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GROUNDWATER DEVELOPMENT IN ARID BASINS

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The committee hopes that the printed volume will help make the Symposium of lasting value to all those who read the proceedings.

J. Stewart Williams, Chairman
Jay M. Bagley
Calvin G. Clyde
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TABLE OF CONTENTS

GROUNDWATER IN ECONOMIC DEVELOPMENT

by

Dean F. Peterson [1]

Summary

Groundwater development frequently provides a means whereby tremendous new economic opportunities are opened up. If supplies are overdrawn (mined) the ensuing regional economy may be able to afford replacements from more costly sources. In the United States the Salt River Valley of Arizona and the valleys of California provide examples.

Two cases are treated in this paper, Israel and West Pakistan. In Israel, besides furnishing more than half of the basic source of water supply, groundwater development provides opportunity for both quantity and quality management, which makes possible use of surface supplies and reclaimed sewage as firm rather than marginal sources. This development will permit the total water resource of this small country, where agricultural production ranks among the world's most efficient, to be utilized effectively down to almost the last drop by the mid 1970's. Israel must then look to desalted water from the sea for further expansion of its overall water supply.

In West Pakistan a combination of level terrain and leaky canals since about 1890 led to threatened waterlogging and salinity of more than 25 million acreas of irrigated land, even though supplies were less than half adequate for good productivity. By the 1950's low yields and increasing population threatened starvation. However, initiation of groundwater development, first by the government and later by private enterprise, has, since 1960, led to construction of 3,500 governmental tube wells of about 3 cfs capacity and 30,000 private tube wells of slightly less than 1 cfs capacity.

Results have been dramatic. Agricultural production and use of fertilizer are rapidly increasing, and opening of well development to private enterprise is providing the irrigator with benefits of free competition for his water custom which he did not previously enjoy. Ultimately, besides providing full supplies for an estimated 26 to 30 million acres, drainage and salinity problems will be mitigated if about 50 million acre-feet are pumped each year from groundwater including about 28 million acre-feet to be mined from a reserve of about 1,900 million acre-feet. With some difficult surface storage development due to terrain, mining may eventually be reduced. Though an eventual technological solution for the continuing overdraft is not now in sight, perhaps an economy may be built which can afford such a solution when the time comes.

Utilization of Groundwater in Israel

With the conquest of Israel by the Jews in 1948, immigration of more than a million people to this small country plus natural increase of indigenous inhabitants caused population to increase from about 650,000 in 1948 to 2,600,000 in 1965 (Central Bureau of Statistics, 1966). This settlement has been accompanied by a dramatic increase in agricultural production and utilization of irrigation water. Based on 1949 prices, the value of agricultural crops has risen from I.L. 44.4 million in 1949 to I.L. 271.1 million in 1965; (price level has risen about four times so that at current prices

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the 1964-65 crop was worth I.L. 1,345.9 million or $448.6 million). (Central Bureau of Statistics, 1966, and Tahal, 1966.) Total consumption of irrigation water has risen from 257 million cubic meters (MCM) (208,000 acre-feet)[2] in 1948-49 to 1,100 MCM (880,000 acre-feet) in 1964-65. Irrigated area increased from 300,000 dunams (75,000 acres) in 1948-49 to 1,580,000 dunams (395,000 acres) in 1964-65. (See Fig. 1.) While there were comparable increases in dry farming, irrigated agriculture is the mainstay of Israel's economy, and exports of citrus and other fruits and vegetables provide the largest net source of foreign exchange– about I.L. 315 million[2], $105 million, in 1965. Total national income has grown from I.L. 827 million in 1950 to I.L. 8,209 million in 1965. Agricultural production per unit area of land is currently among the highest in the world and nutrition levels are excellent (2,830 calories per day). Economic projections indicate that the net marginal productive value of water in agriculture will be 25 to 30 cents per 1,000 gallons by the mid 1970's. (From projections made in Mundak, Yair, 1964, and other sources.)

But there are factors which prevent operation at full economic efficiency because of values which society places on a particular pattern of development. In Israel these are commitments to village-based agriculture and to national defense. MacAvoy and Peterson have estimated the incremental increase in productivity of investments in agriculture already made, apparently for social reasons, to be an additional 10 cents per 1,000 gallons. They argue that this is a measure of the social value of water in agriculture to Israel.

Groundwater has played an important role in the development of this small country. Geology is relatively complicated due to the country's location between the Precambrian Arabian Shield and the moving "Thetys" geosyncline of the Eastern Mediterranean (Tahal, 1966). Of interest, of course, is the Jordan Graben on the East, which is an extension of the Great African - West Asian Rift. Rainfall north of the Negev rapidly increases from about 200 mm at Be'er Sheba to more than 1,000 in Galilee in the North, and decreases rapidly to 30 mm in the South and Dead Sea area. Frost sometimes occurs in the hills and Jordan Valley but is not normal on the coastal plain.

The various groundwater provinces are shown in Fig. 2. (Tahal, 1966.) Because of geological complications no general statement can be made about productivity of aquifers—each province needs separate consideration. Modern irrigation development under Jewish resettlement in Israel began about 80 years ago. Most of the exploitations were based on small-scale developments of local groundwater sources; however, by the 1930's some regional projects conveying water from several wells to entire regions had been constructed. A summary of irrigation development at that time is shown in Table 1 (Tahal, 1966).

Table 1. Summary of Jewish irrigation development in Israel in 1948

Region	Number of Settlements	Irrigated Area Dunams	Source of Irrigation Water
Coastal Plain	177	202,000	Primarily groundwater
Inland Valleys	89	70,000	Gravity and low-lift pumping from rivers and springs
Uplands and Negev	60	20,000	Water from distant pumping plants

[2]One million cubic meters = 810.7 acre-feet. One dunam = 0.25 acres. One Israeli pound (I.L.) = $0.33- 1/3.

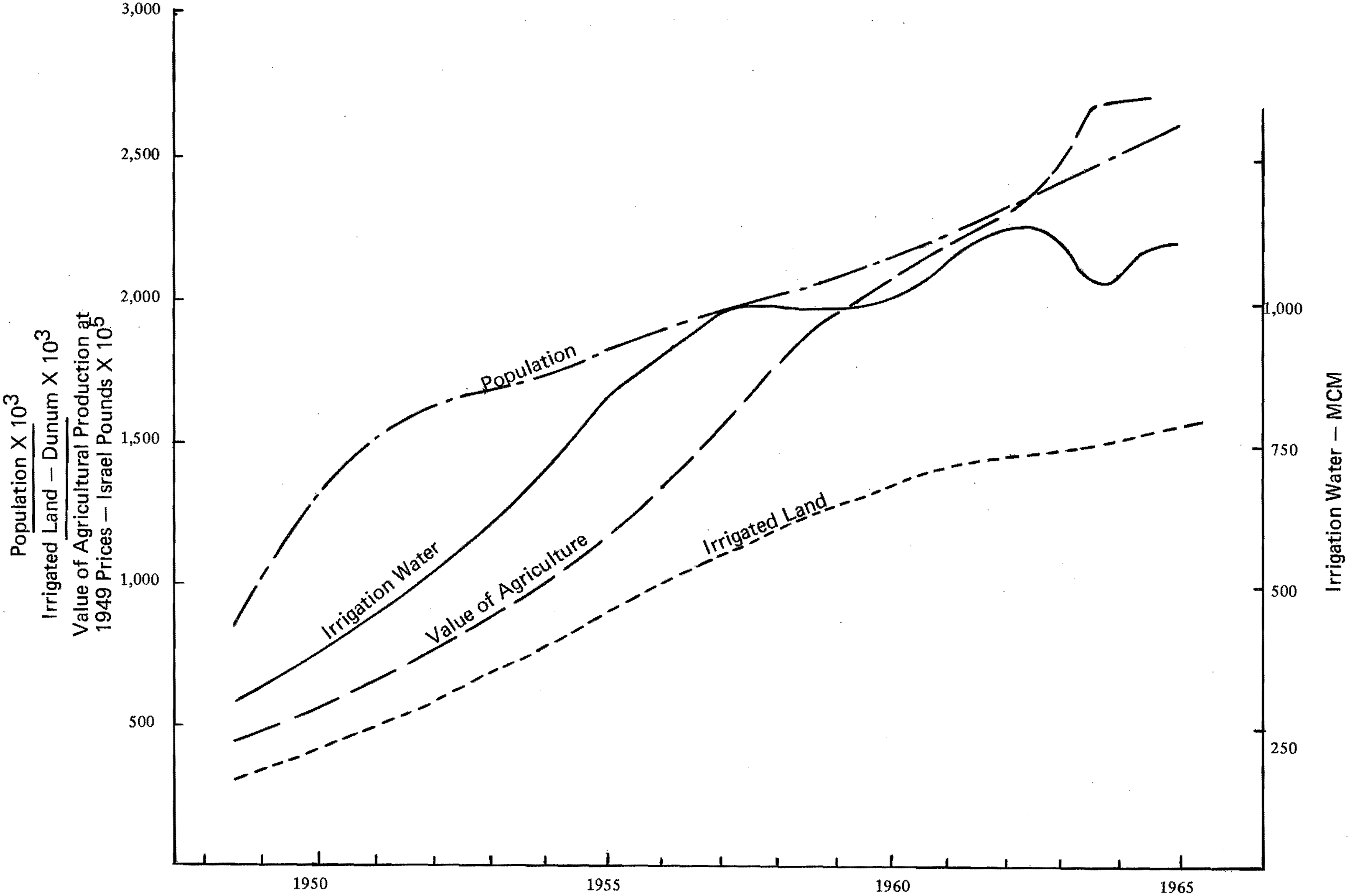

Figure 1. Growth of Population, Irrigation and Agriculture in Israel.

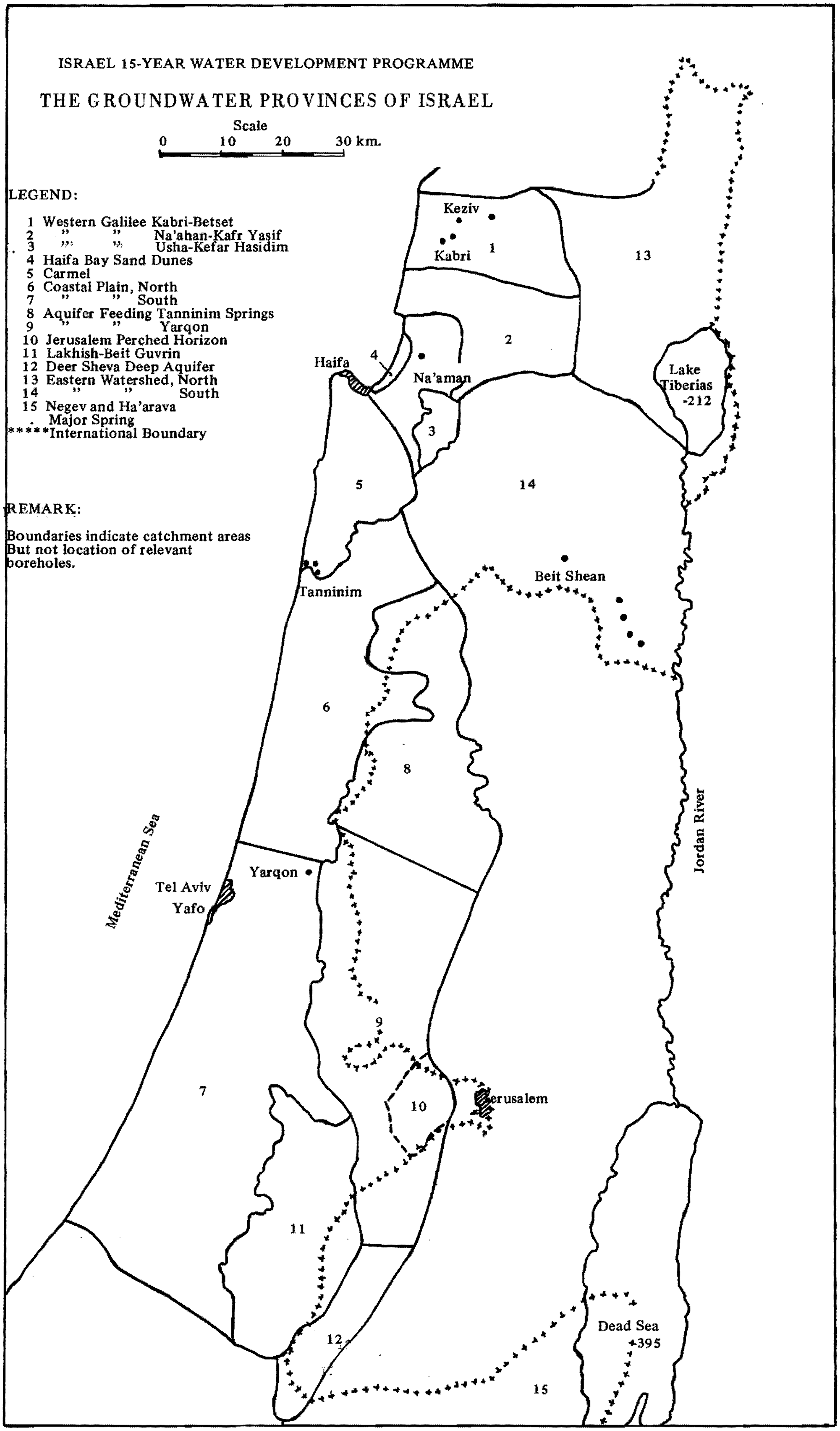

Figure 2. Groundwater Provinces in Israel.

By the 1960's Israel had begun to overdraw groundwater resources fairly heavily in some areas. In 1963-64 sources of water for the 1.5 million dunams of irrigated land and for municipal and industrial use supplied 1,200 MCM annually – of this amount 953 MCM came from sustained yield of surface and groundwater supplies and 247 MCM from groundwater overdrafts. Israel's long-range plans include utilization of about one-half the flow of the Jordan basin, or approximately 430 MCM per annum of which 280 MCM per annum would be pumped into a national aqueduct serving the inland valleys and the coastal plain. (See Fig. 3). With construction of the 108 inch Main Conduit and the Eshed-Kinrot Pumping Station of the Lake Tiberias-Negev project in 1963, almost all of the water supplies of the country have been physically integrated into the national system. Wide flexibility of exchange is possible, and the groundwater overdrafts can be stopped. The net marginal value of the groundwater overdraft of 321 MCM (260,000 acre-feet) in 1962 at a marginal net value in agriculture of 15 Agorot per cubic meter[3] would be 48 million Israeli pounds of about $16 million ($61.35 per acre-foot). The average gross value of agricultural production is I.L. 1.18 per cubic meter (Tahal, 1966) or I.L. 380 million ($126 million) for 1962. Table 2 shows sources of water supplies for the years 1962-63 to 1964-65.

Annual natural water supplies vary from about 500 MCM to 2,500 MCM and some drought periods may last several years. For this reason extensive storage is necessary. Originally live storage of 1,500 MCM was planned for Lake Tiberias but, because of saline springs, this has been projected at 500 MCM and extensive aquifers in the south will be utilized for storage reservoirs. Simulated models and operations analysis show underground storage needs approaching 2,000 MCM in order to maintain firm supplies. Fig. 4 shows estimated future needs and supply.

Groundwater will be managed in such a way that seawater intrusion will be limited to a certain prescribed distance from the coast and a groundwater collection system parallel to the coast will skim off the shallow fresh water overlying the saline intrusion to salvage another 25 MCM per annum.

The 1970 sustained yield is projected as follows:

Jordan River Basin	410 – 460 MCM
Groundwater	800 MCM
Coastal groundwater collector	25 MCM
Reclaimed sewage effluents	90 MCM
Storm runoff	75 MCM
	1410 – 1450 MCM

Israel's water resource plans are certainly the most sophisticated in the world. Every possible source of water is being exploited and efficiencies in irrigation are extremely high. An annual average irrigation requirement of only 535 mm (about 18 inches) is projected. By the mid 1970's Israel desires to add desalted water from the Mediterranean to its supply. Estimated costs (at 8 percent interest) of new water supplies from various sources given by Tahal (1966) follows on page 9.

Besides utilizing groundwater to firm up variations in quantity, the groundwater resource also permits solution of difficult quality problems. Tiberias supplies vary from 300 to 400 ppm chlorides, and groundwater sources are used to dilute these to 170 ppm in the north and 250 ppm in the south. Reclaimed sewage, which will provide about 90 MCM at 380 ppm chloride, will also need dilution. Thus the groundwater resource not only will be used to stabilize quantity, but quality as well.

Summary

Clearly Israel's agriculture and the resulting total economy have been brought about largely through utilization of the groundwater resource. A major social goal of Jewish resettlement to place people on the land and groundwater development has made this possible. All possible natural sources of water supply will be utilized by about 1975 under a system which is highly sophisticated not only in terms of physical plant but in operational management as well. Groundwater will still provide more than one-half of the firm supply. Development of the economy involved appreciable overdrafts

[3]Based on 18 to 21 Agorot per cubic meter estimated marginal value in 1970 and 3 percent annual increase since 1962. One Israeli pound equals 100 Agorot.

MAP OF ISRAEL WATER DISTRIBUTION NETWORK

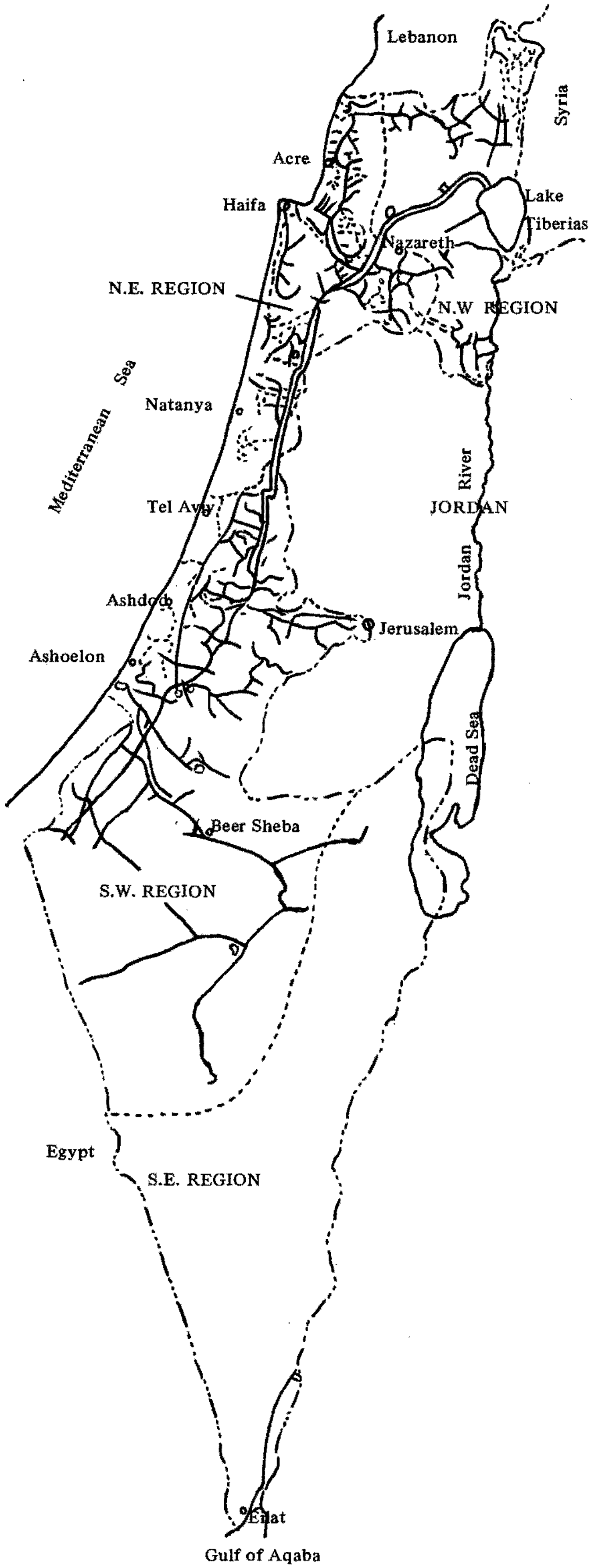

Figure 3. Central Water Distribution System (of the Joint U.S. – Israeli Team. Office of Saline Water. 1964)

WATER SUPPLY ESTIMATES FOR THE 1962–1965 PERIOD

(MCM p.a.)

SOURCE	1962 – 63			1963 – 1964			1964 – 1965		
	Total use	Over-draft	Sustained yield	Total use	Over-draft	Sustained yield	Total use	Over-draft	Sustained yield
Sand and sandstone aquifer	490	288	202	478	247	723	400)	154	735
Mountain aquifer	534	33	501	492	–	–	489)		
Storm runoff	17	–	17	17	–	17	17	–	17
Jordan River	213	–	213	213	–	213	323	–	323
Coastal groundwater collector	0	–	–	–	–	–	1	–	1
TOTAL:	1,254	321	956	1,200	247	953	1,230	154	1,076

ISRAEL 15–YEAR WATER DEVELOPMENT PROGRAMME

WATER CONSUMPTION GROWTH
VS. WATER SUPPLY POTENTIAL
1962 – 1980

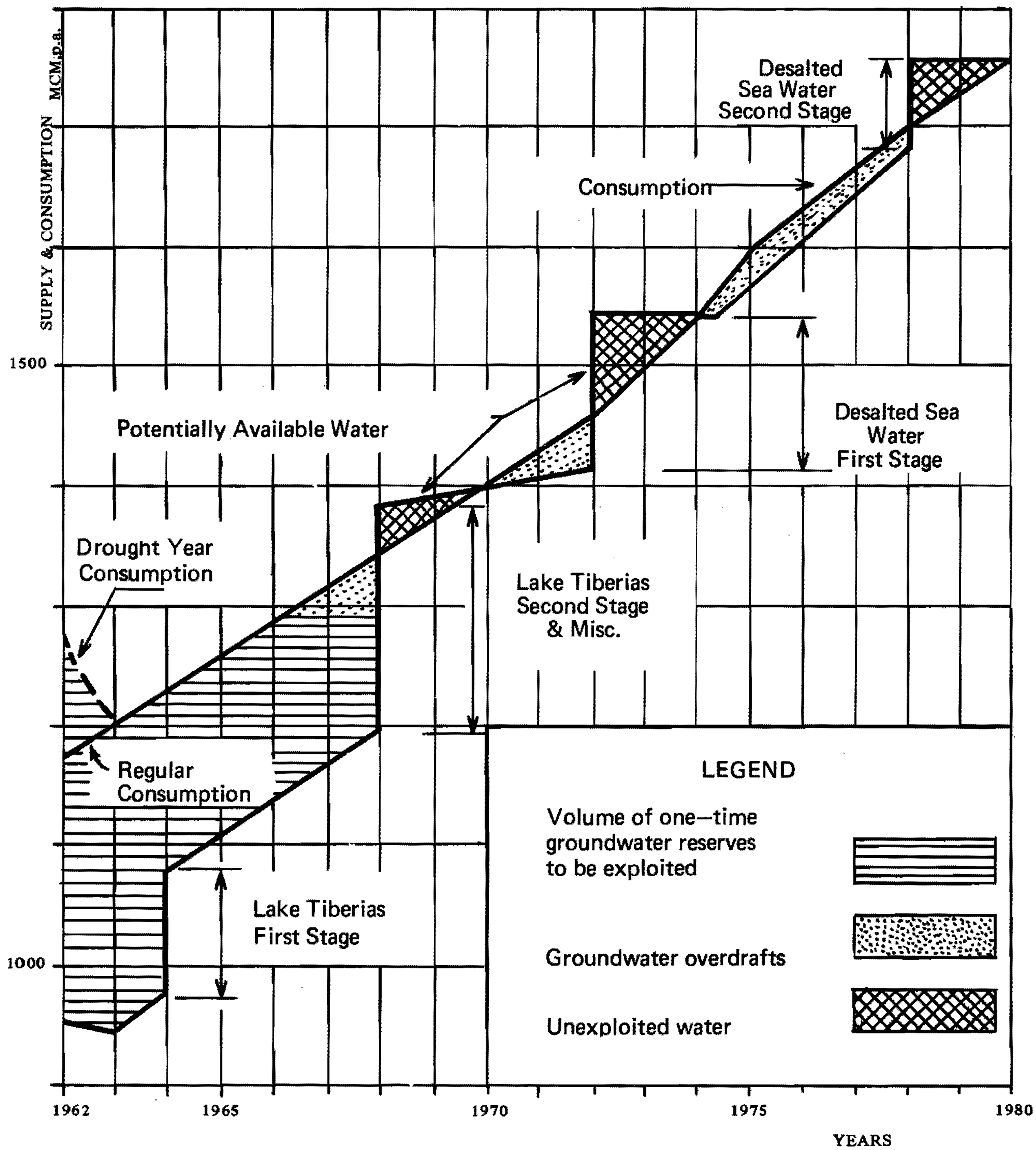

Figure 4. Water Supply and Growth in Israel.

during the late 1950's and early 1960's until Jordan River supplies could be made available to interior valleys and the coastal plains; but the use of groundwater as a peaking source to level out annual and regional variations not only in quantity but quality as well is an essential and major element in the continued economic development of the country. With no foreseeable increase in natural supplies, Israel's next step will be desalting seawater. The gap between cost and value of desalted seawater is still large, but an economy stimulated by groundwater development may one day close this gap.

