. Such an approach would call for storage, treatment, and reticulation of this water, which can only be practical for a very large, integrated shale oil industry.

Such a study is needed:

i. to help to define the ways of achieveing the maximum net benefit from a shale oil industry,

ii. as a guide to long-term action,

iii. as a guide to legislation on water and land use matters for the Basin.

Because of the large scope of such a study, we have made no attempt to detail approach or effort required. However, it is clear from the present study that small industries cannot be viewed in isolation, due to the widespread effects which they create, and their competition for the limiting resource: water.

CHAPTER 17
CONCLUSIONS

17.1 GENERAL CONCLUSIONS

The objective of this study has been:

> "to devise methods of water management with cost data which are technically feasible and environmentally acceptable for three different locations in the Piceance Basin and for various mine sizes and methods". (U.S.B.M. Contract J0265019)

The water management systems have been presented in Chapter 11 (conventional mine/surface retort complexes) and Chapter 14 (true and modified in-situ retorting). General conclusions arising from the study are as follows:

1. Shale oil production is in general very water consumptive: conventional mine/retort complexes require the supply of 5 barrels of water to produce 1 barrel of oil, while in-situ retorting complexes require the supply of 2.5 barrels of water to produce 1 barrel of oil.

2. All of the shale oil production systems in which on-site power generation is included achieve zero discharge of water. Consumption goes primarily to steam and evaporation.

3. Because of the high level of water consumption and the limited water available, it seems likely that an oil shale industry in the Piceance Basin will be limited to an output of about 2 million barrels of oil per day.

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4. It seems clear that the first oil shale developers will seek to use the limited groundwater resource of the Basin as a water supply. However, significant development of the Basin's oil shale resources will require imports of water from outside the Basin.

5. Consumptive groundwater use will have a significant and widespread impact on piezometric pressures, spring flows, and streamflows in the Basin. Augmentation and/or damage payments will probably be required to mitigate these effects.

6. Mine inflow will in general exceed the consumptive use requirements of shale oil industries in the 50,000 barrels of oil per day range or less. Re-injection of the excess into the aquifers from which the water originated seems the most economical and environmentally acceptable disposal strategy.

7. Water resources in and near the Piceance Basin are virtually fully committed. Thus developers in the Basin will have to purchase water rights, or purchase direct water supplies from rights holders.

8. There are no major negative post-mining impacts of development upon the hydrology of the Basin which cannot be economically mitigated by appropriate activities during the mining phase. However, spent shale backfilling of underground mines in oil shale aquifers may not be environmentally acceptable.

9. Although the general level of understanding of the water-related aspects of the Basin is adequate for evaluations of

the type performed in this study, it is clear that a considerable amount of additional work will be necessary before effective regulation of the water-related aspects of Basin development can be achieved. Recommendations for a number of studies have been made.

17.2 OVERVIEW

This study has served to highlight the common aspects of most water management considerations in the Piceance Basin. Several inescapable facts continually reappear:

i. Shale oil extraction is relatively water consumptive.

ii. Water is very limited within the Basin, and is becoming more limited outside the Basin.

iii. Environmental protection of the water resources of the Basin is difficult and expensive.

It is clear from this study, as it has been from others, that water availability will probably be the limiting factor in shale oil exploitation, once the present economic limitation has been overcome. Available water supply appears adequate for production of perhaps 2,000,000 barrels of oil a day as a maximum.

Unless mitigating steps are taken, large scale developments in the Basin will have significant effects upon groundwater levels and streamflows in the Basin. There are a number of possible responses to this situation. One is to insist that developers maintain pre-development conditions outside their lease boundaries at all times. While this is technically feasible, the burden on the economics of the project, and the cost of the resources used to achieve this condition, may create a net negative benefit to the community.

A second approach could be to maintain streamflows, and to compensate any other potential groundwater user for the depletion in piezometric head which the development has created.

A third approach could be to define the Piceance Basin as a special area, and re-define the water laws and environmental impact standards to suit the specific conditions of the Basin.

Whatever is done, we hope that this report helps to define the water management parameters and analytic tools as they presently exist. Many of the questions which might be asked about the Basin's hydrologic system can be answered, and future impacts of planned events can be determined with entirely adequate precision using existing technology. It is clear from this study that there are still a broad range of unresolved questions relating to water management in a shale oil industry. However, it can now fairly be said that there is no reason why any action in the Basin should have a major unexpected hydrologic impact.

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