Source	Annual Yield MCM	Cost	
Groundwater	61	9 Ag/CM or 11 cents /1000 gal.	
Storm runoff	59	19.5 Ag/CM or 25 cents/1000 gal.	
Sewage reclamation	87	7 to 18 Ag/CM or 9 to 23 cents/1000 gal.	
Lake Tiberias – Negev Extension	90	—	—
Coastal groundwater Collector	24	9.5 Ag/CM or 12 cents/1000 gal.	
Desalting *	—	—	55 to 60 cents/100 gal.

* Scheduled for 100 MCM by mid 1970's. Desalted water has an additional value for dilution over natural water in Israel, which could amount to cents per thousand gallons.

Groundwater Development in West Pakistan

At the other end of the size scale from Israel is Pakistan, the fifth largest nation in the world; and in West Pakistan, the World's largest contiguous irrigated area. The Sutlej, Ravi, Chenab, Jhelum and Indus [4] emerge from their westerly courses through the Himalaya and turn southerly to join on the fertile and level Indus Plain discharging some 150 million acre-feet annually. (See Fig. 5.) Irrigation has been practiced to some degree since ancient times, but modern development on the Indus began in 1859 with erection of a barrage on the Ravi to feed the Upper Bari Doab Canal. (Asghar, 1960). But it was until 1885 before irrigation actually began (Nath, 1958). By 1948, 10,000 miles of canals some nearly as large as the rivers themselves, commanded 23 million acres. (Harvard Water Resources Group, 1965.) A gridlike pattern of "canal colonies" cultivated the adjacent land –the soil was fertile and the population rapidly increased.

[4] Punjab Five Waters in Urdu. Doab, Two Waters in Urdu.

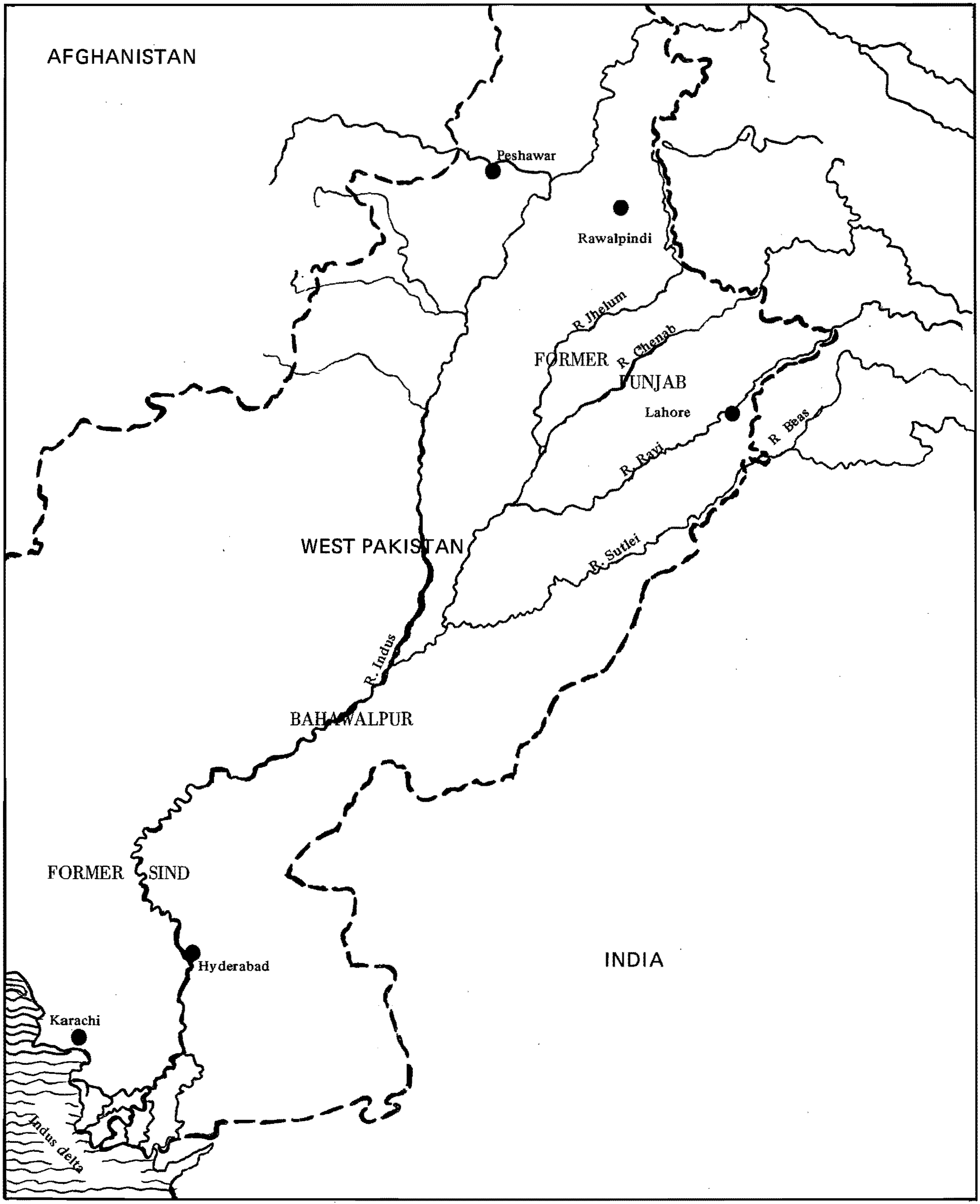

Figure 5. Map of West Pakistan

All was not well. The inherent low slope of the plain, about one foot to the mile, made waterlogging a certainty and water supplies were spread too thin--perhaps because of fear of waterlogging, optimism of the designer about water supply, or of colonization policy largely based on revenue considerations, but probably all three. Ironically, even though gross water applications were too low to wash the salts down, these and canal leakage still caused waterlogging in many areas. By 1963 (The White House – Interior Panel, 1964) 5 million acres had been seriously damaged and this was increasing at the rate of about 100,000 acres per year. Producing about 75 percent of the food and fiber for the now 50 million inhabitants of West Pakistan, productivity under the primitive agriculture existing was among the lowest in the world and dietary levels had reduced to less than 2,000 calories per day with less than 8 grams of animal protein. (Population growth rate of 2.5 to 3 percent outstrip productivity increases of only about 2 percent.) While cropping is possible year-round, the complicated system of rotating fallow led to cultivation of less than half the land in any one year. Water supplies were quite inadequate and the drainage hazard too great to risk modern agricultural inputs. With headworks in India, after partition, availability of waters of the Sutlej and Ravi to West Pakistan were materially reduced.

Strangely, but correctly, reclamation of designated areas of badly salted soils were attempted by <u>increasing</u> the water allowance under the management of a <u>Soil Reclamation Board</u>; but poor drainage, of course, limited this potential. By 1953, under FAO assistance, the Pakistan Government had begun experimentation with tube wells as a means of providing drainage and additional water supply in reclamation areas. (Olafsen, 1955). The need for developing upstream reservoir storage and hydroelectricity, and a large link canal to bring the flow of the more westerly tributaries to the Ravi and Sutlej to replace the waters diverted in India led to formation of West Pakistan's <u>Water and Power Development Authority</u> (WAPDA) and by the late 1950's initiation of its famous SCARP I (Hamid, 1964) whereby 1,800 tube wells were to be drilled in Rechna Doab (between the Ravi and Chenab) to drain and provide increased water supply for 1.2 million acres. Concurrently WAPDA began development of extensive natural gas deposits to provide the electricity. SCARP I was completed in 1962. Wells are drilled 18 or 22 inches in diameter from 250 to 300 feet deep and produce an average of about 3 cubic feet per second each.

In 1961, a study of the Indus Basin problem was begun by a joint White House-Department of Interior Panel (1964) under Roger Revelle. This panel fully recognized the physical and economic problems of the area and, utilizing the extensive groundwater investigations which preceeded SCARP I as well as other information from many other sources, made extensive systems analyses in which groundwater played a central physical role. About 1,900 million acre-feet, more than 10 times the annual flow of the Indus are stored in the deep sediments of the Indus Plain above 450 feet depth. While physically the structure of the aquifer is relatively simple, there is wide variation in water quality and its physical distribution is complicated. The Panel recognized groundwater as possessing wonderful potential for quick and relatively inexpensive exploitation both to supplement river water supplies and to provide drainage. Even though well water quality may vary between wide limits (in the northern zone 80 percent of the area is underlain by groundwater having a total salinity less than 3,000 mg/liter), the flexibility of well installation and opportunity for blending with river supplies, which contain only about 250 mg/liter salinity, led to a conclusion that cropping intensity levels of up to 150 percent (annual area of crops x 100/area) could be reached using 4,000 ppm well water. (Kalmbach, 1966.) The Panel recognized the many advantages of well <u>drainage</u> including: horizontal drains must operate with a relatively high water table and do not have the advantage of increasing and stabilizing the water supply; horizontal drains are a passive system, the amount of water discharged depends entirely on the amount applied to the land and the amount of salt removed depends on the salinity of the upper layers of groundwater, but with wells drainage can be carried out continuously at any desired rate and salt can be returned to rivers during periods of high runoff; horizontal systems waste drainage water because its salinity cannot be controlled; well drainage is easier to apply in a flat topography under intensive irrigation because it avoids the problem of crossings with conveyance channels; open drain systems are wasteful of land; deep open drains are difficult to maintain; stagnant water in open drains may constitute a health hazard. With well drainage one can change the leaching ratio without changing the other variables simply by increasing the amount of pumping and irrigation application.

Water Budget

The Revelle Panel (The White House — Interior Panel, 1964) estimated that from a firm yield of 136 million acre feet, surface diversions could be raised by about 18 million to 92 million acre feet. Evaporation from reservoirs, other unavoidable evapotranspiration and nonrecoverable seepage would account for 18 million acre-feet, leaving 26 million acre-feet to flow to the sea.

Of the 92 million acre-feet, 48 million acre-feet would be diverted to former Punjab and Bahalwalpur. Fourteen million acre-feet of the diversions would be lost from canals and 6 million acre-feet from the rivers. In addition, 22 million acre-feet of fresh water would be mined from groundwater reserves. With unavoidable losses this would provide 59 million acre-feet out of 76 million (diversions less seepage plus pumpage) for irrigation and salinity control — double the amount now provided. Pumpage would total about 50 million acre-feet annually. With mining, this would fully irrigate 16.4 million acres, but only 11.6 million acres if no water is mined.

In the Sind, of the 44 million acre-feet diverted, 11 million acre-feet may be lost by canal seepage and 6 million from nonbeneficial evapotranspiration. Wells drawing from the relatively sweet water supplies near the Indus may provide from 4 to 12 million acre-feet. This will provide an estimated 35 million acre-feet for irrigation supply; enough for a full supply for 9 million to 11 million acres.

Successful operation of the project also requires that wells be used for quality management. This means pumping and exporting groundwater from areas of dangerous salinity to the river during flood stages or to interior basins in order to prevent spread of salinity to pumped regions of better quality.

By providing storage of about 41 million acre-feet, some of it underground, eventually mining can be reduced to about 11 million acre-feet (this will be desirable because of increasing salinity) and irrigation supplies to former Punjab and Bahalwalpur can be increased to about 66 million acre-feet and to 40 million acre-feet in the Sind. This will permit irrigation of an additional 1.9 million acres in former Punjab and Bahalwalpur and 1.4 million acres in Sind. Present plans call for surface storage of 32.4 million acre-feet behind Mangla, Tarbela, Dhok Pattian, and Makkad dams. Underground storage in the 23-million acre nonsaline groundwater reservoir of the north could provide the required additional 8 million acre-feet with a rise and fall of the water table of only 1.5 feet.

Present and Future Developments

With success of SCARP I additional governmental tube well units are being constructed and as many as 34,000 government tube wells were planned. About 3,500 are now in operation (Anon, 1966). SCARP I design was based on reducing the duty of one second foot of water from about 350 acres to 150 acres — or essentially doubling the supply. But like irrigators everywhere, the ones in Pakistan prefer plenty of water and wells are being operated 65 to 70 percent of the time instead of the designed 35 percent Production has increased 29.4 percent under SCARP I and use of chemical fertilizers is rapidly increasing.

Reclamation has been dramatic. Of 427,717 acres wholly or partially out of production 248,900 acres were reclaimed by October 1, 1965, and water tables have been lowered by about 8 feet (Anon, 1966). Startlingly, 30,000 additional wells, smaller to be sure (100 feet in depth yielding about 0.9 cfs), have been installed since about 1960 and this number may reach 60,000 in three more years. Capital investment is recovered by owners of these wells in two or three years and the government is said to be questioning the need for further public investment in production wells as such. Success of private enterprise has doubtlessly changed things. No longer is the cultivator quite so much the captive of the complicated bureaucracy which seems inherent in surface irrigation systems everywhere and is particularly massive and impenetrable in the large government irrigation establishments of the Indian subcontinent. The ability of the farmer to purchase his water — as much as he wants — at a competitive price, with quantities fairly measured to him when he wants it, certainly will have a profound effect on morale and production. Hopefully, future taxation, land rental, and water pricing policies may leave room within this new production capability for the hopes and incentives of 25 million desperate farmers, and also a great nation, to achieve some consummation of success.

While some mining, 28 million acre-feet annually from reserve about 100 times that large, is necessary for the first phase; irrigation still can be expanded from these targets as surface storage reservoirs come into service, and mining demands can be cut back as the water level drops below 100 feet. This is not a permanent solution because there is no way to replace the mined water, but by doubling the usable water supply and virtually eliminating drainage and salinity problems it can go a long way toward closing the nutrition gap in West Pakistan over the next two or three decades. An eventual source of water to replace that mined is not now in site, but groundwater development may have provided the break-through toward an economy which can offer a new technological solution when the time comes.

Costs

Besides rapid development potentials, capital costs of groundwater development may be of the order of ten limes less than those for suface water. In the northern sector, costs of electrified wells were estimated (The White House – Interior Panel, 1964) at $41 per acre with an additional $20.7 per acre for drains, salt exportation, and transportation of pumped water in canals. In the Sind, costs were estimated at 25 to 40 percent higher. A recent review by the writer of costs of several dozen surface irrigation projects throughout the world showed these to range from $200 to $2000 per acre and to average more than $500 per acre.

Summary

Development of surface supplies in the nearly-level Indus Plain has resulted in the threat of waterlogging and salinity to some 25 million acres of irrigated land; yet, at the same time, water supplies delivered are inadequate by at least a factor of two to permit even minimum production levels achieved elsewhere in the world. Increasing population is rapidly outrunning production by about 1 percent per year and nutrition levels are already far below acceptability. By extensive groundwater development and some mining – 1 or 2 percent of the reserves per year – adequate supplies can be provided for about 26.5 million acres in former Punjab, Bahalwalpur, and Sind and with surface storage developments and feasible groundwater storage this can eventually be raised to 30 million and the waterlogging salinity threat removed. About 50 million acre-feet of groundwater must be pumped each year in the Upper Indus Valley plus perhaps 8 million in the Sind.

Installation of some 3,500 tube wells producing on an average of about 3 cfs each and serving 4,000,000 acres by the government since 1962 has demonstrated the effectiveness and profitability of groundwater development so well that 30,000 wells (each having about one-third the capacity of the government's wells) have already been installed by private enterprise. Results have been dramatic. Production has increased on SCARP I (the first government project) by 30 percent; use of fertilizer is rapidly increasing and reclamation of waterlogged and saline lands has been rapid. Entry of private enterprise has opened a new dimension of service to the cultivator because of competition – he can get water in desired quantities when he wants it at a competitive cost.

No solution is in sight for the eventual problem of providing a replacement for the mined groundwater source, but if the farmer's incentives, which he has not previously enjoyed, are protected; West Pakistan could perhaps develop an economy which could afford a technological replacement when the time comes.

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DETERMINING PERENNIAL RECHARGE [1]

by

Harold E. Thomas [2]

We all know that groundwater recharge, whether from rain or snowmelt or streams or lakes or canals or water distributed on the land for irrigation or other purposes, must vary as those sources of water vary. Perennial recharge is thus a human concept, an average rate, somewhat like the average annual surface runoff from a mountain drainage basin. Generally, however, we cannot measure the fluctuating rates of recharge, and so we have no long-term records for determination of average recharge. Thus, determining perennial recharge is necessarily by indirect methods. I have been involved with the problem in several of Utah's groundwater basins, and I would like to treat the subject historically, because in that way I can trace the evolution of some of our scientific concepts concerning groundwater in Utah.

I came to Utah in 1935, indirectly as a result of two decisions by the Utah Supreme Court. Prior to 1935 most groundwater was regarded as appurtenant to the land, first under the common law rule that the landowner had absolute ownership, and subsequently that the landowners had a right correlative with their proportion of the surface area overlying an artesian basin. In January 1935 the Supreme Court announced, first in the case of Wrathall vs. Johnson (86 Utah 50, 40 Pac (2d) 755, 1935) and then in Justesen vs. Olsen (86 Utah 158, 40 Pac (2d) 802, 1935) that the appropriation doctrine was applicable to the waters of an artesian basin. Immediately thereafter the Legislature amended the Utah water law: "All waters in this State, whether above or under the ground are hereby declared to be the property of the public, subject to all existing rights to the use thereof. Rights to the use of the unappropriated public waters in this State may be acquired only as provided in this title." It is the duty of the State Engineer to approve an application that meets these provisions if there is unappropriated water in the proposed source, and if the proposed use will not impair existing rights or interfere with a more beneficial use of the water. The Geological Survey, by cooperative agreement with the State Engineer, was to provide data and scientific studies that would assist the State Engineer in determining where and whether there was unappropriated water. And that is the indirect tie between the Supreme Court and my career in Utah.

Cedar City Valley

The mid–30's drought and consequent deficiency of streamflow had been the incentive for drilling many new wells for irrigation in Cedar City Valley. By 1935, water levels in wells were declining generally, particularly in the irrigation pumping area, and the residents were asking whether more water was being pumped than could be counted on perennially. Our studies showed that there was practically no outflow from the valley – someone had dug a trench across the outlet at a 20-mile gap in the vain hope of intercepting some groundwater outflow – and all the water that came into the valley by precipitation and by way of Coal Creek and minor tributaries was evaporated or transpired within the valley. In the drought years at least, pumping had exceeded the recharge and groundwater storage had been reduced; the State Engineer in 1936 therefore closed the irrigation pumping area to further development.

Although Coal Creek is not the sole source of groundwater recharge, and although much of the water in Coal Creek does not recharge the groundwater basin, it is known to be an important source

[1] Publication authorized by the Director, U.S. Geological Survey.

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of recharge to the closed district. Using the Coal Creek runoff as an index of recharge, and water levels in 14 wells as indexes of changes in storage, the records in the succeeding decades indicated that the annual runoff of Coal Creek must be 12,000 acre-feet to balance the natural discharge and prevent depletion of storage. In 1951 the runoff was less than 10,000 acre-feet, and water levels in wells would have declined even if all pumping had been prohibited; however, at least 15,000 acre-feet was pumped from wells in that year, and the flow of Coal Creek would have had to be at least 27,000 acre-feet to balance this rate of withdrawal.

In the 50-year period 1907-56 the average annual precipitation at Cedar City was 12.1 inches, but in the latter half of this period (1931-56) it was less than this amount in all but 5 years. The water levels in observation wells declined an average of 20 feet from 1942 to 1958, but many of these were years of drought, when streamflow and groundwater recharge were less than the long-term average. Thus, even though we had a fair estimate of the annual recharge, we did not have the basis for determining the perennial recharge. The water users in the valley appear to be making the most of their combined supplies, depending on surface water as much as possible, and pumping chiefly in periods when stream supplies are deficient: in 1951 more than 70 percent of the water used for irrigation was pumped from wells, but in 1952, with greater streamflow, only about 20 percent was pumped from wells (Waite and Thomas, 1963).

Parowan Valley is similar to Cedar City in that several tributaries with headwaters in the high plateaus contribute to the recharge of the groundwater reservoir; but the flow of these streams is ungaged. Also, like Cedar City Valley, Parowan Valley is a closed basin whose only outflow is by evapotranspiration. Here, too, determining perennial recharge was by the indirect means of the hydrologic equation, requiring estimates of the groundwater discharge and changes in storage.

Escalante Valley

The groundwater reservoir of Escalante Valley has far greater area and volume than those of Cedar City and Parowan valleys combined. However, most of the tributary drainage basin is arid, and the valley received very little inflow. The largest tirbutary stream is Beaver River, regulated by Rocky Ford reservoir and used for irrigation in the Minersville area. The Milford pumping district is somewhat farther north and down the alluvial fan from Minersville. During the 1930's water was diverted northward from Minersville to irrigate lands in the vicinity of these pumped wells. I recommended conjunctive use of surface water and groundwater there, pumping from wells when surface water was not available, but using the surface water to the maximum extent possible so as to replenish the groundwater while irrigating the land (Thomas, 1944), but progress went in the other direction. The seepage losses from the high-line canals – which recharged the groundwater reservoir – were untenable to holders of surface-water rights, and canal maintenance was expensive because of local runoff. So these canals were abandoned in the 40's and the water was used elsewhere.

In the larger, southern part of Escalante Valley (the Beryl-Enterprise area) the only perennial inflow to the valley is by Shoal and Mountain Meadow Creeks near Enterprise and Piute Creek at Newcastle – rather meager supporters for so vast a groundwater reservoir. There is also some recharge from numerous ephemeral streams, by underflow from the mountains and by precipitation on the valley. There is no indication of outflow from the valley, and hence this valley became the site for Walter White's pioneer studies of use of water by plants (White, 1932), leading ultimately to estimates of the groundwater discharge from Escalante Valley, amounting to less than 10,000 acre-feet. By the hydrologic equation, this constituted also an estimate of the perennial recharge.

Until 1945 the pumpage from wells in the Beryl-Enterprise district probably did not exceed 4,000 acre-feet a year – therefore less than the estimated natural discharge and less than the perennial recharge. By 1950 the pumpage had exceeded 50,000 acre-feet, and it has ranged up to 70,000 acre-feet in some subsequent years. The water levels in wells in the pumping district have declined in rough proportion to the pumpage, at an average rate less than 2 feet a year. But the water table in the area of natural discharge has not been affected by the pumping, and the rate of natural discharge continues unabated. Clearly the well owners are not pumping "unappropriated" water in the sense that the supplies are replenished by the perennial recharge. Instead they are mining water that has accumulated over a long time, and amounts to a volume of probably millions of acre-feet.

The Source of Water Derived from Wells

In the arid Southwestern States there are many groundwater reservoirs similar to Escalante Valley in that the natural discharge from them and the perennial recharge to them are very small in comparison to the large volume of water in them. Studying one of these — the High Plains of New Mexico and Texas — Theis (1935) pointed out that the natural equilibrium is destroyed when wells are pumped, and introduced his nonequilibrium formula to express the progressive changes resulting from the pumping. Subsequently, Theis (1940) summarized the significance of this basic physical concept to groundwater conservation and statutory regulation, as follows:

1. All water discharged by wells is balanced by a loss of water somewhere.
2. This loss is always to some extent and in many cases largely from storage in the aquifer. Some groundwater is always mined. The reservoir from which the water is taken is in effect bounded by time and by the structure of the aquifer as well as by material boundaries. The amount of water removed from any area is proportional to the drawdown, which in turn is proportional to the rate of pumping....
3. After sufficient time has elapsed for the cone to reach the area of recharge, further discharge by wells will be made up at least in part by an increase in the recharge if previously there has been rejected recharge. If the recharge was previously rejected through transpiration from nonbeneficial vegetation, no economic loss is suffered. If the recharge was rejected through springs or refusal of the aquifer to absorb surface waters, rights to these surface waters may be injured.
4. Again, after sufficient time has elapsed for the cone to reach the areas of natural discharge, further discharge by wells will be made up in part by a diminution in the natural discharge. If this natural discharge fed surface streams, prior rights to the surface water may be injured.

In the arid Escalante Valley, natural recharge is limited by the quantity of water available — from precipitation or from streams — and areas of "rejected recharge" are unknown. If the only "unappropriated" groundwater in the valley is the small quantity that can be replenished by the perennial recharge, it should be developed in the area of natural discharge, but this is an area of high water table and poor soils, where wells might be poor both in yield and in quality of water; even here there must be some mining before the natural discharge can be salvaged. In any other part of the valley a greater proportion of mining is inevitable. The present scale of development in Escalante Valley is evidence of tacit recognition by the State of Utah that the accumulated storage is also "unappropriated" water. An inevitable corollary is that water levels in wells will decline as pumping continues. Here the prior appropriator who claims a right to maintenance of a specified water level is confounded by natural laws: the lowering at his own well is primarily caused by his own pumping; and if over the years he has pumped more water than his neighbors, he may have greater responsibility than anyone else for regional depletion of storage.

East Shore Area

Between Salt Lake City and Brigham City, the Weber River and numerous creeks and ephemeral canyons flow from the Wasatch Range and out upon the narrow belt of inhabited land between the mountains and Great Salt Lake, designated as the East Shore area. Wells close to the mountains show seasonal rises of water level and therefore recharge from the streams or precipitation or canal water applied for irrigation or subsurface flow from the mountains. Farther west some of this groundwater is discharged by springs or by evapotranspiration, but some moves westward in artesian aquifers that yield flowing wells even in the westernmost inhabited areas. Clearly some groundwater is moving westward toward Great Salt Lake, under sufficient head to bring it to the land surface or lake bed, although it must do so slowly, through clayey "confining" materials. In Tooele Valley south of the lake, there is a similar movement of groundwater toward the lake.

According to a recently published report on the East Shore area in Weber County and most of Davis County (Feth, 1966), the average annual recharge was calculated to be 70,000 acre-feet, of which 30,000 was from mountain-front subsurface flows, 30,000 from surface streams and from irrigation canals and irrigated lands, and 10,000 acre-feet by direct infiltration of precipitation. About 18,000 acre-feet is discharged by flowing wells and 7,000 acre-feet by pumped wells, but an estimated 40,000 acre-feet moves westward to be discharged by evapotranspiration in the lowlands bordering Great Salt Lake, or to continue under and into the lake. Water levels in wells indicate variations in groundwater storage reflecting climatic variations, but little overall change in storage since 1935. Clearly from the record, there is unappropriated water in the district, and this water is wasting to Great Salt Lake or the bordering lake flats – wasting because the aquifers are "bursting at the seams" –under sufficient pressure that the water rises to the land surface or lake bed and nonbeneficial discharge. Pumping from wells can reduce this wastage, and instead salvage the water for beneficial use. But it will also reduce the artesian pressure that serves the existing wells. If existing rights to water include the initial head that produces free flow from the wells, further development must be prohibited, but such prohibition is at considerable cost to the State – wastage of as much water in the Weber delta as is now withdrawn from all existing wells for beneficial use.

The groundwater conditions described by Feth and others are not the natural or "virgin" conditions, but those pertaining in the 1950's and as modified by man's uses of water and the facilities for storage and diversion for those uses and subsequent disposal. The groundwater is only a small part of the total water budget for the area, which accounted for 950,000 acre-feet – in and out – during 1952. Now that the Weber Basin project has been completed, I do not know whether there is urgent need for the additional water that is unappropriated and could be developed by wells. In any case, the groundwater reservoir constitutes a vast storage that can be drawn upon in times of need, and replenished during subsequent periods of greater precipitation and surface inflow to the area.

The East Shore area is one of many areas in Utah where existing wells appear to be withdrawing less water than the "perennial recharge" – or, as seen from the other end of the groundwater reservoir, where significant quantities of groundwater are being discharged naturally that could instead be salvaged and put to beneficial use. Although the State Engineer could thus approve applications for new wells on the basis that there is unappropriated water, he must also consider another proviso of the Utah law that these additional appropriations must not interfere with existing rights. Does this right to water include also the right to artesian pressure sufficient for a flowing well to continue its former yield, and the right to a water level in a pumped well such that the owner would not be put to additional expense of greater pumping lift or even deepening his well?

The Problem of Interference Among Wells

In the early days of the groundwater law, we spent considerable time determining the effects of new wells upon the older wells, in such diverse places as Woods Cross, Lehi, Willard, Benson, Ephraim, Erda, West Ogden, Delta. There were many conferences with John Ward and later Francis Mayo of the State Engineer's office concerning applications for new wells, as to where and how deep the wells should be to cause minimum interference with others. Almost universally the applicants wanted to get along with their neighbors and not "take their water," and they welcomed these suggestions.

Looking back to these short-term interference tests I realize that my career extends back to the days of groundwater primatives. It had long been known that when a well discharges by pumping or artesian flow, water levels in wells in its vicinity are lowered. The development of the cone of depression was generally considered to be a local phenomenon; several early 20th Century books and papers on groundwater gave formulas for determining the radius of the cone of depression, or the "area of influence," of a well. A similar idea had found expression centuries earlier in the teachings of the Prophet Mahomet: each well should have a harim (protected area) on which it is forbidden to dig a new well so as not to damage the quality or lower the quantity of water in the existing well (Caponera, 1954). By tradition in many Moslem countries, a harim comprises 40 cubits if the well is used for watering camels, and 60 cubits if used for irrigation.

In his paper introducing the physical principles of groundwater motion when the natural balance is destroyed by a discharging well, Theis (1935) presented theoretical curves to show the effects in time and distance of a typical pumping well: "... when the well is pumped, the water level close to the well at first falls very rapidly, but the rate of fall soon slackens.... The rate of fall after considerable pumping is so small that it might easily lead to a false assumption of equilibrium.... The water level at a point 100 feet from the pumped well would fall during the first year of pumping more than half the distance it would fall in 1,000 years. A delayed effect of pumping is shown at distant points. The water level at a point about 6 miles from the pumped well would fall only minutely for about 5 years but would then begin to fall perceptibly, although at a much less rate than the water level close to the well."

The complete extent of cones of depression of existing wells has not been recognized by observation and perhaps can never be. The interference caused by a well becomes quite small and long delayed at considerable distances. Finally, discharge by other nearby wells, and other factors, cause fluctuations great enough to mask completely the effects of individual distant wells. Thus, determining the full effect of any specific well upon an aquifer may be a hopeless task. The California Supreme Court, working under a doctrine of water rights different from Utah's but confronted with similar physical processes in a heavily pumped aquifer, concluded (Pasadena vs. Alhambra, 1949) that each well user had been the perpetrator and the victim of what was termed "mutual prescription."

Summary

Most groundwater recharge is traceable to seepage from streams or directly to precipitation, and like precipitation and streamflow its rate varies from year to year. The rate of recharge is commonly determined indirectly, by means of the hydrologic equation: in any specified period the total recharge to a groundwater reservoir equals the total discharge from it plus or minus any changes in storage during the specified period. In many groundwater reservoirs the rate of natural discharge does not vary greatly from year to year, and fluctuations in recharge are reflected chiefly in fluctuations in storage, as evidenced by changes of water level in wells. Over a sufficiently long period the reservoir is in a state of dynamic equilibrium, and the rate of natural discharge is a reasonable approximation of the long term average recharge, or "perennial recharge."

It has sometimes been assumed that the perennial recharge is a measure of the "safe yield" of a groundwater reservoir, or the maximum amount that can be withdrawn perennially by means of wells. This may be by analogy with diversions from a stream, which necessarily reduce the quantity of water in the channel downstream from the point of diversion. However, each well first takes water from storage in the aquifer, and may continue to do so for a long time without causing significant reduction in the natural discharge. This removal from storage causes lowering of water levels, first in the vicinity of the discharging well, and then at progressively greater distances until the water levels are lowered in the natural discharge area — and that is the lowering that reduces the natural discharge. Eventually the discharge by wells will approach a "safe yield" that cannot exceed the perennial recharge. But in the meantime the wells may withdraw quantities of water far in excess of the perennial recharge, by depleting the storage. Some depletion of storage is essential for reducing the natural discharge and salvaging the water for beneficial use of man.

To the question whether there is still unappropriated groundwater in Utah's valleys, the answer must be that in several valleys the perennial recharge exceeds the quantities withdrawn by existing wells, and the evidence for this is the groundwater being discharged naturally and nonbeneficially in the lower parts of those valleys.

If existing rights include the right to water levels or artesian pressure in existing wells without interference by new wells, very little of this unappropriated water can be developed for use. Indeed, if this rule were rigidly applied for the benefit of senior appropriators throughout the history of the State, many existing wells would not exist, and the use of groundwater would be reduced drastically. On the other hand, the senior wells — those that have been discharging longest — are responsible for the most widespread lowering of water levels; to the extent that they have achieved a reduction of natural discharge, this achievement has been by reducing the water levels and artesian pressures in those natural discharge areas. In a common reservoir every owner of a discharging well shares in responsibility for lowering water levels, and the physical process is such that the older wells are likely to have a greater share of this responsibility. But if the unappropriated water now wasting naturally is to be appropriated for beneficial use, some lowering of water levels in the reservoir is inevitable.

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NATURAL CONTAMINATION HAZARDS IN ARID BASINS [1]

by

J.H. Feth [2]

This discussion of contamination hazards in arid basins will be restricted to naturally occurring chemical substances. Many examples cited will be from the Great Basin – some from areas less than 50 miles from where we now are gathered. I shall point out sources of contamination in the atmosphere, lithosphere, hydrosphere, and biosphere, although they are not always readily distinguished one from another. And the talk will close with a statement of some remaining areas of ignorance – which unfortunately are large and numerous.

In order to have contaminants, there must be something to contaminate. As a point of departure, then, let us look at what is known about the chemical quality of groundwater in a large, arid region as exemplified by the Great Basin. The available information was summarized (Feth, 1966) in a recent paper which is excerpted in the following discussion. Although conditions in the Great Basin represent extremes, the general patterns that appear upon study are much like those in Arizona, New Mexico, and parts of Texas, for example. My limited knowledge of other countries suggests that generally comparable conditions prevail in parts of Australia, the Sahara, the Middle East, and other arid and semiarid regions as well.

Groundwater Quality in the Great Basin

The Great Basin, as outlined in Fig. 1, includes most of Nevada, large areas in California, Utah, and Oregon, a small part of southeastern Idaho, and a thin sliver along the southwestern border of Wyoming. Most of the Great Basin was without exterior drainage in Pleistocene time, as it is now. Therefore for tens of thousands of years water was discharged only by evaporation and transpiration and from much of the region no salts were carried out by streamflow.

One might assume with seeming logic that the internal drainage and warm climate of the Great Basin would make it a region yielding highly mineralized groundwater in most places and potable water in only a few. The facts of matter are quite different.

Overall chemical quality of groundwater

Much of the hydrologic work in the Great Basin has been of the reconnaissance type; few areas have been studied in detail. Consequently chemical data are sparse for most of the area and nonexistent for parts. Those areas for which at least some groundwater - quality information is available are shown in Fig 1. Surface-water quality was not considered in the report here being summarized, but is known to be acceptable to excellent in most streams of the region.

For the Great Basin as a whole, more than 80 percent of the available analyses of groundwater show less than 1,000 ppm (parts per million) of dissolved solids and 57 percent report less than 500 ppm. The percentages of analyses showing concentrations in different ranges, (Table 1) indicate that the distribution of groundwater salinity from region to region within the Great Basin is nearly the same.

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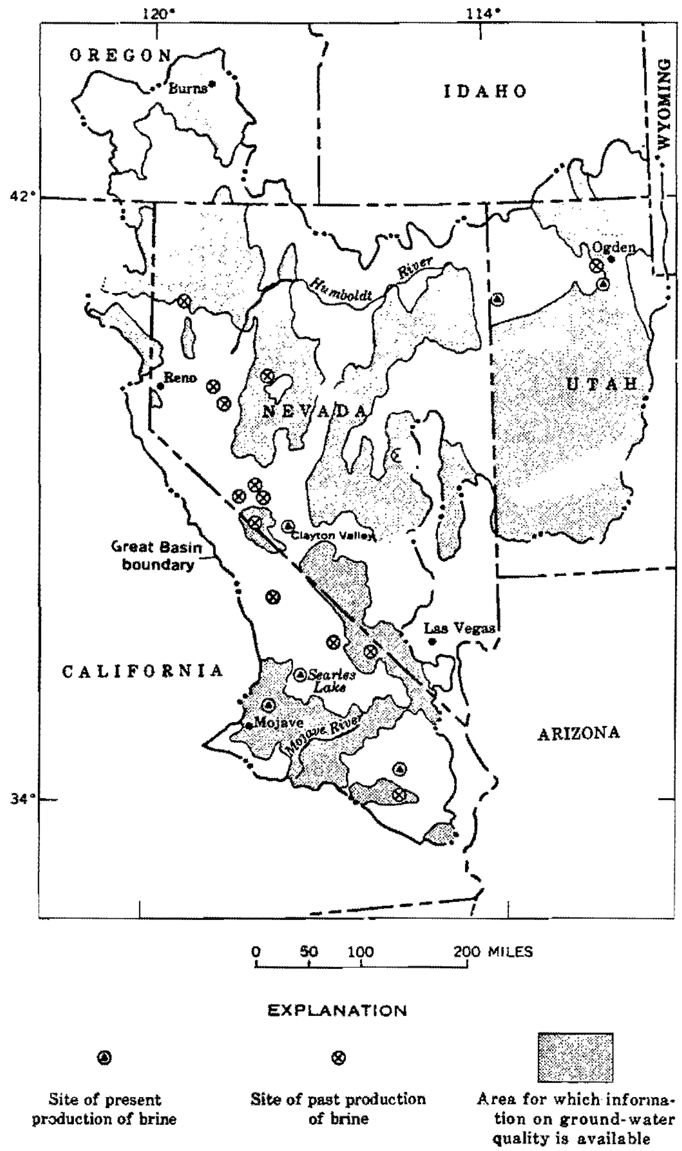


FIGURE 1.—Outline map of the Great Basin, showing areas where data are available on water quality, and sites of past and present production of salines from brines. Boundary of Great Basin, except in Wyoming, after Snyder and others (1964).
After Feth, 1966.

Groundwater displays a wide variety of chemical types in the Great Basin. Where dissolved-solids concentrations are less than 500 ppm, calcium magnesium bicarbonate, calcium sodium bicarbonate, or sodium bicarbonate types are commonly found. Water with mixed anions is common in ranges from 500-2,000 ppm of dissolved solids, and sodium bicarbonate water continues as a type to concentrations greater than 1,000 ppm (but not as much as 3,000 ppm). In the range of 2,000-10,000 ppm, sodium is the dominant cation and sulfate and especially chloride dominate among the anions. With but few exceptions, water having more than 10,000 ppm is sodium chloride in character. Distribution and chemical types of water of 1,000 ppm dissolved-solids content or more have been illustrated by Feth and others (1965, sheet 2).

The potability and palatability of water are determined largely, though not entirely, by its anion content. A bicarbonate water with 1,000 ppm may taste a little flat, but is potable. A chloride water with the same concentration is hardly tolerated save by persons long accustomed to its use. To a somewhat lesser degree, the same comparison can be made between bicarbonate water and sulfate water. So dissolved-solids content offers only a general — but convenient — criterion for evaluating potability of water. It is used as a general guideline in this discussion.

Occurrence of brines

Concentrated brines are processed for their content of commercially useful minerals at 6 places at the present time; at 14 other places brines have been processed in the past (Fig. 1). Brines pumped from wells for mineral production contain as much as 325,000 ppm of dissolved solids. The brines typically underlie playas or salt crusted marshes in the lowest — commonly nearly central — parts of the basins in which they occur. Most concentrated brines occur at shallow depth, and scanty data suggest that beneath at least some playas dissolved-solids concentrations decrease progressively with increasing depth. The available evidence indicates that potable water also occurs in virtually all basins where brines are known to occur, except the basin of Searles Lake (G.I. Smith, oral commun., 1965), and perhaps that in Clayton Valley, Nev. (Dole, 1913, p. 331-332).

Bias in the data

The data for Utah were examined critically to evaluate the bias introduced into the tabulated values by grossly uneven regional distribution. In the Great Basin part of that State, about 60 percent of the 1,018 available analyses are of water samples taken in the heavily populated area that extends along the west base of the Wasatch Mountains from the northeast shore of Great Salt Lake southward to Utah Lake (Fig. 2). Runoff from the Wasatch Mountains is a source of abundant recharge, and the mineral content of the water is low. As might be expected, a larger percentage of groundwater samples from this part of Utah fall in the "less than 500 ppm" range than do those from other areas in the State. Shown graphically in Fig. 3 are the percentages of the groundwater samples from the area at the west base of the Wasatch Mountains, from other areas in Utah, and from the State as a whole that fall within different ranges of dissolved-solids concentration. The maximum difference between the percentages is 10.5 percent and between those for the area along the west base of the Wasatch Mountains and the State total is 4.5 percent. Inasmuch as the maldistribution of samples from Utah presents the maximum opportunity for bias among the presently considered data on groundwater quality, it is likely that the percentage values shown in Table 1 are reasonably representative of actual conditions throughout those areas in the Great Basin for which water-quality data are available. The bias caused by emphasis placed on location and development of water of quality suited for use and by rejection of water of inferior quality cannot be evaluated.

The questions of why there is so much groundwater of tolerable to good chemical quality in arid-basin aquifers and of the extent to which those resources are renewable remain largely unanswered. Happily they are outside the scope of the present discussion.

Natural Sources of Chemical Contamination

Atmosphere

Contributions of chemical constituents from the atmosphere to surface and groundwater are

Table 1. Distribution of analyses by region and concentration ranges. (Ferth, 1966)

Dissolved-solids concentration (parts per million)	Southeastern California (Mojave Desert region)		Oregon and Northeastern California		Nevada		Utah		Idaho		Great Basin	
	No. of samples	Percent	No. of samples	Percent	No. of samples	Percent	No. of samples	Percent	No. of samples	Percent	No. of samples	Percent
Less than 500	545	50.8	121	60.5	230	57.4	641	63.0	17	42.5	1,554	56.9
500-1,000	297	27.7	37	18.5	116	28.9	212	20.8	9	22.5	671	24.6
1,000-2,000	150	14.0	25	12.5	36	9.0	88	8.6	9	11.5	308	11.3
2,000-10,000	66	6.2	13	6.5	17	4.2	60	5.9	5	12.5	161	5.9
10,000-100,000	14	1.3	4	2.0	2	.5	17	1.7	0	0	37	1.3
Total	1,072	100	200	100	401	100	1,018	100	40	100	2,731	100

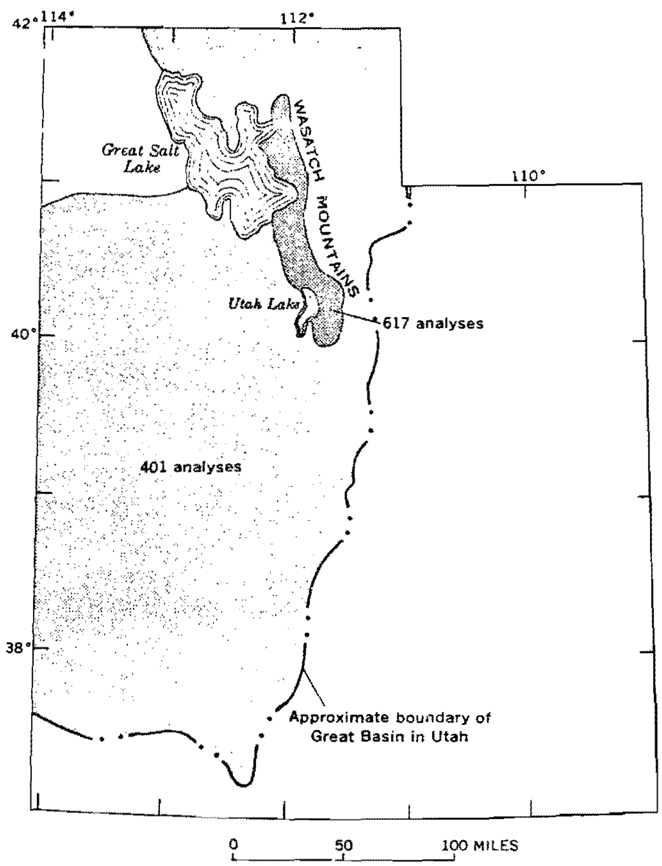


FIGURE 2.—Map showing the area along the west base of the Wasatch Mountains (heavy shading), and other areas in Utah (light shading), for which data on ground-water quality are available. After Feth, 1966.

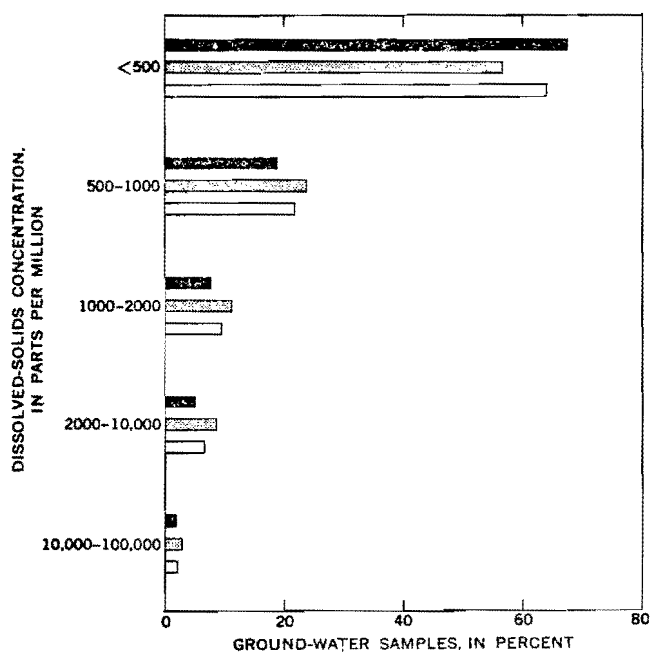


FIGURE 3.—Percentage distribution of ground-water samples from Utah in selected ranges of dissolved-solids concentration. Upper bar, area along west base of Wasatch Mountains (617 analyses); middle bar, other areas (401 analyses): lower bar, State total (1,018 analyses). After Feth, 1966.

imperfectly known but occur dissolved in moisture and as particulate aerosols including saline dust. Two major considerations are involved. First is the chemical load brought in by precipitation, and second is the degree of concentration by evaporation of precipitation.

By their very nature, arid and semiarid regions are unfavorable to the study of precipitation, and data are sparse. In 1955-56, Junge (Junge and Werby, 1958) maintained a network of some 60 sampling stations in the United States; necessarily only a handful were in the semiarid parts of the country. Their maps show, however, that concentrations of all chemical constituents analyzed for in the study were present in rain in very small concentrations, generally 1 ppm or less, except directly along the coastline where oceanic spray caused materially greater concentrations. The Junge network sampled rain — that is aqueous precipitation collected in a container that was chemically clean when installed and was kept covered except during precipitation events.

A study (Feth, in press) of bulk precipitation in the Mojave Desert region in 1965-66 showed that concentrations ranged from a few ppm [3] (specific conductance 8.3 micromhos) to nearly 500 ppm. Bulk precipitation was defined (Whitehead and Feth, 1964, p. 3319-3320) as the geochemically significant solution that results from a mixture of rain and dry fallout. "In nature, melting snow or rain falling on the land surface — whether in its native state or modified by man — collects and incorporates the products of dry fallout. The resulting solution is bulk precipitation." In the semiarid environment, dry fallout is highly influential in controlling the chemical character of precipitation. Interestingly enough, the concentrations of bulk precipitation sampled in 1957-59 at Menlo Park, Calif., were closely analogous to those determined in the Mojave Desert study, and were about 4 to nearly 10 times higher in mineral concentration than rainwater sampled at the same place (Whitehead and Feth, 1964, p. 3327). Menlo Park is between San Francisco Bay and the Pacific Ocean, in a densely populated area, and close to sites of heavy industry. The high similarity in chemical composition and concentration of bulk precipitation at Menlo Park and in the Mojave Desert is a puzzling phenomenon.

Clearly, some of the mineral content of Mojave Desert bulk precipitation is derived from saline dust that becomes air-borne and returns to earth either as dry fallout or when incorporated in falling rain or snow. The sample with highest concentration (840 ppm) in the Mojave Desert group was from Saline Valley, Calif. The concentrations of SO_4^{-1}, Cl^{-1}, and Na^{+1} mirror accurately the sodium sulphate and sodium chloride salts present on the Saline Valley playa. The sources of other constituents — and indeed of all constituents at most places in the Mojave — are less readily identified.

Junge and Manson (1961) and Mossop (1965) cited the existence of a constantly renewing, world wide aerosol layer consisting of ammonium sulfate and persulfate. According to their interpretations, those constituents are constantly raining down upon the earth from the aerosol layer, and constantly being renewed. The importance of that process, in adding to the nitrogen and sulfur content of water — whether in arid or humid regions — has not been evaluated.

According to Yaalon (1961, p. 14), dry fallout and rain deposit about 100,000 tons of sodium chloride per year over Israel. He further calculated (p. 20) that about one half of the 105 ppm Cl^{-1} characteristic of water in the coastal aquifers of Israel is "concentrated from recent atmospheric accession." The Cl^{-1} concentration in rain in that region was estimated (p. 12) from scanty data to be about 10 ppm. On this basis, about 80 percent of the moisture evaporates, about 20 percent reaches the aquifers, and the concentration of Cl^{-1} is increased five-fold.

Broecker and Walton (1957, p. 603, 614-615) calculated that the 187,000 ppm of Cl^{-1} in Great Salt Lake, the 14,000 ppm in Mono Lake, and the 1,685 ppm in Pyramid Lake could have been concentrated exclusively from air-borne salt precipitated over their respective drainage basins in about 73,000 years. However, Feth (1959) pointed out that their estimates omitted several critical geologic and hydrologic considerations. These few examples perhaps suggest that increments of mineralization from precipitation may be an appreciable factor in contamination of surface and groundwater, especially in arid and semiarid regions where rates of evaporation are high. They may also have made it plain that we know really very little about the atmosphere as a source of mineral contamination

[3]Sample volume was too small to allow determination of total solids.

of water. And, considering saline dust, it is hard to separate sources in the atmosphere from those assigned to the lithosphere.

The influence of concentration by evaporation has not been quantitatively determined. Yaalon's estimate for Israel was cited above. The 5:1 factor cannot apply, however, to areas where precipitation is characteristically very light — from negligible to a few inches per year; where in some years there is virtually no runoff and no groundwater recharge either directly from precipitation or from runoff; and where products of dry fallout and mineral matter brought down by precipitation concentrate at or near ground surface for several years until an exceptional, heavy rain incorporates the soluble parts of the accumulation and sends a slug of mineral-laden water downward to the aquifers. Intuitively, we must conclude that the dissolved-solids loads of some such slugs of recharge are large. But I know of no studies that have been made to quantify the inference.

In this connection, it is instructive to examine the dissolved-solids content of springs from granitic rock in the Sierra Nevada and of springs from granitic rock in the Mojave Desert. The data are from Feth and others (1964, Table 2, Fig. 12).

	Dissolved-solids concentrations in parts per million			
	Max.	Median	Min.	Mean
Sierra Nevada (56 springs)	162	72	15	75
Mojave Desert (7 springs)	860	583	334	579

The disparity suggested by the table may result partly from inadequate sampling; it might reflect differences in rates of chemical weathering of granitic rock and removal of weathering products in the two environments. But it almost surely also results from increments of desert salines and concentration by evaporation along the lines suggested earlier in this discussion.

Lithosphere

Major sources of contamination in the lithosphere are bedded and dispersed evaporities, principally halite, gypsum, or sodium sulfate salts. Locally, there may be exotic sources such as deposits of bat guano formed originally in caves, protected from solution, but later exposed to leaching by roof collapse or other processes. It is not likely that such occurrences are numerous or important. Contamination occurs as water moves over or through the rocks.

Arid basins are sites of deposition of salines, both at the present time and in the past. Some basins are partly underlain by oceanic salines from the more distant geologic past. The effects of salines on water quality can be observed readily in some semiarid and arid basins.

Those of you who live along the East Shore of Great Salt Lake doubtless have experienced the salt-mud rains that form when west winds sweep across the Bonneville Salt Flats and adjacent areas and pick up quantities of salt and silt. The rain-out of those substances with aqueous precipitation in areas near the base of the Wasatch Mountains is a dramatic demonstration of the phenomenon of lithospheric contaminants becoming incorporated in one phase of the hydrologic cycle — namely precipitation. Succeeding rains must wash the salt from land, roof, and pavement and deliver it to surface-water streams or to groundwater aquifers. Again, there are effectively no data with which to estimate the degree of contamination that occurs in the affected water bodies. Eardley and others (1957, p. 1151-1152) estimated that the wind removes about 3×10^6 tons of salt yearly from Great Salt Lake and the surrounding salt flats, and that only about 7 percent of that amount leaves the Great Salt Lake Basin.

Again we face a quandary brought about by lack of detailed information, and must turn to an exercise in arithmetic supported only by general knowledge. If we assume the value of 3×10^6 tons per year of salt — mainly sodium chloride — and an average streamflow into the basin of 3,000 cfs (cubic feet per second) then the average concentration of Na^{+1} plus Cl^{-1} in the streamflow should be about 1,000 ppm. I doubt that this is a reasonable value. All that remains is the conclusion that the potential for contamination is very real, but its quantitative significance remains to be demonstrated.

The effects of bedded evaporites on surface-water quality are readily seen in the examples of two rivers, the Sevier in Utah and the Pecos in New Mexico (Feth, 1965). In the valley of the Sevier River upstream from about Richfield, the drainage basin is underlain by a variety of rocks none of them contributing heavily to mineralization of the water. In the reach approximately from Richfield down to Sevier Bridge Reservoir the halite - and gypsum-bearing Arapien Shale of Jurassic age is widely exposed. All inflows in that reach contribute large quantities of Cl^{-1} and SO_4^{-2} to the river. The maximum Cl^{-1} concentration reported to 1957 upstream from Richfield was less than 100 ppm. In the reach from Richfield to Sevier Bridge Reservoir the maximum value was 492 ppm. The daily sampling station near Lynndyl, still farther downstream, showed a range of Cl^{-1} concentration from 115-1520 ppm in water year 1955. The corresponding values for SO_4^{-2} were less than 50 ppm above Richfield, 521 ppm between Richfield and Sevier Bridge Reservoir, and 191-812 ppm near Lynndyl. Admittedly evaporation and return flows from irrigation influenced the observed changes downstream, but the main sources of contamination undoubtedly are in the evaporite sequence.

There are many more data available for the Pecos River, but only a few will be cited. The daily sampling station at Puerta de Luna, near Santa Rosa, N. Mex., had a range of 10-166 ppm Cl^{-1} in water year 1954. In the same year, the range at the daily station at Red Bluff, below Carlsbad, was 240-7,900 ppm. The comparable values for SO_4^{-2} were 19-1,650 ppm at Puerta de Luna, and 301-2,280 ppm at Red Bluff. As with the Sevier, a complex of factors causes the changes in quality that are observed, but a major share of the contaminants comes from bedded halite and gypsum in several rock formations, mostly of Permian age, that underlie the Pecos River valley in New Mexico, approximately from Roswell downstream to — and beyond — the Red Bluff station which is the farthest downstream sampling station in New Mexico.

In some places, emanations from magma bodies cooling at some depth, or near-surface rocks that have been hydrothermally altered by magmatic emanations, add distinctly to contamination of surface and groundwater. In Truckee Meadows, near Reno, Nev., Cohen (1962, p. C132) found that a stream draining areas of bleached rock carried 2,570 ppm of SO_4^{-2} and a shallow well in similarly altered rock yielded water with 1,680 ppm of SO_4^{-2}. Downgradient, where the streams flow over alluvial fill and where the aquifers are in alluvium, water quality improves materially. The evidence is conclusive that the high SO_4^{-2} content in areas peripheral to the Meadows comes from the altered rock and not from minerals within the alluvium.

Perhaps a word should be said about sediment, although it is not strictly within the confines of the topic of natural chemical substances. All of us who have lived in the semiarid West have time and again seen the red, brown, or yellow slurries that are characteristic of flashy runoff from easily eroded terranes; we also have seen the plumes of sediment-laden water that extend into clear-water bodies at times; and perhaps we have visualized the effects of infiltration of such slurries where aquifers crop out. The immediate effects are to make the sediment-laden water unfit for most uses until enough time has elapsed for the water to become clear again. The longer-term effects include direct silt damage to reservoirs, river channels, and other structures, and at least locally, clogging of open spaces in aquifers. The solid particles in suspension doubtless react with the carrier water and mineral matter probably goes into solution, further degrading the quality of the water. But the chemical effects of water-borne solids are virtually unexplored.

Hydrosphere

By contamination from the hydrosphere, I mean degradation of useable water by mixing with naturally occurring water of high mineral concentration, whatever its ultimate source. Messrs. Milligan, Marsell and Bagley recently surveyed the mineralized springs in Utah and their effect on manageable water supplies. According to their calculations (Milligan and others, 1966, Table 1) those springs discharge water containing almost 2,000 tons of dissolved solids each day — nearly three quarters of a million tons yearly. Some of the springs discharge to Great Salt Lake; some have small discharge which is readily diluted to insignificant proportions in the receiving streams. But some pose major problems. Springs tributary to Utah Lake, for example, produce only about 5 percent of inflow to the lake, but add 20-25 percent of the total salt load, according to the U.S. Bureau of Reclamation (cited by Milligan and others, 1966, p. 34). In the Virgin River basin, LaVerkin springs discharge about 100,000 tons of dissolved solids each year (Milligan and others, 1966, p. 47), materially contaminating the water of the river especially during low flows. Hot springs near Clifton, Arizona (Hem, 1950, p. 34-35) discharge on the average more than 50 tons of dissolved solids daily, or on the order of one half the total load of the San Francisco river at Clifton. The spring discharge degrades not only the water of the San Francisco River, but also that of the Gila River below its confluence with the San Francisco.

Perhaps the ultimate in geothermal brines has been taken from a 5,232-foot well in the Imperial Valley, Calif., near the Salton Sea. Its properties were described by White and others (1963) as those to be expected of an ore-forming solution. The well was drilled in an area of hot springs, mud volcanoes, and shallow wells that produced CO_2, associated with a line of rhyolite and obsidian domes of Quaternary age. The composition and concentration of the deep-well water are so unusual that many analytical problems were met in attempts to analyze it in detail. Evidence available in 1963 indicated, however, approximate values as follows:

Concentrations in ppm	
Na^{+1}	54,000
K^{+1}	23,800
Li^{+1}	321
Ca^{+2}	40,000
Total halides as Cl^{-1}	184,000
Evaporated residue	332,000

In addition, there are high concentrations of iron, manganese, boron, barium, strontium and other elements. While the well was allowed to flow, thick deposits of black material containing 381 ounces of silver per ton and 0.11 ounces of gold per ton formed in the discharge pipe.

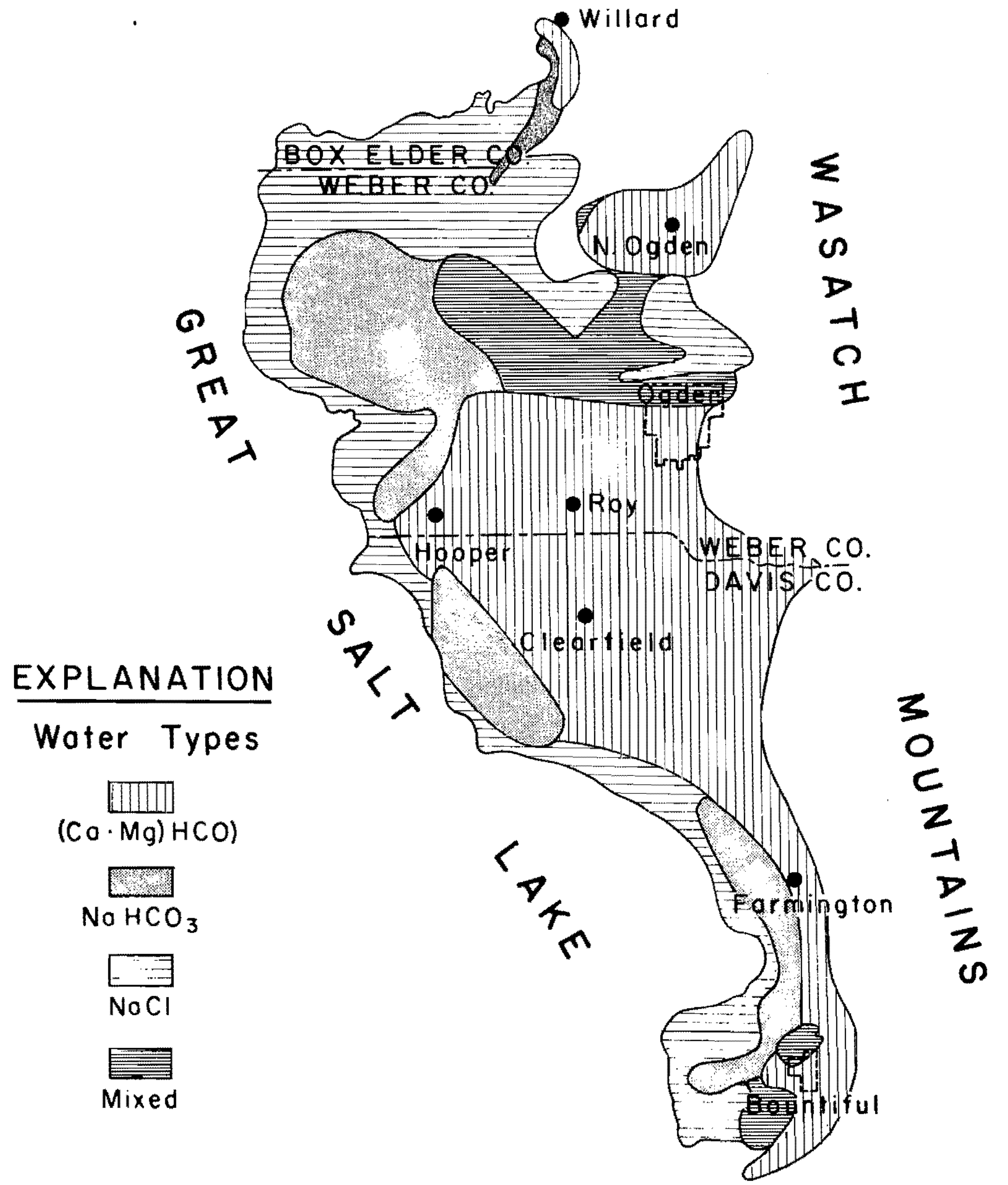
White and others (1963, p. 919) considered that the brine might be largely a direct emanation from a body of magma. More recently, (D.E. White, oral commun., 1967) evidence from isotope studies has cast doubt on the magmatic interpretation, although cooling magma presumably is responsible for much of the high temperature ($> 270^{\circ}$ C). The mineral content of the water may express largely metamorphism of sedimentary rocks that is proceeding at fairly shallow depth in that region.

None of the mineralized waters mentioned in the preceeding discussion, except the springs at LaVerkin, Utah, are in areas where appreciable deposits of evaporites are known. On the other hand, probably all are on or near major fault zones. The association of mineralized springs—commonly thermal—with faulting was recognized long ago by investigators such as Meinzer (1923, p. 186-188) and Sterns and others (1937, Fig. 14) for example. To date, however, no one has satisfactorily explained why fault-zone springs should be high in mineral content, especially content of Cl^{-1}, SO_4^{-2}, B, and F^{-1} as they commonly are. Whatever the ultimate source, mineral springs are major sources of contamination in semiarid regions.

Lateral and vertical variations

Fig. 4, shows lateral variations in chemical types of groundwater in the East Shore area, Utah, from Bountiful northward to Willard. The presentation (Fig. 4) is modified from earlier publications (Feth and others, 1966, pl. 11; Smith and Gares, 1963, Fig. 8). The map shows large areas underlain by calcium magnesium bicarbonate type water generally near the mountain front and extending westward where permeability of the aquifers is high (Feth, and others, 1966, pls. 2 and 3). The sodium bicarbonate water occurs generally lakeward of the calcium magnesium bicarbonate type and is encountered where aquifer materials become less permeable and where opportunities for cation exchange are ubiquitous. Areas underlain by sodium chloride type water are those near the shore of Great Salt Lake, and others where mineralized thermal springs influence water quality.

The important points are that saline soils and saline groundwater combine in large parts of the East Shore area to make irrigation infeasible and that mountain runoff and subsurface percolation of excellent quality deteriorate progressively westward in response to cation exchange and to mixing with sodium chloride type water. The origin of the sodium chloride type water is not easily explained.



WATER-QUALITY TYPES, EAST SHORE AREA, UTAH

Fig. 4. Map of the East Shore area, Utah, showing generalized occurrence of chemical types of groundwater. (Modified from Feth and others, 1966, pl. 11, and Smith and Gates, 1963, Fig. 8)

The deepest wells in the East Shore area have not encountered any bedded evaporities, so bedded salt deposits probably are not responsible although disseminated salines cannot be ruled out. Saline springs discharge at three places, at least, in the area, and additional mineralized water may escape from fault zones to the aquifers without ever reaching land surface. And the few deep wells throughout the area have tapped aquifers at 1000-1300 feet below land surface that yielded mineralized water.

I conclude that the sodium chloride type water is residual in aquifers that were charged with saline water during one or more lake stages earlier than those of Lake Bonneville. Where the aquifers are highly permeable, the saline water has been displaced over the years by fresh-water recharge from the mountains. But where there is less permeability, replacement has not been complete. Through the East Shore area virtually complete replacement has penetrated not much more than 1,000 feet even in the most permeable areas. In addition, some aquifers probably receive renewed supplies of saline water that rises from unknown depths and sources along fault zones. Comparable conditions — varied in detail — prevail in many closed-basin valleys where a central zone of saline water is surrounded by aquifers that produce fresh water.

Vertical zonation poses a complex of unresolved problems. According to White (1965), deep basins that contain bodies of saline water characteristically show vertical zonation. At the base is a layer of Cl^{-1} brine; at intermediate depths SO_4^{-2} dominates among the anions; and overlying the SO_4^{-2} zone is CO_3^{-2}-HCO_3^{-1} water generally not of very high concentration. The zonation is displayed most completely in some of the great saline structures underlain by evaporites of Paleozoic age, such as the Michigan Basin. I do not know of an alluvial-aquifer arid-land basin in which full zonation has been reported. But in many closed basins where discharge of groundwater is entirely by evapotranspiration — a large part of that from a central playa — some vertical zonation apparently is developed, and the processes that cause high concentration of mineral matter may include ion filtration, the process invoked to explain hyperconcentration and zonation of water in the major saline basins (White, 1965).

In outline, the hypothesis of ion filtration states that where types of shale or clay are suitable and where conditions of hydraulic head permit, the fine-grained sediments act as semipermeable membranes, allowing passage of water molecules, but retarding the passage of negatively charged ions. Presumably electrostatic charges on sediment particles repel anions causing them to lag on the high-pressure side of the membrane. Considerations of electrical balance then require that an appropriate number of cations (positively charged) remain with the lagging anions. Concentration by filtration thus results. Adsorption also plays a part in the concentration process. The elements of the theory were stated by de Sitter (1947), discussed theoretically by various authors during the early 1960's, and summarized in two fairly recent papers (Graf and others, 1966; White 1965) that include extensive references to earlier literature on the subject.

In the typical arid-land basin that discharges water from alluvial aquifers upward through the silt and clay of a central playa, the playa sediments, which may be surficial only or may extend to considerable depth, form the membrane. Hydraulic head is developed in artesian aquifers formed by interfingering of gravel and sand with confining layers of silt and clay. The mineral content of water beneath the playa is increased by ion filtration. In another process, near-surface water is concentrated by evaporation at the playa surface. The combined processes of ultrafiltration and evaporation seem to explain some of the common situations where a playa area is underlain by highly saline water but aquifers in the surrounding areas in the basin produce fresh water. Where playa muds do not extend to great depth, it is easy to visualize fresh water persisting in deep aquifers even beneath the playa area itself. In yet another pattern, artesian circulation may entrain deep residual brines in desert basins and carry highly mineralized water upward to discharge through the playa area.

Biosphere

Both plants and animals discharge virtually pure water to the atmosphere during respiration. The salt content of the water ingested is eliminated by other mechanisms. In quantitative terms, the most important probably are the plants classed as phreatophytes, tamarisk (salt cedar), cottonwood, willow, arrowweed, pickleweed, salt grass, mesquite and the like. Part of the mineral content of the water they use is rejected by the roots and part is incorporated in the plant tissues to be released when the plant drops its leaves — if deciduous — or dies and decays. The tamarisk has the additional capacity to excrete salt from its foliage by the process known as guttation (Hem, 1967). The result of all the processes is to concentrate mineral matter in the water that is not discharged to the atmosphere. In thick growths of tamarisk, both the soil and underlying water tend to become damagingly saline. The increase of mineralization resulting from use of water by phreatophytes has seldom been determined. In one study, however, (Gatewood and others, 1950, p. 177-182) the transpiration rate of tamarisk was calculated by observing the increase in Cl^{-1} concentration in water that passed beneath the tamarisk thickets. The concentration of Cl^{-1} in groundwater moving out from the thicket was increased about one-third in two test areas and nearly doubled in a third area.

Summary

We have seen that arid and semiarid basins more often than not are underlain by aquifers that produce potable water — indeed that water quality is surprisingly good, considering the hot and dry climates that characterize those regions. There are, however, sources of contamination in the atmosphere, surface deposits of saline dust, bedded evaporities, probable lacustrine connate water, mineral springs, volcanic emanations and hydrothermally altered rocks, waters concentrated by evaporation and perhaps by ultrafiltration on and beneath playas, and minerals concentrated in, and later released from tissues of plants.

The initial precipitation that falls on semiarid lands is a very dilute solution. When the water incorporates the soluble parts of dry fallout and picks up residual minerals from preceding rains that evaporated without penetrating far below surface, the water is already in a sense contaminated. Locally, groundwater becomes mineralized to the point where it is no longer fit for use. Surface water is materially contaminated in some places, but generally evaporates or goes underground to become recharge rather than continuing long as surface flow. The interrelations between surface and groundwater are imperfectly known, and the relations between fresh-water and saline-water aquifers in arid basins have hardly been explored.

Further work

The discussion of natural contaminants in arid basins probably has been distinguished more by recital of what remains unknown than of what is known about the biology, physics, chemistry, hydraulics, and meteorology of the system. I hope I have made it plain that sources of contamination abound, and some of them cause material degradation of water quality. The following list cites some — by no means all — of the problems and areas of further work that demand the attention of investigators.

1. Quantity and chemical quality of precipitation as rain, snow, and bulk precipitation.
2. Quantitative information on removal and deposition of saline dusts.
3. Rates of recharge of fresh and saline aquifers.
4. Relation of fresh and saline aquifers with special regard to contamination of potable water by overpumping.
5. Lateral and vertical zonation of water-quality types in alluvial basins.
6. Role of ion filtration in control of water quality beneath playas.
7. Subsurface occurrence of bedded or disseminated evaporites.
8. Degradation of water quality by phreatophytes.
9. Contamination by discharge from thermal, mineral springs.

It is not too soon to attack problems such as these, even the thorny ones. The rapid expansion of population centers and of industry and agriculture in semiarid regions demands our attention, for management of the water resource, important everywhere, is critical in arid regions. We have much to learn before optimum management can be achieved.

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MANMADE CONTAMINATION HAZARDS

by

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Man has overrun the earth like no other creature; and wherever he goes nothing is ever again the same. Therefore, we may begin a consideration of manmade contamination hazards with the assumption that man is going to change the quality of the groundwater. In discussing that change I shall consider as "manmade" any quality factor which reaches the groundwater as a result of man's presence on earth or of his activities. Further, I shall call these quality factors "contaminants" whether they be natural or synthetic materials. And I shall look upon these contaminants as "hazards" if they might injure the health of man or animals; significantly limit the usefulness of groundwater for other beneficial uses such as agriculture and industry; or upon outcropping as surface water be inimical to wildlife or any other beneficial use. Thus though the title of my remarks may have intended to limit the area in which I am authorized to speak I have staked out for myself a large field in which to wander. However, in deference to the speakers who come before and after me, and to the audience, which measures time in minutes rather than in geologic ages, I shall limit myself to more reasonable boundary conditions. In this I shall be assisted by the profundity of man's general ignorance, and my own particular ignorance, of the subtle interrelationships between man's activities and the hazards they create through contamination of the groundwater.

As a specific limiting procedure I shall consider as "natural" contamination any acceleration in rate of buildup or amount of the compounds or ions characteristic of groundwaters which results from man's plowing of fields, denuding of forest lands, construction of highways, and similar actions which serve to expedite the normal movement of water into soil. On the other hand, I shall consider as manmade these same or other chemicals, as well as biological agents and organic compounds, associated with municipal, industrial, and agricultural uses of water. Specifically, I propose to summarize the significance to groundwater quality of the natural and synthetic fractions which appear in:

1. Wastes from human life processes.
2. Wastes from industrial processes.
3. Agricultural return flows or percolates.
4. Solid residues resulting from the use of resources or industrial products.

Wastes From Human Life Processes

By far the greatest concern for contamination of groundwaters has been directed to human wastes in the form of municipal sewage. Curiously enough, such concern has not generally been expressed over septic tank effluents discharged directly underground. At least such concern is so recent in origin that groundwater quality considerations did not prevent the use of septic tanks in urban subdivisions in the past 25 years on a scale sufficient to run the total of persons served by such systems to more than 30 million. However, from the viewpoint of contamination hazards from human wastes it matters little whether the percolating liquid comes from subsurface leaching fields or from operations involving surface application of sewage effluents, as will presently be noted.

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In the practical case municipal sewage contains both domestic and industrial waste products. From the domestic fraction comes wastes from the human body, grease, ground garbage, and residues from commercial products such as soap and detergents. The industrial fraction normally includes a variety of biochemically unstable organic matter and a wide spectrum of common chemicals as well as more exotic organics and toxic ions, generally in concentrations below that critical to waste treatment processes. Therefore, in evaluating contamination hazards involved in municipal sewage the fate of several kinds of material in soil systems must be considered.

For purpose of discussion these materials may be divided into such general classes as:

1. Organic and inorganic particles, other than living organisms.
2. Micro-organisms, including bacteria and viruses.
3. Chemical products of degradation of organic matter.
4. Chemicals from industrial wastes or from industrial products in commercial use.
5. Leachings from landfills.

Of this group the organic degradation products may be generated under either aerobic or anaerobic conditions and so develop a variety of intermediate products. All of the group are generated or commonly discarded by man at the earth's surface, with a few rare exceptions, and hence are initially separated from the groundwater by the soil mantle of the earth. They are further separated from the user of groundwater by the extent of aquifer between the point of possible entry of contaminants and point of outcrop or withdrawal of water. Further, the soil mantle of the earth is biologically active. Under these circumstances the question of manmade hazards to the groundwater involves two basic considerations:

1. The nature of contaminants in each of the general classes of material.
2. The fate of each contaminant in water percolating downward through the biologically active mantle of the earth; or in water translated laterally as groundwater in saturated aquifer sands and gravels.

To these may be added the question of contaminants in water moving through fractured strata or dissolution channels. However, in this latter case the "hazards" of manmade pollution may be directly assumed from the nature of the contaminants in five classes of material listed, for while phenomena such as sedimentation, adsorption, time-decay, and the like may reduce the concentration of contaminants, the hazard remains. Hazard prevention, therefore, is related to management of wastes above ground — a subject beyond the scope of this assignment today.

Therefore, attention is turned to the nature of contaminants in five arbitrary classes of man's wastes and to their movement with percolating water. In this more attention shall be given to what fractions get through than to the scientific aspects of removal, which are discussed elsewhere. (McGauhey, Krone, Winneberger, 1966.)

Organic and Inorganic Particles

The fact that groundwaters are derived from rain falling through an atmosphere containing dust particles and bacteria, passing through a soil mantle containing bacteria and organic and inorganic particles, and yet historically has been notable for its clarity, tells us that suspended matter is not a groundwater contaminant to be expected from man's activities. Such, indeed, is shown to be the case in numerous experiments with soils and waste waters from cities, industries, and agriculture.

Micro-Organisms

Bacteria: Not only has groundwater resulting from percolation or moving through aquifer sands been noted for its clarity, its traditional purity is also well known. This does not mean that all groundwater is uncontaminated, because the micro-geology of the earth is not always favorable. Certainly, bacteria will flow with water in fissures just as readily as in pipes at similar velocities, although gravity and time are against bacterial contamination of an outcropping groundwater. Thus contamination with pathogenic bacteria must always, but not in all situations, be considered as a "hazard" to groundwater quality if nondisinfected sewage effluents are carelessly managed. However, where a protective mantle of soil is involved, bacteria behave as other particulate matter and are removed by such forces as sedimentation, entrapment, and adsorption. Studies of the movement of bacteria with percolating water have been widely reported in the literature. For example, the historic work of A M Rawn and associates (McGauhey, Krone, Winneberger, 1966, p. 157-158) in Los Angeles County found bacteria in sewage removed in from 3 to 7 feet of quite coarse soil. Pilot infiltration ponds at Lodi, California, (McGauhey, Krone, Winneberger, 1966, p. 42) gave the same results for a fine soil. More recently, the well known Santee Project at San Diego reported the removal of coliform bacteria in 200 feet of travel of water in quite coarse gravel.

When injected directly into a water bearing stratum, coliform organisms have been found (McGauhey, Krone, Winneberger, 1966, p. 135, 180) to travel only limited distances – less than 100 feet at Richmond, California. These are but a fraction of the references that support the conclusion that under any circumstances where normal soil bacteria do not reach the groundwater, man's activities do not pose a bacterial "hazard" to groundwater quality. However, where fractures or dissolution channels reach the soil surface and transport water underground, sewage disinfection is necessary if released waters are with certainty to pose no hazard to groundwater quality.

Viruses: Viruses are known to be present in sewage but until quite recent years there was no evidence in the literature relative to their movement with percolating water. Being more resistant to chlorine than are enteric bacteria, the possibility of viral contamination of groundwater has long been entertained. Recently, however, studies at the Santee Project (McGauhey, Krone, Winneberger, 1966, p. 164-165, 194-195) have shown viruses to be removed in less than 200 feet of flow through a gravel bed. These and other data support the conclusion that viral contamination of groundwater is no more of a hazard than bacterial contamination.

Chemical Products of Bio-Degradation

Organic solids in sewage, whether from ground garbage, vegetable and meat trimmings, or from the human body, differ from the natural contribution of organic matter to the soil only in that they are associated with man's activities and may reach the soil in varying degrees of degradation. Fundamentally they are proteinaceous in nature and under aerobic conditions oxidize to normal nitrates, sulfates, carbonates, phosphates, etc. Along the way there may be ammonia, nitrates, and similar unoxidized compounds. Under anaerobic conditions degradation products include amino acids and a considerable spectrum of intermediate compounds of notable fragrance and unpleasant taste. Organic molecules themselves are heavily adsorbed on many soils (McGauhey, Krone, Winneberger, 1966, p. 109, 197) hence they behave very much as particulate matter and there is little likelihood of contamination of groundwater by migrating undegraded organic matter of sewage origin. The question is then one of the degree of degradation occurring in a soil system and the nature of the products produced.

Biodegradable organic solids applied to a soil quickly develop a heavy growth of bacteria in the top centimeter or so of the soil. This serves as a reactor in which biostabilization of compounds occur. It also acts as a clogging zone to limit the rate of infiltration. Under aerobic conditions oxidized compounds result. If it becomes anaerobic, ferric sulfide is also produced, which as a particulate matter, helps to clog the soil completely. Therefore, infiltration is essentially precluded and intermediate compounds which might cause tastes and odors and bacterial aftergrowths cannot reach the groundwater.

In high rate direct injection experiments at Richmond, California (McGauhey, Krone, Winneberger, 1966, p. 180) partially degraded soluble organic compounds were forced into an aquifer beyond the bacterially active zone and traveled with groundwater to support bacterial life when again pumped to the surface. Protection against such migration in soil, however, is the normal situation. For example, measurements of degradable material passing through sand and gravel columns reported by Robeck (McGauhey, Krone, Winneberger, 1966, p. 211) showed that from a septic tank effluent all BOD and 90 percent of the COD was removed.

Of the decomposition products, ammonia is notably adsorbed on soil, where it displaces calcium, magnesium, sodium, and potassium ions which are then carried away by percolating water. Later the ammonia is oxidized to nitrates by microbial activity and so becomes soluble and free to move with water. Phosphates too are adsorbed and taken out in the top horizons of soil. Numerous data show that when sewage is applied to a soil the result is simply an increase in the sulfates, bicarbonates, nitrates and other anions and cations normally found in groundwater. Thus in summary it may be said that contamination of groundwater by degradable organics is largely confined to an increase in concentration of normal groundwater ions.

Dissolved Chemicals of Industrial and Commercial Origin

Chemicals of industrial and commercial origin may reach the earth with municipal sewage, industrial wastes, agricultural fertilization, and the use of pesticides and herbicides for a number of purposes. Prior to 1965 ABS was the principal example of commercial products used in the household which might reach the groundwater with domestic sewage effluents. Although degradable in soil systems, its residence time was not always adequate to prevent migration with percolating water. Adoption of the more degradable LAS, however, removed this problem of contamination. Hence from a commercial formulation the phosphates might be expected to be adsorbed on soil and the detergent biodegraded to an inorganic sulfate, which will travel with percolating water or with moving groundwater.

Of the agricultural chemicals, commercial fertilizers are perhaps the most significant. Recently (San Francisco Chronicle, January 25, 1967) the State Health Department of California reported concentrations of nitrate of 176 mg/1 in groundwaters in California's San Joaquin Valley and warned against its use for young babies. The recommended (P.H.S.) maximum of 45 mg/1 has been observed elsewhere (Tucker, Cordy, Berry, Harvey, Fuller, 1961) in recent years to produce intoxication of livestock on high nitrogen diets.

The effect of fertilization of land can therefore involve both the displacement of alkaline ions by ammonia and the subsequent migration of nitrates derived from residual ammonia or direct application of nitrates.

Perhaps the most serious effect of man's use of water is a buildup in concentration of the salts normally found in surface waters, soils, and groundwater. Above all others, this seems to be the greatest of manmade hazards to groundwater quality. It begins perhaps with the concentration of salts by evaporation of water from reservoirs, canals, and industrial cooling, plus regeneration of water softeners, water distillation, etc. This concentrate is then applied to the land in irrigation where it leaches out more salts. Percolating downward or flowing as return flows in open channels some of it percolates to the groundwater. Heavy use of groundwater recycles an appreciable amount of water and the net result in the semiarid west is a continuous increase of the salinity of the groundwater resource. The hazard of manmade contamination here is that although we have learned how to prevent the poisoning of land from our irrigation practice, we may go the way of Mesopotamia by poisoning the water instead.

In addition to the buildup of normal salts, industrial wastes contribute a hazard to groundwater quality by delivering a vast and ever changing spectrum of ions and compounds which move with percolating water. Some of the most commonly deplored are phenols, picric acid, metal ions such as Fe, Mn, Cr, oil field brines, oils, tar residues, weed killer wastes, and a host of miscellaneous chemicals. Instances of long distance travel of such materials are to be found in the literature. Control of discharges is the normal method of preventing groundwater contamination with industrial wastes, but it must be recognized that the wastes from many industrial processes always represent a hazard to groundwater through accidental spill, carelessness, or deliberate discharge, as well as through ignorance of the behavior of the waste from some newly developed processes.

Commercial use of industry's products presents a varied picture. Attention has already been called to detergents and commercial fertilizers. Of much concern today are the so-called exotic organics — the refractory compounds — of which pesticides and herbicides are the most frequently cited examples.

While a great deal of speculation exists concerning the ability of pesticides to move with percolating water, and most of the literature deals with surface water contamination, there is some evidence of hazard to groundwaters. Walton (Proceedings, National Conference on Water Pollution, 1960) of the USPHS noted a case near Henderson, Colorado, where groundwater contaminated by arsenals which eventually formed 2, 4, —D traveled 3 miles in eight years to affect crops and eventually seriously affect some 60 square miles. At Montebello, California, seepage of 2,4, —D from a manufacturing plant persisted in water for five years after the plant ceased operation.

Leachings From Solid Waste Fills

When the soil mantle of the earth is looked upon as the infiltrative surface from which groundwater derives, it is evident that the necessary concentration of solid wastes in landfills creates a local pocket of potential infection overlying the groundwater. Therefore, man's activity in managing his solid wastes must be examined in relation to groundwater contamination.

A hazard to groundwater quality might be created by landfill both directly and indirectly. A direct hazard exists, except in unusual geological situations, in the disposal of old cylinder oil, cleaning fluid, and miscellaneous liquid chemicals within a dump. Although good practice, and local ordinances, prohibits such discharges, one need not become particularly familiar with dump operation to observe that it does occur.

Assuming that contact between groundwater and fill material is prohibited — a quite generally valid assumption — an indirect hazard exists in most landfill operations. This is the possibility that poor operation will permit rain water or flood waters to enter the fill and so dissolve soluble dry chemicals which might be present, leach iron and various earth minerals from incinerator ashes, pick up soluble fractions of organic degradation and transport them to the groundwater table. Good operation, involving surface drainage of the finished fill, is unfortunately not enough to remove this indirect threat. Cracking of the fill cover due to shrinkage of the fill, poor maintenance of the finished fill during the first decade or two after its completion, and seismic disturbances are among the ways in which avenues of entry of water may be opened with time.

More recent studies (In—Situ Investigation of Movement of Gases Produced from Decomposing Refuse, 1966) of diffusion of gases from fills into the surrounding soil show the possibility of carbon dioxide from the decomposing fill material becoming dissolved in percolating water and so increasing its aggressiveness to the primary rocks from which the content of calcium and magnesium bicarbonates in groundwater is normally derived.

Summary

Groundwater may derive a wide variety of materials from man's waste producing activities. Chemicals characteristic of normal groundwaters may be increased in concentration from the degradation of organic solids in human and industrial wastes, and from the storage, transport, and use of water, particularly in irrigation and industry. Similar compounds might come from leaching of a solid waste landfill. Toxic, odorous, and bad tasting compounds may reach the groundwater with industrial wastes, or with municipal effluents containing such wastes or the residues of industrial products used in commerce. The variety of such wastes is endless but includes all types of liquid or soluble chemicals. Particular concern is felt for the pesticide residues. Chemical residues of various nature may come also from their illegal disposal in landfills or dumps. Disease producing bacteria or viruses are no particular hazard, nor is particulate matter which might produce turbidity. However, if fractures or fissures bypass the biologically active mantle of the earth and lead water directly from the surface to the groundwater or spring, microorganisms may join the soluble chemicals as contaminants.

In general, all of man's waste producing activities would create "manmade hazards" to groundwater if accident, carelessness, or lack of vigilance and constraint were permitted to prevail. The most serious current hazard of man's activities lies in the buildup of salinity of the groundwater to levels inimical to all beneficial uses to which such water is put.

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MINERALIZED SPRINGS AND THEIR EFFECT ON UTAH'S WATER SUPPLIES

by

J.H. Milligan [1]

Introduction

As our available water supplies are used more completely by making a given supply satisfy more than one use, water quality problems become more pronounced. The multiplicity of uses to which water may be put as it moves through a hydrologic system is limited only as its quality is reduced below acceptable standards of particular users, or as its quantity is reduced through evapotranspiration. Thus, a water supply may be reduced just as effectively by lowering its quality as if it is consumed or otherwise transported from a region.

In several areas of Utah, water quality problems are aggravated by contributions of highly mineralized springs. These feed into regular water supplies, thus impairing or completely destroying their usefulness— especially during periods of low streamflow. An inventory of sources of such mineralized springs, their quantities and qualities, along with an evaluation of their effects on natural waters, might suggest possible management and control measures which could materially extend the usefulness of certain water supplies in the state.

Specifically, the major objectives of this investigation were:

1. To obtain an inventory of mineralized spring waters with respect to location, hydrologic and geologic setting, and quantity and quality of water.

2. To make an appraisal of current and potential effects of these springs on important usable supplies.

3. To evaluate possible management and control measures aimed at extending the usefulness of principal water supplies.

Quality as a Dimension of Water

The ever enlarging spectrum of water demands places increasing emphasis on quality as an important and often critical dimension of water. Quality is a dynamic parameter inextricably associated with the hydrologic flow system. Many natural processes and human activities affect the quality of surface and subsurface waters. Quality becomes a term to describe the composite, chemical, physical, and biological characteristics of water with respect to its suitability for a particular use. Most interest in water quality still centers around supplies for ordinary household or domestic, agricultural, and industrial purposes. However, the spectrum of beneficial uses is extending rapidly beyond these.

A detailed discussion of water quality criteria, standards, or requirements is not appropriate here. Suffice it to say that the harmful effects of the kind of waters reported herein could extend

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to nearly all kinds of uses principally through their chemical and thermal properties. The high temperatures of most mineralized springs would make them unsuitable for many industrial used and could injure aquatic life. The mineral content of such springs is commonly much higher than can be tolerated (without special treatment) in domestic, industrial, or agricultural use. Regardless of the current or potential water use, an understanding of the quality of these spring waters and the ability to predict the effect of their contributions at various downstream points is essential to any overall quality management program.

History of Mineralized Spring Studies

The earliest interest in mineralized springs lay in their use as health resorts. Remnants of a number of these can be seen at various spring locations throughout the state. Physicians once studied mineral springs for their supposed medicinal value, and certain of these springs are still visited and utilized by persons seeking these benefits.

In the latter part of the 1800's, geologists became interested in the study of mineralized springs as an index concerning the composition and structure of the earth's crust. In 1876, G.K. Gilbert compiled a very reliable table and map of thermal springs in the United States. Later work by Stearns and Stearns gave good general description of such springs throughout the country.

At the present time the mineralized springs in Utah generally have very little economic use and appear destined to create increasingly troublesome problems by impairment of the usefulness of fresh-water supplies.

Geographic Distribution of Mineralized Springs in Utah

The general location and distribution of mineralized springs in Utah are shown in Fig. 1. The major river systems of the state are also outlined in this figure. From this illustration it is evident that the stream systems most affected by mineralized springs are the Bear, the Malad, the Jordan, and the Virgin rivers. Some springs cause local water quality problems without directly affecting one of the major river systems. This is true, for example, at Fish Springs, located in the western desert area of Utah.

Fig. 1 also shows that most of the mineralized springs lie in the Great Basin drainage and only a few are found in the Colorado River drainage. This distributional pattern relates to geological differences between the two drainages.

The location of the mineralized springs with relation to the fault patterns in the state is indicated in Fig 2. One can observe that most of the mineralized springs in the state are directly associated with the geologic fault pattern. The faults nearly all lie in the Basin and Range Physiographic Province and reflect the geologic history of the area. The mineral content of the springs also reflects this geologic history. Western Utah is a part of an extensive region known as the Cordilleran geosyncline, which was once covered by the sea and into which were deposited marine sediments. Parts of the states of Nevada, Oregon, Idaho, and parts of California, Arizona, and New Mexico were also a part of this vast geosyncline. The area was later uplifted, folded, and faulted. The faults facilitate the conveyance of meteoric water to and from these marine sediment deposits. Dissolved salts from these geologic formations are brought to the surface by springs. Thus, most of these springs are high in sodium, calcium, carbonates, and chlorides, reflecting their contact with the old marine sediments. This pattern or trend as found in Utah could be expected throughout the entire Basin and Range Province.

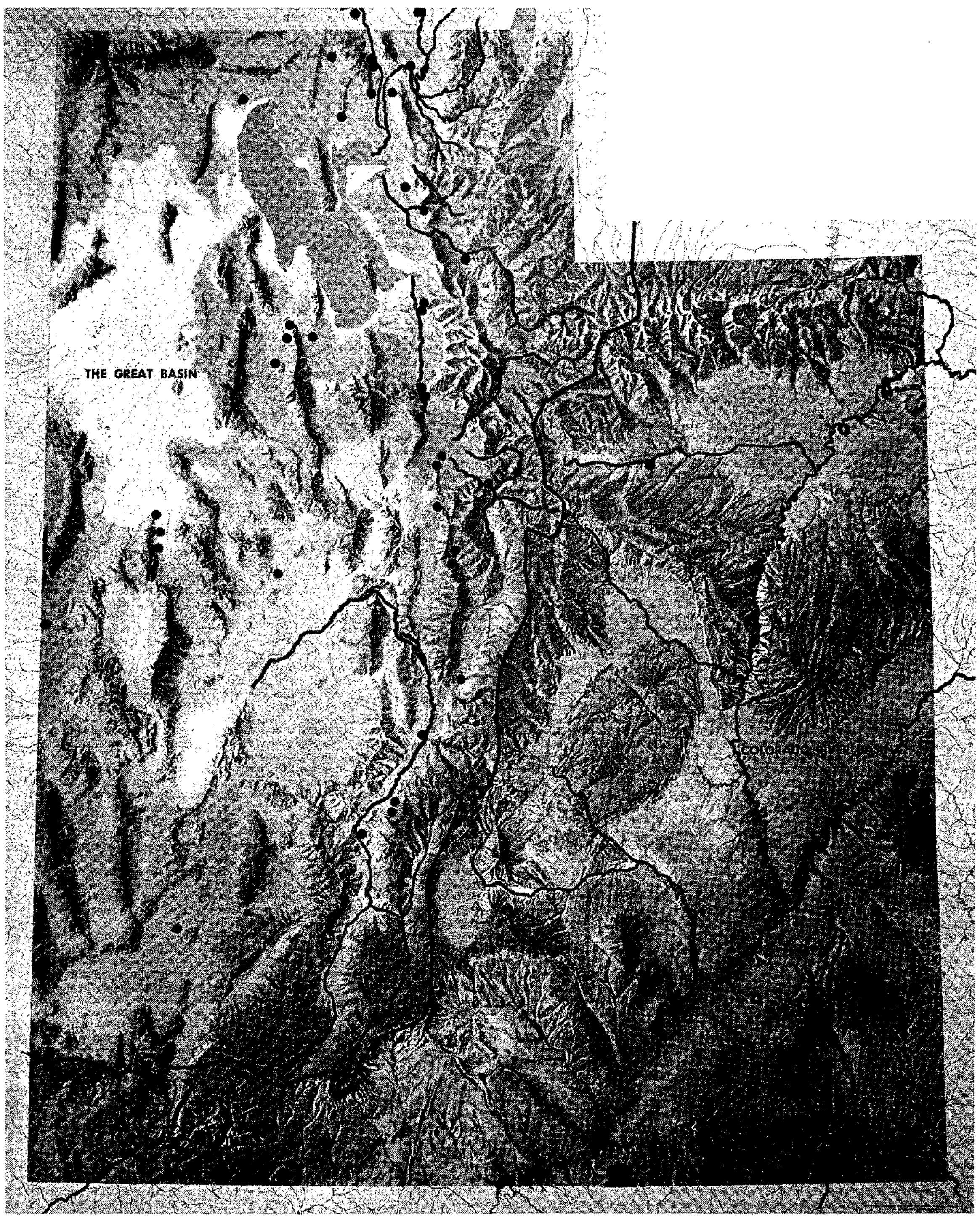

Fig. 1. General location and distribution of Utah's mineral springs.

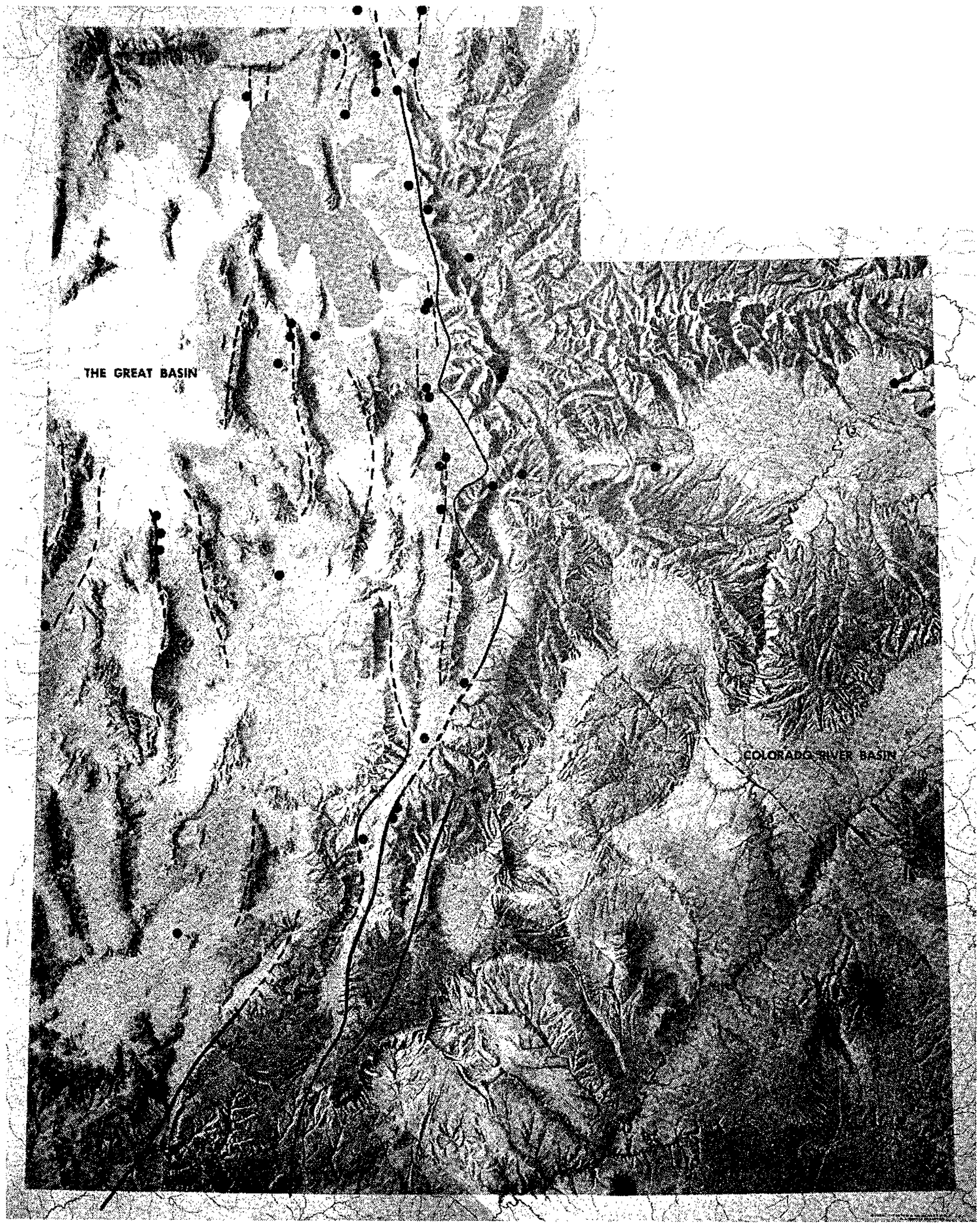

Fig. 2. Relation of mineral spring locations to major fault zones.

Quality Characteristics and Effect on Usable Supplies

Some of these springs which are high in mineral output merely spread out over the desert and evaporate leaving dry salt beds. Others flow directly into live streams. It is the detrimental effect which these mineralized waters have on the quality of water flowing in the "live" streams that is important to assess. In an extensive reach of a river, of course, there are other effluents which enter the system and which may contribute to the overall increase in total dissolved solids (TDS). However, the effect of springs is rather obvious from the sudden change in TDS in the vicinity of the spring. A few noteworthy examples can be pointed out.

The Malad River, arising in Idaho and joining the Bear River at a point below Cutler Dam, has three major spring areas which issue into the river itself. The TDS of the Malad River is high to begin with as the headwaters of the Malad are fed by mineralized springs; but the TDS of the Malad then increases from 3,900 ppm to 4,900 ppm with the contribution of Price's Hot Springs; drops to 4,500 ppm by the time it reaches Udy's Hot Springs as the flow picks up from tributary inflow; and jumps again to 5,500 ppm with the contribution of Udy's Hot Springs.

As the Bear River approaches the Utah state line from Idaho, it receives salt contributions from two salty springs just north and west of Preston, Idaho. Since the TDS of the Bear River at this point is normally very low, the relative effect on river quality as a result of the springs is quite pronounced. Typically the river TDS may be increased from 400 ppm to 800 ppm by these springs. Two other mineral springs issue into the Bear River before its confluence with the Malad River. These are at Cutler Narrows, where the TDS may increase from 850 ppm to 1,900 ppm, and near Corinne where the salt content of the Bear River increases to some 2,800 ppm TDS, largely as a result of large flows of mineralized water from Crystal Springs.

Another striking example of the influence of mineralized springs on water quality of natural streams is found on the Virgin River near LaVerkin. Here, LaVerkin Hot Springs discharges nearly 12 cfs of highly mineralized water directly into the river. In fact, at certain times in the year, when normal streamflow is diverted for irrigation, practically the only flow in the river for some distance is due to this hot spring. As other tributaries and irrigation return flow enter the river downstream from the LaVerkin Hot Springs, the river flow from the hot spring is diluted. But even the diluted water is nearly three times as salty as that above the springs since it has a TDS concentration near 2,000 ppm.

It should be remembered that the information reported here represents a condition observed at a particular period of time during the summer of 1964. These flow systems are dynamic, of course, and since the stream flows do not remain constant, the relative effect of springs on the stream system of which they are a part would vary with time. The affect of mineral springs would be less detrimental during the spring and early summer runoff period but might be more detrimental in late summer and autumn than has been indicated.

Management and Control Possibilities

Of the several springs sampled and measured in connection with this study, only a few have a noticeably harmful effect on the important surface water supplies. This is not to infer that there may not be an effect on groundwater supplies through intermixing as flows rise toward the ground surface.

A brief discussion of considerations in management of some of the more notable springs sampled in this study follows in the next few paragraphs.

Water from Blue Spring near Howell is impounded in Howell Reservoir from which the water is diverted and used for irrigation. Water having about 2,000 ppm of TDS might be of questionable quality for irrigation except that most of the water used for irrigation during the early part of the season is mixed and diluted by spring runoff waters of Blue Creek. This allows leaching of the soil with better quality water during the early part of the irrigation season when plants are particularly susceptible to salt damage. During the latter part of the irrigation season, the salt concentration of the reservoir water is increased slightly, since the only source of supply to the reservoir during this time of the year is the mineralized spring. This water has been used effectively for many years, and farmers in the area using this water indicate that there seem to be no deleterious effects on crops from the Howell Reservoir water. Proper management practices have been the key to the beneficial use of this water for irrigation.

Nearly all of the mineralized springs in the Bear River drainage have some effect on downstream surface supplies, since most of the springs are located on the stream banks or in the channel of the Bear River or its tributaries. As the Bear River approaches the Utah state line from Idaho, it receives salt contributions from two major spring groups. These are Battle Creek Hot Springs and Vincent Hot Springs. Other springs on the Bear River itself, which cause an increase in the salt concentration of the Bear River, are Cutler Springs and Crystal Springs near Honeyville.

If management and control of the waters from Battle Creek Hot Springs and Vincent Hot Springs should become necessary in the future, the best possibility for these appears to be diversion to holding ponds from which the water could be diverted to the Bear River during high flow stages in the spring of each year. In both cases nearby meadow land could be used for the purpose.

Since the present salt concentration of the Bear River above Cutler Narrows is not high, control and management of the springs is not critical However, as upstream development of the Bear River proceeds, quantities entering Utah will be decreased and the mineral concentration increased. The relative detrimental effect of the springs at the time will be significantly increased. The location of the springs at Cutler Narrows in the river channel makes removal and treatment possibilities extremely difficult. To be aware of the water quality problem in the downstream waters and to adopt irrigation practices suitable for the situation may be the only reasonable course of management action for these springs. During high flows in the river, the quality of water below the spring area is not a problem.

The deleterious effect of Crystal Springs near Honeyville is noticeable on the quality of Bear River water, and consideration of management and control schemes for these springs is warranted now. The water from the cold springs is comingled with the water from the hot springs to form Salt Creek, which eventually flows into the Bear River several miles to the south. Management possibilities would suggest a number of alternatives. The most apparent possibility may be to channel the water from the hot spring directly to Great Salt Lake without comingling or storing. Or it may prove more efficient to divert the hot spring discharge to a storage pond for complete evaporation. Other alternatives may be to convey Salt Creek water to an offstream storage site where the water could be partly evaporated and stored for timed releases to Great Salt Lake via the Bear River. The storage requirement for nine months would be 4,000 to 5,000 acre-feet. The three-month release period would have to be timed so as not to interfere with other users who may be using Bear River waters for leaching or flushing, such as in the bird refuge at the mouth of the river.

Another spring in the Bear River unit that has some potential for better management is the Bothwell Salt Creek Spring with a flow of about 16 cfs to 32 cfs, depending on the time of year. This spring has a salt load of about 90 tons per day. The major present use of this water is for wildlife ponds in the marshes and mud flats at the north end of Great Salt Lake. The vegetation thus supplied is of a relatively salt tolerant variety. However, the quality of Bothwell Salt Creek water is such that if it could be mixed with other fresh water supplies it could be safely used for irrigation or other uses.

Since a large fraction of the mineral contribution to Utah Lake enters the south end of the lake by way of Goshen Bay and Lincoln Point, it has been estimated that from 13,000 to 21,000 tons of chloride, or from 17 to 27 percent of the computed inflow chloride load to Utah Lake could be withheld from the Lake by constructing the Goshen Bay Dike, as proposed in the Central Utah Project plan report of the Bureau of Reclamation. This dike would effect an improvement in the chemical quality of Utah Lake and the Jordan River, not only from the withholding of salts from the lake, but also by the reduction in evaporation due to the reduced water surface area of Utah Lake.

Strawberry Springs in the Strawberry River drainage also present some management possibilities. Toxic contents of boron in the Strawberry and Duchesne rivers are undoubtedly due, in part, to the boron contributions from Strawberry Springs. Harmful concentrations of boron and other salts could possibly be kept from water supply sources by providing off-channel evaporation ponds near the springs. This may require building the adjacent road fill somewhat higher. Since most of the present contribution of salts appears to be reaching the Strawberry River through the alluvium, an underground cutoff by piling or by alluvial grouting would be the major management consideration. The economic justification of such measures would have to be studied in more detail, but prevention of crop damages due to boron contamination would seem to justify the management measures here.

The possible increase in salt concentration with increased depletion under the proposed Dixie Project in southwestern Utah has come under considerable discussion and study in recent years. Of principal concern in this regard is the effect of LaVerkin Springs on downstream flows. The U.S. Bureau of Reclamation has made operational studies of the project with and without the water from LaVerkin Springs to determine the effects on quality of water leaving Utah. Under a plan which contemplated a dam and reservoir near the town of Virgin, Utah, the effect of the LaVerkin Springs was estimated to cause an increase of approximately 600 ppm of TDS in Virgin River at Littlefield, Arizona. The annual weighted mean quality in terms of TDS would increase from 1,560 ppm before Dixie Project to 1,790 ppm with LaVerkin Springs removed, and up to 2,370 ppm without removal of LaVerkin Springs water.

The physical accomplishment of the collection and removal of LaVerkin Springs water would not be simple. The springs emerge in a narrow, steep canyon. There are one or two draws at the mouth of the canyon which might offer some possibility for temporary storage if it were not for the porous lava formations existing. Any removal scheme would likely involve pumping the mineral water out of the river channel during low flow periods. It might be possible to convey the water to the Bench Lake area and there provide evaporation opportunity. Whether or not the minerals precipitated would have some commercial value which would add to the economic feasibility of removing the spring waters would have to be investigated. Over 100,000 tons of dissolved solids are carried in the waters of LaVerkin Springs each year. Investigations still underway indicate that the development of a storage reservoir on the Virgin River under the Dixie Project will likely have to be below rather than above LaVerkin Springs. This change in plans will have a considerable effect on management considerations for LaVerkin Hot Springs.

Management possibilities are still being explored for the many springs included in this study. Many of these springs occur under such circumstances that they represent no problem in the foreseeable future. Others, while not of great concern at present are likely to become so as water use pressures mount. In any event, the information collected and its evaluation and interpretation will be of assistance to those engaged in planning and development of Utah's water resources. It provides a small but significant element of a more comprehensive water management program. The study has been conducted from a hydrologic or river basin perspective so that the results and interpretations are readily incorporated into any integrated pattern of water management and planning from either a quality or quantity standpoint.

The question might still remain in your mind, what does all of this have to do with groundwater? Most of what I've said has to do with surface waters almost exclusively.

These spring areas do represent a groundwater outflow. They represent points of groundwater outflow and as such they may be indicators of contamination of our groundwater supplies as well as contaminators of our surface water supplies. This possibility, to my knowledge, hasn't been studied extensively, except, perhaps in the Salt Lake County studies carried out by the Geological Survey where they have studied the contributions of waters arising along the faults of which these mineralized springs are associated. The waters arise along these faults and move out into the alluvium contaminating the groundwater in these areas and this has been studied in recent Salt Lake County studies by the Geological Survey. These studies do confirm the fact that contamination is reaching our groundwater supplies from the fault zones of which these mineralized springs are associated.

So in summary, this study of the mineralized springs might serve to point out some of the problems that may exist and to point out the need for further study in some areas. Further studies are being carried out by the Geological Survey. They are carrying out a fairly detailed study of all the springs in the state in which they are including these mineralized springs.

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PANEL DISCUSSION: GROUNDWATER LAWS AND ADMINISTRATION

Remarks by Wayne D. Criddle [1]

Sometime ago Dr. Jay M. Bagley told me of plans for this particular meeting. First, he diplomatically asked if I would participate and then he was kind enough to ask me for my suggestions for a program. He had already decided that our capable Assistant Attorney General, Dallin Jensen, should be invited to participate. However, he was a little dubious, I think, about asking anyone from the Court. With my moral support, he decided that without the court this particular program would not be complete. I think this was a most fortunate decision.

Some ten years ago, as a researcher in irrigation, drainage, and hydrology, I thought I had most of the answers as to how much water there was, where it was, how it could be developed, and the best economic use that could be made of it. Then, somehow, I slipped into the job of a water administrator and I soon found out that somewhere along the line somebody had neglected to drive home to me that I needed more than hydrology, I needed a better understanding of the law, and a strong course in the human relations. I'm still in need of such information. At the beginning of my experience as water administrator, I was too inclined to feel, as many of you may, that the court always walked backwards, with big blinders on so it could only see where it had been and not be distracted by anything off the beaten path. However, I feel now that the Honorable Judge Lewis Jones, who is with us here today, has a rather wide scope of vision and that his decisions on water cases are good (unless he reverses my administrative decisions). Thus, I feel we hydrologists, geologists, and others interested in the development and utilization of our water resources are fortunate to have the Judge here. He can help us arrive at reasonable answers which we engineers are too prone to want to solve only with mathematics. I'm sure we all appreciate having the Judge and the Assistant Attorney General participating on this program.

Now, after throwing cold water on the independent action of we hydrologists, I'd like to discuss some of the water problems in the State of Utah as I see them. But first, I would like to make the general observation that I'm a little disappointed with the title of this program. A symposium on groundwater management and administration in Utah is not complete now nor has it been in the past. There is a strong tendency for the general public to talk about groundwater as if it were something separate and apart from all other waters. Most usable groundwater is merely a "sluggish" branch of the river or general flow. The velocity at which the underground branch moves can be measured usually in a few feet per year, whereas the more obvious surface branch is measured in feet per second. However, each branch heads towards the low spot in the drainage basin, whether it be the ocean or the Great Salt Lake. And, although the surface flow is relatively easy to see and measure, few of us can see the water flowing underground, and the effects the varying recharge or discharge have on this branch sometimes take years to become noticeable. As a result, there is always the tendency for the man seeking water to claim that an unlimited amount is available underground, whereas the existing users of groundwater are quick to claim immediate and irreparable damage if the new appropriator is allowed to proceed with development.

As man's understanding and ability to control the elements improves, particularly his ability to "milk" the clouds, we may find another relatively invisible branch of the river that must be considered in administering the total waters of a basin. This stream may be far less dense than water flowing on or under the land surface, but it can be carrying vast quantities of water because of its dimensions and speed of movement. It seems only logical to assume that rainmaking in one area could deprive other areas of some surface and ground flows. The affect may be felt in the same basin or in adjacent basins, or possibly in some distant basin. Thus, can we limit our discussions to groundwater laws and their administration when "not all of the parties to the suit have been served"?

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Some precipitation falling on our land masses is consumed at or from near the land surface through evapotranspiration. The balance is lost by surface runoff or it percolates on down towards the groundwater table. The relative and total amounts of water disposed of by the various means are constantly changing. Groundwater leaks back to the stream in places, while at other points it is replenished from the stream. Thus, with the atmospheric, surface, and groundwater so intimately connected, laws established to govern but one source without considering the others that can be tapped has little meaning. Still, most of the general public thinks of them as being separate. Even our governmental, administrative, and investigative agencies have until recently tended to maintain separate groundwater and surface water divisions. Only within the past decade has the U.S. Geological Survey broken down the high, impermeable walls that have been built up between the surface water and groundwater branches. Before this shotgun marriage, each had been a power unto itself. One looked at, talked, and wrote about groundwater and the other about surface water; but neither wrote just about water.

Some researchers and administrators are now talking water, and the general public is slowly becoming aware that there might be some interconnection of groundwater and surface water. Users of river water where the water tables fluctuate directly with flows in the river, soon learn about this connection when new wells are drilled and heavy pumping begins to draw on the river supply.

For anyone to administer water satisfactorily, the laws of man must fit the laws of nature. Thus, regardless of claims as to what water will or will not do, the court cannot repeal the law of gravity, and man's effect on stream flow is downstream, not upstream. However, experience in water administration suggests that "reasonableness" is the key to successful application of the law. If a man is ordered by the court to install a measuring device on his water supply, it is quite unlikely that the court will expect installation on the same day as the decree. However, neither does he expect seasons to pass without action. Likewise, the court is reluctant to order expensive meters installed unless needed and unless the water administrator or others make use of the data such meters collect.

One of the most difficult problems facing any water administrator and the Courts, is the interpretation and application of the term "beneficial use." The meaning of this term fluctuates widely depending upon the state of the art, the education and desires of the user, the general public need, and on economics. For most purposes, actual needs can seldom be defined and limited to an exact amount. The administrator should constantly review and determine benefits and injuries that will result from certain levels of control which may be required under the term "beneficial use."

Also, as Mr. Jay Bingham has already mentioned, we not only have to measure the water, but we have to keep measuring the benefits and costs of maintaining efficient use of water. Throughout the United States and in most other areas of the world, costs and benefits resulting from use of water makes the law necessary to a large extent. I feel that, in the future, economics will increasingly influence the kind of laws adopted. Engineers, or hydrologists, must work very closely with the legal profession, with the Courts, and with the people, to get good water laws and good administration. Study of hydrology is not a requirement for admittance to the bar and it is up to us to help the Court to understand the physical relationships if he is to make sound decisions. Likewise, it is imperative that we engineers understand more of the court's problems and the reasons for certain legal decisions.

Thus, we are fortunate to have the legal and judicial arms of government meeting with us here today to give us some of the balance needed in our discussion of water administration.

Remarks by Judge Lewis Jones[2]

Taking up the serious subject at hand first, so that I can get your attention on the main thing I want to talk about — that's groundwater. We've started here in Utah, I'm sorry I didn't have the authority to order all the judges in the state to be here, to hear me talk, among others. We all need educating about this groundwater business. This idea that these sixty lakes in Utah, for example, are not inexhaustible is an astounding thing. And the idea that this water percolating through the gravel that is not in the lakes

[2]Judge Lewis Jones is State District Judge at Brigham City, Utah.

might fluctuate with snowfall or be affected by diversions of surface water is something that takes many of us some time to understand. That's why, between the two professions which are essentially charged with administering water law — the engineers and the lawyers — if there were just some magic way of catapulting the senior law class at the University of Utah and getting them up here for a few days and then taking some of the senior engineering students and getting them down in the mock court they hold at Salt Lake City so that they could advance some of these highly technical things that are put out from the rostrum here at this college, if you permit me to strain things a little bit, we would accomplish a great deal.

We all understand that there is a lack of communication, and when it comes to the public generally there is a great lack of understanding about this groundwater business. Now I think we're started in Utah, and in neighboring states on groundwater. We've got a long ways to go. Jay Bingham and these other people made a Bear River compact. I haven't read it today, but I've been sitting here thinking. There is a surface water compact. I am now adjudicating the waters of Bear River in Utah. Summit County is in my jurisdiction along with Cache and Box Elder Counties. We're busy parceling the water out. Some of the surface water for Wyoming is diverted in Summit County, and used in Wyoming. And we still have to make provisions for groundwater. Question: Can Utah get steam shovels and go up there and put in a giant cement wall and divert that underground water so we can use it some other place. And what about Idaho? We talk about this inexhaustible supply of groundwater for Cache County. Supposing somebody up there in Boise conceived the idea of diverting the groundwater, if you please, that creates these lakes in part in Cache County, heaven forbid we ever get into these situations, but I'm merely pointing out an extreme thing. So, what I'm trying to say is that the Bear River compact is only taking care of part of the problem. We need to have another compact covering groundwater, and the sooner the better because this groundwater is becoming more valuable.

Well, there are a lot of things that have been going through my mind. Hubert C. Lambert and his staff have been compiling these adjudications, these doomsday books. My shelves in the various courthouses are being weighted down with thick volumes. But my, they're precious. If you know your way around and you're buying a ranch, line no. 64 in that book would probably be worth more to you and your descendants on the value of that land — the water rights, than anything else you can get.

The so-called Kimball decree which was signed by Jim Kimball of Ogden, the late Judge Kimball in Logan, many years ago, is our old testament, that is on six days a week. That original volume down there in the courthouse has been thumbed through and so worn I guess we'll have to print some more. There were I guess a hundred copies printed. And the law firms that happen to have a copy of that book — they're on the in. They know what the law is. The new law firm that can't steal, bargain, or buy one of those books — they don't know much about water law.

So, it's fine we're doing these things. We must remember next to stringing up horse thieves and murderers there were a number of deaths in this state and in adjoining states before water rights became secured. We've not only codified the water law in part — we've got the surface water pretty well codified — but we've become civilized. We can go to the courthouse now and at least as to the surface waters we can pretty well find out what our rights are. We need to do the same thing to the groundwater.

Now let's talk about these underground claims that appear in these books, these doomsday books. Maybe in the future, the 1980 edition or the 2,000 AD edition, if we're still here, and the spaceships haven't taken us over, maybe at that time instead of saying that the filing is from Pine Canyon area, referring to thesurface right, we'll say referring to the Burley Valley area out west of Snowville, for example, underground well no. 64, Locomotive stream diversion from Snake River, if that's where Locomotive Springs comes from — no one seems to know that yet, and I don't know it either. I don't know how many have seen all that water that comes out of Locomotive Springs. Some of the old timers will tell you that there is a hole up there by Burley somewhere, that part of Snake River pours right down through the valley and that's where those surface wells at Malta are coming from. So maybe we'll have to say Escalante Lake, underground lake, is the source of underground well instead of just giving a legal description. And maybe we'll come to the proposition that first in time is first in right as to groundwater. So why spend my $25,000 and develop the first well on underground Lake Elsinore, for example, or underground Lake Milford, or whatever you call that down there if I am not to be protected: What's the name of that? Escalante Valley. Maybe I should have a prior right over these other guys that come in after me and file after I've proved the area. I pose that question to you. Why shouldn't the first fellow who spends his dough have a prior right against the other fellow? I don't mean that the other fellow can't have any water, but when the lake gets way down, and we haven't got the Yukon water down by that time, and these lakes begin getting low, maybe the fellow who spends his dough first ought to have the last of that water anyway. I merely raise these questions.

As to surface waters, as you all know, the appropriator sets forth his point of diversion from the surface stream. Now, supposing I want to file on the percolating water that's going down a certain strata through my farm. Shouldn't I be able to put a pump well in that strata all the way along if I'm the first guy in right? Well, why make me file a half a dozen applications on my own farm? Or supposing I'm over an underground lake, shouldn't the law be liberalized so as to permit me to put in more than one well, to come from that particular source? Well, I'm asking these questions. I don't claim to know exactly what the answers are, but they are questions posed by this groundwater business and I think this groundwater is, from the standpoint of we laymen, the new seseme, the new eureka. And we must administer it properly and I believe that the principles we've followed on the surface rights can be applied to the groundwater.

First in time, first in right. Beneficial use. Let the man file his application for an appropriation. In other words, apply the present practices as nearly as may be to the groundwater. Let's have compacts covering groundwater; we must have compacts. We must make provision to, if necessary, condemn winter water, winter surface rights which are mainly in some cases used for stock water, and take steam shovels and gas shovels and go down to the right place and open up these lids on these reservoirs and pour the water back down there some way. There are many things that need to be done.

Now you old timers pardon me for saying something about horn book law to the younger people here. Remember, the Anglo Saxons came in here and a few Swedes and Danes. Of course, we know the Danes are part of the Angloes and Saxons. I am part Danish myself. We brought the English common law with us here. We soon found out that the riparian rights as to water as administered in England at the time of the American Revolution had no application here. So, it was the courts, the territorial courts, with the aid of the then engineers like the man by the name of Brigham Young, who I understand had a pretty good idea of engineering, who steered the thought and the trend so that some territorial judge became brave enough to announce that while the English common law in effect at the time of the American Revolution was the basic law of this territory; yet because of the nature of this land an exception be made and the doctrine of appropriation was announced. Now I am not sure whether Utah was first, or Colorado, or Nevada. I can't remember which one of the territorial courts announced that doctrine. And that is the basic doctrine. I see no reason, gentlemen, why that doctrine can't and shouldn't apply to the groundwater principles just the same as it has applied to the surface water.

In conclusion, maybe this isn't apropos to Hubert's story about the lady going out and getting a bucket and filling up that reservoir, but I was in the army a year or two and in the back rooms, in the latrines if you please, there was a story that was told of a fellow by the name of Douglas McArthur that didn't get into Doug's books, but I guess Doug had a sense of humor. When he was a 2nd Lieutenant stationed down in San Antonio there came a War Department order. (In those days, all orders transferring officers came from Washington.) There came a War Department order on one of those famous stencils that most of us have become acquainted with in one way or another. It said, "by order of the President, 2nd Lieutenant McArthur will proceed by water from San Antonio to Washington, D.C., and he will make all the necessary preparations and the necessary orders will be issued in order to accomplish that purpose."

Well, I guess Doug wasn't very busy chasing Indians or going down to Mexico or doing all these other things that he wrote about in his biography. I don't know how many of you read it. So, he took a day or so off and wrote up an elaborate special order and I can't recite all of it, but it started out: by command of the President, the dredging operations on the Panama Canal are hereby suspended. The Panama dredging company will move by all possible draft up to the mouth of the Rio Grande River. All the engineering companies and battalions in the United States are hereby directed to proceed by all possible dispatch with all their equipment to the San Antonio, and the Panama dredging command under General So and So will commence at the mouth of the Rio Grande River with the river dredges working up the river and the engineers will start up at San Antonio and work down the river. The battleship Utah is ordered to be steamed up and prepared and cleaned up. When this work is accomplished the battleship Utah will steam up to San Antonio in order that 2nd Lieutenant Doug McArthur can ride by water as directed by the Commander in Chief, from San Antonio to Chesapeake Bay.

Remarks by Dallin W. Jensen [3]

If it isn't, it ought to be fairly obvious at this point in the proceedings that the major problem with water is people. This isn't meant to be facetious, nor is this an original statement. However, it couldn't be truer. Water only becomes an issue when man's conflicting needs become involved. Absent the human problems created by conflicting rights and uses, the job of applying the principles of hydrology to a water source to obtain a desired use would be much easier. However, once the legislatures and courts act to define property rights in water the scientist has to apply his skills to solve problems within this legal framework. For instance, existing rights to water cannot be ignored in determining how to get the maximum benefits from the resource. I am not suggesting that you buy bad concepts, but nevertheless, changes in the law occur gradually and may not keep pace with scientific development. A court is not apt to readily abandon time honored concepts to embrace a new scientific approach to a problem until it is thoroughly convinced that the new solution has substantial advantages over the old one.

As you are probably aware, under the appropriation doctrine water is considered public property even though the individual may acquire a vested right to the use of it. This furnishes a legal basis for the exercise of public control over this resource by the state. And it is imperative to have some public control over our water resources if there is to be sound water administration.

I would like to turn briefly to the question of what principles should be set forth in a good groundwater code in order to have effective use and administration of the resource. There must be a designation of the waters which are included, and a designation of the administration agency which is to administer the waters. A procedure must be provided for the acquisition of new rights, as well as a system for making a record of preexisting rights. A means should be set out for the determination of existing rights , and the code should also provide machinery for proper distribution of existing rights. A provision should be made for changes in the exercise of groundwater rights and conditions set up governing the loss of these rights. Of course, these principles would also be applicable to a good surface-water code.

Laws should provide for the orderly development of the resource but they must be workable. In other words, from the viewpoint of administration the legislative pronouncements on water rights should set forth broad general guidelines for the administrator. But the statutes ought not to be so detailed that they hamper effective administration. There must be some room for discretion or judgment on the part of the administrator. Whether his judgment, in a particular case, is good or bad is beside the point. While it is the legislature's responsibility to set forth the guiding principles, it is the responsibility of the administrator to fill in the interstices and implement these principles. The administrator must take the lead. He's the one that people come to complain to first. Sometimes the water user will file an action directly in court, but in most cases he will ask the administrator to try to solve his problem. Of course, once the administrator acts an appeal may be taken to the court and the administrator's decision reviewed. Under Utah law when an appeal is taken from a decision of the State Engineer it proceeds as a trial de novo. This simply means that the judge hears the entire matter over just as if the State Engineer hadn't acted.

I think it's worth echoing a concept already stated, namely, that there ought to be an integration of our thinking on ground and surface water. The same legal principles should apply to both, and most states are moving in this direction. The trend has been away from the elaborate classifications that were set up in some of the early water codes and court decisions where groundwater was classified as percolating water, subterranean water courses, underflow, etc. Most modern water codes now make

[3] Dallin W. Jensen is Assistant Attorney General for the State of Utah.

a fairly simple declaration encompassing both surface and groundwater. I believe this is a better approach because treating water as one resource, which it is, will undoubtedly aid in solving surface and groundwater problems rather than contributing to them.

The integration of surface and groundwater has got to carry through the appropriation, adjudication, and distribution processes. An obvious example of this need is the situation where someone comes to the State Engineer and applies for a well which is adjacent to a fully appropriated stream. The administrator simply can't ignore these facts, he must determine the possible effect of the well on the stream. It is only by treating surface and groundwater as one resource that he is able to make this determination. The same philosophy is applicable to the adjudication and distribution of water rights.

I would like to mention another area of groundwater administration that has been receiving additional emphasis lately. This involves well drillers. Utah has had control over well drilling for a number of years, but there are a number of states with no control over the drilling of wells. Regulation is needed and serves at least two worthwhile purposes. One is that it assures proper construction of the well thereby guarding against contamination of the aquifers. Secondly, it provides a source of resource data through the well logs. This information may not be technically the most accurate, but I am advised it can be very useful.

I would like to touch on the legal aspects of the groundwater administrative problems of greatest concern in Utah. Some of these problems are general throughout the west.

The problem of development and utilization of a groundwater basin or reservoir involves the balancing of two general interests. One is the private property rights in groundwater and the other is the general public interest in seeing that the resource is fully utilized. Private rights should not extend to a point that the resource is wasted or development foreclosed. On the other hand the public interest must not be extended to such a point that vested rights are jeopardized. It is questions arising in this framework that cause courts so much concern. These are somewhat nebulous concepts to wrestle with, and don't lend themselves to an easy solution.

The route that water law has followed to get the maximum benefit from the resource is by the granting of private property rights in water as opposed to public development. Under this philosophy private rights must be secure enough that the individual will expend capital for development but the right should also have enough flexibility that it can be changed by economic forces. If the public interest is not being protected it may be necessary to determine if new laws or more laws are needed to get maximum utilization of the resource.

One area that I'm sure has been discussed amply from a technical point of view at this symposium is to what extent should our groundwater basins be depleted. The battle lines on this question usually shape up behind either mining the groundwater basin or restricting withdrawal to annual yield. This problem gives the courts the same concern that is does hydrologists. In a given lawsuit a judge will be presented such technical data as the limits of the basin, its sources of supply, the outflow both natural and artificial. He must then determine how this evidence is to be applied to the issues presented by the litigants.

The Utah Supreme Court in a decision about a year ago stated that groundwater use in Utah is to be governed by safe annual yield. While the case turned primarily on the question of interference the court did conclude: "That prudent management of water resources requires that only the average annual recharge be withdrawn." However, I don't believe we should stop with an analysis of water supply. There is another element in this equation and this is the question of economics. This seems to be coming more into focus in recent court decisions. It's not much comfort to the individual water users appearing before the administrator or the court to be assured that there is plenty of water at a depth of 300 feet if it's only economically feasible to get it at 250 feet. The user should be required to have a realistic means of diversion but this means should also be economically feasible for him. I think economic considerations are going to receive additional attention in the future, and rightly so.

Any analysis of legal concepts applicable to groundwater in Utah would be incomplete without a review of the law as it relates to hydrostatic pressure in artesian basins. The question is often asked whether the individual user from an artesian basin is entitled to the hydrostatic pressure as a part of his means of diversion. The Utah court has announced that where a user has appropriated water by means of artesian pressure this means of diversion is a part of the individual's property right. For better or worse, that is the present status of the law in Utah. So the question is whether or not this is the best rule. The obvious argument against maintaining pressure is that it is too wasteful. Personally, I am sympathetic to this argument. The hydrologists claim that when a basin has a substantial artesian pressure it is overflowing, it's too full, and there is additional water available for use. It would seem to be very analogous to always maintaining a surface reservoir essentially full and only utilizing part of the inflow. With our increased demands for water there is bound to be a greater effort made to unlock this valuable resource. Therefore, the pressure question is bound to receive additional consideration in the future.

It should be noted there are not a lot of other states that consider the hydrostatic pressure as part of the water right. Most other states protect quality and quantity but not pressure. For instance, the Nevada groundwater code provides that the static water level is not a part of the right. The prior appropriator must suffer some reasonable reduction in static water level for the benefit of junior appropriations. The determination as to the reasonableness of the reduction is left to the State Engineer and I don't envy him his job. However, I think this rule allows for a more complete and realistic development of a groundwater basin.

It should be noted that Utah has a replacement statute which allows the junior appropriator, whose appropriation diminishes the quantity of water of the prior appropriator, to make a replacement to the prior right. Therefore, even though the junior appropriator does reduce the pressure he may replace the water and maintain his own appropriation. This seems to work quite well for a municipality drilling next to a group of small wells where the users may be satisfied with free connections. However, in a lot of farming operations the farmer can hardly afford to drill his well, much less make a replacement of water to a neighbor. To this extent I don't think that the statute is quite realistic.

A few thoughts on what might be some trends of the future. There will probably be more administration control over water use with groundwater administration becoming more sophisticated. I can't help but think that the increasing technological data that you hydrologists are talking about will be an important element in this metamorphosis. Additional data will materially aid in giving administrators and courts an insight under ground they don't have now. A better understanding of the nature of the basins, with more accurate information on the depth, nature and capacity of aquifers, should result. The data is becoming more refined and will continue to do so in the future. This should materially aid in arriving at better decisions.

Due to the complex interrelationships in groundwater basins there will be increased emphasis on the installation of measuring devices, and control structures as an aid to administrative control. This point was highlighted by a recent Utah Supreme Court decision which involved a determination of the parties' rights in a groundwater basin. In order to effectuate proper distribution of the rights the court ordered the installation of measuring devices on the junior appropriator's well. The court concluded this was essential in order to protect already established rights.

Once groundwater rights have been determined, the distribution of groundwater reservoirs are going to receive more attention in the future. It will be necessary to determine if restrictions are necessary and if so how they should be put into effect. These controls can take two forms. The less drastic is simply closing a basin to further appropriation. However, it it is determined there is insufficient water to meet the demands and safe annual yield is the governing criteria it will be necessary to restrict withdrawals in reverse order of priority. In my judgment this is going to be one of the major areas of concern in the future.

The question of more efficient use of water will receive more attention in the future. This won't be unique with groundwater but will also apply to surface water. Greater efficiency will be required and again it's just a question of time. In 1960 the Utah Supreme Court in an appeal from an order setting a temporary duty on groundwater in Escalante Valley at four acre-feet made a significant announcement. In effect the court said: The right of the prior appropriator has got to be beneficial, not only in relation to the requirements of his land but also in relation to the reasonable requirements of the junior appropriator. At first blush this pronouncement may not overwhelm you, but it is significant when compared to some of the language in early decisions which merely stated that the prior user had the right to the water up to the extent of his right but said nothing about efficiency.

Also, as has been pointed out, there is going to be more planned use groundwater as well as surface water. Many states are making an attempt to formulate a state water plan. This makes good sense in that is insures that the public interest is protected and preserved.

In connection with groundwater development there will probably be more use of the public districts. These districts may be able to solve some of the domestic water supply problems that exist in unincorporated but fairly heavily populated areas.

OPTIMIZING CONJUNCTIVE USE OF SURFACE WATER AND GROUNDWATER

by

Calvin G. Clyde,[1] Bartell C. Jensen[2] and James H. Milligan[3]

The quantity and quality of available water resources have long been recognized as limiting factors in the development of most arid and semi-arid regions. Recent experiences have shown that these limiting factors may also apply in the more humid areas previously thought to be immune to water shortage problems. The optimum utilization of existing water resources is therefore of everincreasing importance.

While the water supply is replenished in a general recurring seasonal and annual pattern, it is not yet within man's power to significantly increase the overall supply. The best that can be done is to conserve the recurring supply and bring it under control, to preserve the quality, and to better serve the more vital uses. The planning and execution of the best possible programs for the conservation and control of water should be recognized as one of the nation's most important natural resource problems — especially in arid regions.

The Conjunctive Use Concept

Investigators such as Clendenen (1957), Banks (1966) and Bittinger (1965) have pointed out that the maximum beneficial use of the total water supply in a given basin requires that both surface and underground water be utilized. Storage and distribution facilities both on the surface and underground must be considered in the plan. This integrated approach to water use is called "conjunctive use." Todd (1959) has summarized the positive and negative economic factors of conjunctive use based on the earlier work of Clendenen.

Past Practices in Water Planning

Early water development projects were typically small, single purpose systems built with a minimum of engineering and with but little formal planning. Topography, the location and size of the water source, and the necessity to get water at any cost usually dicated the configuration of the works. Little attempt was made to plan and build the best possible project. These systems grew as small project was added to small project. The resulting development was often haphazard and inefficient at best.

Subsequent projects became larger and more complex as available undeveloped water supplies dwindled, and efficient use of the water resource became more and more necessary. Since many different types and arrangements of irrigation works or water supply works were possible on any particular project, the advantages and disadvantages of all practicable schemes should have been considered. Engineers attempted to do this by selecting several of the most promising schemes of water development for detailed analysis. The overall benefits from each plan were estimated and the probable costs were determined. Benefit to cost ratio was then assigned to each alternative plan

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which gave a rational basis for picking the best development of the plans studied. While such a procedure was a big step forward, it did not necessarily comprise a true optimization of the water system since only the best among a few alternatives was chosen; conceivably the optimum combination of ground and surface water development was not considered. In more recent years projects have become even more complex as multiple water uses, multiple water sources, and multiple water conveyance methods for the proposed projects have been considered.

Early water development projects tended to favor surface water supplies and to ignore the groundwater resource. This followed quite naturally from the difficulty of getting the water out of the ground. Even after drilling techniques had been perfected and after efficient, low cost pumps were available, groundwater development lagged in many areas of the nation. When groundwater has been utilized, it has usually been developed as a separate groundwater project. The first attempts to integrate surface and groundwater resources into a true "conjunctive use" system have come only in the last few years.

Thus the water planning policies of the past, even when considering multiple purpose aspects of the problem, have considered but a few of the possible alternatives. These may or may not have included the optimum system. Furthermore, conventional planning methods have not considered the advantages of integrated or conjunctive use of surface and groundwater. This paper is a progress report of Utah Water Research Laboratory project which is working on these problems under the joint sponsorship of the Office of Water Resources Research, Department of the Interior, and the Utah Water and Power Board.

Application of Systems Analysis to Water Resources Planning

One of the most significant and important advances in engineering has been the recent development of the analytical tools and the methodolgy for the analysis, understanding, and design of large engineering systems. Early steps in this field came during World War II with efforts to improve combat and logistics systems. Later work in economics, transportation, weapons, communication, and aerospace systems contributed to this rapidly growing field of systems engineering. Over the same time period the applied mathematical discipline of operations research has developed out of the need for solving optimizing problems. In very recent times the tools and techniques of systems analysis and operations research have been applied to water resource systems for both planning and decision purposes.

Contributions of a few of the recent inovators in this field are summarized below:

A noted application of a systems analysis approach to water resource allocation and design was formulated under the Harvard Water Program. The results of this large-scale research project were published as a book, Design of Water Resource Systems, by Maass et al. (1962). The research was devoted to the methodology of planning or designing complex, multiunit, multipurpose water resource systems. Simulation of river-basin systems on high-speed digital computers and the construction of mathematical models that produce optimal solutions are two techniques discussed in some detail in the book.

Buras (1963) analyzed the conjunctive utilization of a surface reservoir and a groundwater aquifer from the point of view of its optimal operation. A mathematical model was set up in which the consecutive stages in the operation of the systems were related, and then dynamic programming was adapted to determine an optimal operation of the system.

A report by the Harvard Water Resources Group entitled "Indus River Basin Studies" was the product of an investigation of the feasibility of tubewell schemes in the Indus Plain. Optimization schemes were developed in this study for the spacing and depth of tubewells under typical or specified conditions. Optimum pumping schedules for a year were also determined.

Hall (1964) applied systems analysis to the optimal design of a multiple-purpose reservoir. Here again dynamic programming was used to determine the optimum design of a multiple-purpose water project.

The tool of parametric linear programming was applied by Dracup (1966) to the optimum use of a groundwater and surface water system. A simplified mathematical model for a ground and surface water system was formulated to represent the San Gabriel Valley in Southern California. Decision rules were analyzed to determine the optimum operating procedure for this water resource system.

Objectives of the Project

The general objective of the research reported in this paper is to develop the guidelines and planning procedures for optimizing conjunctive use of surface and groundwater. The emphasis is in formulating optimum planning decisions for a new water resource development rather than defining operating rules for an already existing project.

Mean annual values of inputs are used in initial stages of the investigations. Stochastic (random) inputs for appropriate parameters will be considered in later stages of the investigation.

It is necessary to completely describe the system and all its limits and interactions by means of equations and inequalities. This model is then optimized with respect to planning decisions by an appropriate programming algorithm. A brief summary of the steps involved follows:

1. Describe the complete water resource system along with the objectives to be attained by the planned project.
2. Determine the objective function, i.e., the equation that describes the costs of and the benefits resulting from the system.
3. Determine the constraints over which the benefit function is to be optimized. These constraints consisting of both equations and inequalities describe the interrelationships among the variables as well as their limitations.
4. Carry out the optimization to find the parameter values that yield the maximum benefits.
5. Perform a sensitivity analysis, i.e., investigate how much the maximized benefits are affected by changes in selected parameters.
6. Describe the final configuration of the best project. That is, describe the acreage, water use, storage facilities, etc., of the optimized project.

Development of the Hydrologic Model

Many of the water resource system models developed in recent years included only surface water while others include groundwater in a simplified way without emphasizing the actual hydrologic relationships existing in the system. It is a specific aim of this project to emphasize the groundwater surface water relationships existing in the hydrologic cycle in order to obtain a more realistic model to which the optimizing techniques of mathematical programming can be applied.

The groundwater — surface water model

The ground and surface water model in its present state of development is depicted schematically in Figure 1 and consists of the following:

1. Surface water supply made up of precipitation and locally available surface streamflow. No imported waters have been incorporated. The surface supply may be diverted to canal flows, downstream flows, or artificial recharge, or it may be stored in surface storage to level out seasonal sluctuations.
2. Downstream surface flow commitments which must be met. Return flows from irrigation may be used for this requirement.
3. Groundwater supply made up of natural recharge and artificial recharge. Underground inflow has been considered as negligible and thus eliminated from the model. Natural recharge consists of inflow from too deep percolation of precipitation and from seepage losses from natural streams. Artificial recharge consists of incidental and deliberate recharge. Incidental recharge includes deep percolation of applied irrigation waters, and distribution system seepage accompanying normal operations. Deliberate recharge includes any recharge due to operations carried out

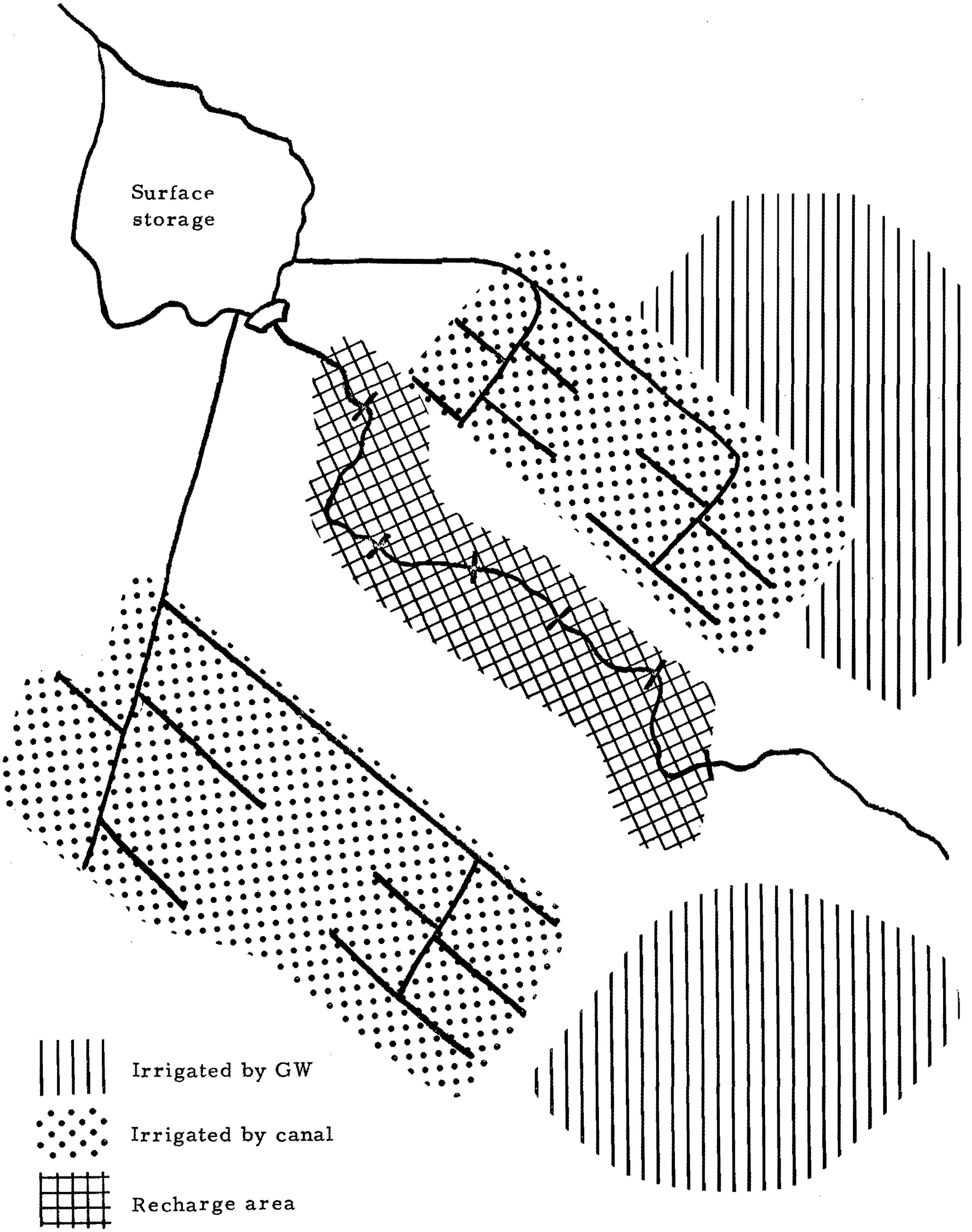

Fig. 1. Schematic Representation of the Hydrologic Model.

specifically for the purpose of adding to the groundwater supply. Thus far in the model this item has been a single lump sum.

4. Groundwater outflows which consist of natural underground outflow, evapotranspiration from groundwater, baseflow to streams, as well as pumpage for various uses.

Multiple sources and demands for water have not yet been incorporated into the model since the major problem has been to delineate the groundwater surface water relationships. All sources and demands are of a deterministic nature. It is anticipated that these variables will be represented as stochastic variables and included at a later stage.

Groundwater — surface water relationships

To begin the study some rather simple relationships were used to express the hydrologic system. Nearly all of these are simple proportions or percentages. For example, water conveyance through canals is assumed to be 70 percent efficient, so that 30 percent of the water diverted to canals is assumed to be lost to seepage and recharges the groundwater. The remaining 60 percent of the applied irrigation water, one half or 30 percent shows up as return flow while the other half is groundwater recharge through deep percolation. These are general relationships which hold in some areas but not in others. Similar assumptions are made for such items as recharge from the distribution system, recharge from precipitation and natural stream flow, and evapotranspiration losses. Base flow and induced recharge are related to the groundwater levels as is the volume of groundwater storage. Pumping costs are also related to groundwater levels.

More sophisticated relationships will be developed as the study progresses. It is anticipated that analog computer simulation will be a useful tool for this purpose.

The current hydrologic model along with the assumed relationships are shown in Figure 2.

Development of the Linear Programming Model

In order to find the optimum combination of ground and surface water supply for a specified agricultural demand, the mathematical tool of linear programming is used. This requires that the hydrologic model be transformed into a system of linear equations and inequalities. The linearity requirement is not a serious limitation for the simple relationships assumed in the current model, but as the realtionships become more complex and further refinements are made, linear functions may not be appropriate. The system of constraints representing the hydrologic model is related to costs and benefits by means of a linear objective function, the value of which is to be maximized.

The constraint system

The constraints and limitations on the groundwater — surface water system are formulated from the following:

1. Surface supply during the dry season.
2. Surface supply during the wet season.
3. Water demand during the dry season.
4. Water demand during the wet season.
5. Hydraulic continuity of the groundwater system.
6. Groundwater storage capacities at various groundwater levels.
7. Downstream water requirements.
8. Recharge to the groundwater aquifer.

The constraints are first written as equations and inequalities which represent the physical situation. The inequalities are converted to equations by the addition of slack variables. Physically, the slack variables represent overfulfillments of requirements or under-utilization of capacity.

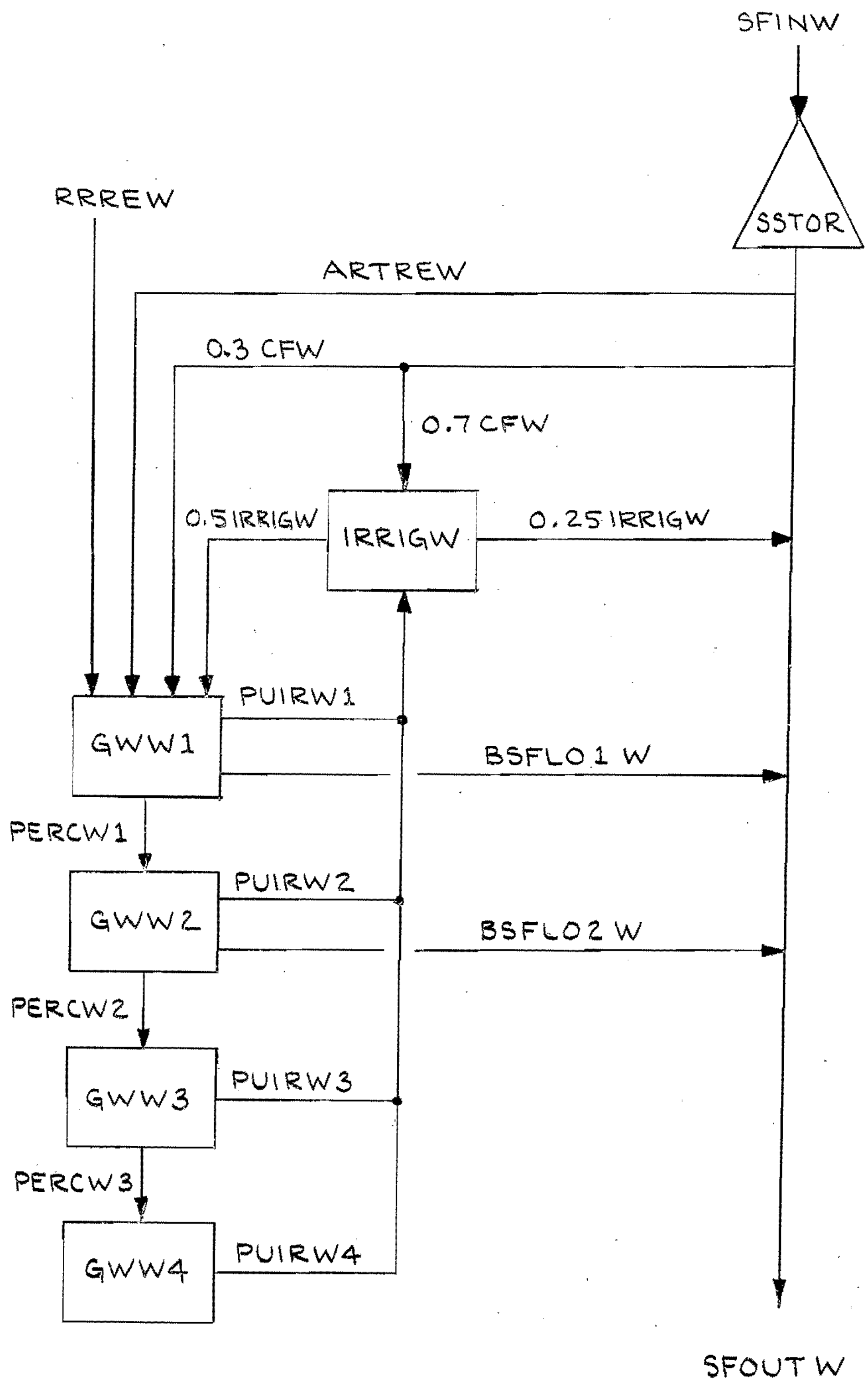

Fig. 2a. Flow diagram of the hydrologic model (wet season).

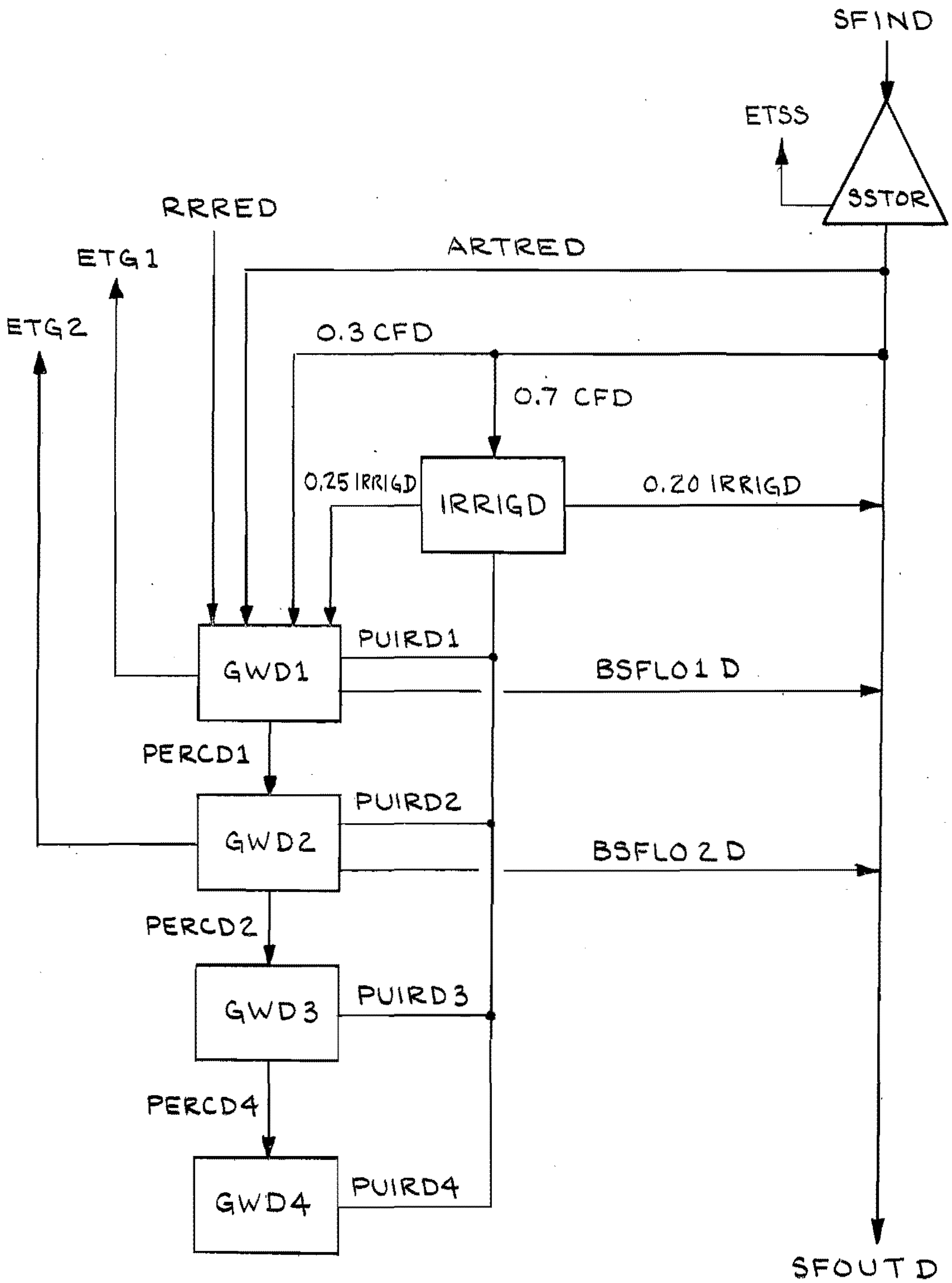

Fig. 2b. Flow diagram of the hydrologic model (dry season).

The objective function

The objective function for this particular model expresses the total net benefits to be derived from the water resources system. A cost or benefit in terms of dollars per acre foot is assigned to each variable which appears in the objective function as well as the constraint system. The sign of each coefficient determines cost or benefit. A matrix map representing the mathematical model is shown in Figure 3. The elements of the matrix map are code symbols representing the magnitude of the elements of the actual matrix which is the mathematical expression of the objective function and the constraint system. The code representation for the matrix map is given below.

The matrix elements are represented as follows:

Code	Magnitude of Elements: Greater than	Magnitude of Elements: Equal to or less than	Occurrences
0	0.0	0.0001	0
2	0.0001	0.001	0
3	0.001	0.01	0
4	0.01	0.1	10
5	0.1	0.9999	10
1	=1.0		88
6	1.0	10.0	56
7	10.0	100.0	34
8	100.0	1000.0	6
9	1000.0		0

The row labels given in the matrix tableau are coded to the objective function and the constraints of the mathematical model. Row label BENI represents the objective function. All other row labels represent the various constraints. The column labels represent the variables included in the model with the exception of column labels cost, B-VEC, *B1, *B2, and *B3. The label cost has no meaning for this model. The labels B-VEC, *B1, *B2, and *B3 represent the right-hand-side vector in the model. The remaining column labels are defined as follows:

Definition of variables

GW — groundwater storage; D or W following refers to dry to wet season, number following refers to level
PUIR — pumping for irrigation; same as above
PUEX — pumping for export same as above
PERC — percolation same as above
IRRIG — irrigation
SSTOR — surface storage
CF — canal flow; D refers to dry season, W refers to wet season
ARTRE — artificial recharge same as above

The complete mathematical expression of the objective function and the constraint system is given in Figure 4, Matrix Tableau, which occupies several pages. The row and column labels in the Matrix Tableau are the same as those in the matrix map.

The Optimizing Method

The linear constraints represent a set of hyperplanes dividing the space into a series of half spaces, the intersection of which forms a convex set. Only points in this set satisfy the constraints and become feasible solutions to the problem. The extreme points of this convex set of solutions are basic feasible solutions and if an optimal solution exists, at least one basic feasible solution will be optimal. If the optimal solution is not unique, points other than extreme points are also optimal.

	COST	B-VEC	GWD1	GWD2	GWD3	GWD4	PUIRD1	PUIRD2	PUIRD3	PUIRD4	PUEXD1	PUEXD2	PUEXD3	PUEXD4	PERCD1	PERCD2	PERCD3	IRRIGD	IRRIGW	CFD	ARTRED	SSTOR	CFW	ARTREW	GWW1	GWW2	GWW3	GWW4	PUIRW1	PUIRW2	PUIRW3	PUIRW4	PUEXW1	PUEXW2	PUEXW3	PUEXW4	PERCW1	PERCW2	PERCW3	*B1	*B2	*B3
COST	.	.	.	6	6	6	-6	-6	-6	-7	-6	-6	-6	-6	.	.	.	7	6	-6	-7	-6	-6	-7	.	6	6	6	-6	-6	-7	-7	-6	-6	-6	-6	.	.	.	.	.	.
BEN1	.	.	.	6	6	6	-6	-6	-6	-7	-6	-6	-6	-6	.	.	.	7	6	-6	-7	-6	-6	-7	.	6	6	6	-6	-6	-7	-7	-6	-6	-6	-6	.	.	.	.	.	.
GWS1D	.	7	6	.	.	.	1	.	.	.	1	.	.	.	1	.	.	-5	.	-5	-1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	7	.	.
SS1D	.	7	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	7	.	.
GWS2D	.	7	.	6	.	.	.	1	.	.	.	1	.	.	-1	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	7	.	.
SS2D	.	7	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	7	.	.
GWS3D	.	7	.	.	1	.	.	.	1	.	.	.	1	.	.	-1	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	7	.	.
SS3D	.	7	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	7	.	.
GWS4D	.	8	.	.	.	1	.	.	.	1	.	.	.	1	.	.	-1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	8	.	.
SS4D	.	8	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	8	.	.
DIVD	.	7	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	1	-1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	7	.	.
DIVW	.	7	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	1	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	7	.	.
IRRD	.	.	.	.	.	.	1	1	1	1	.	.	.	.	.	.	.	-1	.	5	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
IRRW	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	-1	.	.	.	5	.	.	.	.	.	1	1	1	1	.	.	.	.	.	.	.	.	.	.
GWS1W	.	6	-1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	-5	.	.	.	-5	-1	6	.	.	.	1	.	.	.	1	.	.	.	1	.	.	6	1	-1
SS1W	.	7	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	7	.	.
GWS2W	.	.	.	-1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	6	.	.	.	1	.	.	.	1	.	.	-1	1	.	.	.	.
SS2W	.	7	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	7	.	.
GWS3W	.	.	.	.	-1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	1	.	.	.	1	.	.	-1	1	.	.	.
SS3W	.	7	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	7	.	.
GWS4W	.	.	.	.	.	-1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	1	.	.	.	1	.	.	-1	.	.	.
SS4W	.	8	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	8	.	.
CONT	.	6	-4	-4	.	.	.	.	.	.	-1	-1	-1	-1	.	.	.	-5	-5	1	1	4	1	1	-4	-4	.	.	.	.	.	.	-1	-1	-1	-1	.	.	.	6	.	.
CONMAX	.	-6	4	4	.	.	.	.	.	.	1	1	1	1	.	.	.	5	5	-1	-1	-4	-1	-1	4	4	.	.	.	.	.	.	1	1	1	1	.	.	.	-6	.	.

19 JUN 67 CONJUNCTIVE USE MODEL TWO .000.003.00

CASE FIG. 4. MATRIX TABLEAU

Label	COST	B-VEC	GWD1	GWD2	GWD3
Cost	.000000	.000000	.000000	2.510000	5.020000
Row Label					
1 BEN1	.000000	.000000	.000000	2.510000	5.020000
2 GWS1D	.000000	34.500000	1.155000	.000000	.000000
3 SS1D	.000000	59.999999	1.000000	.000000	.000000
4 GWS2D	.000000	59.999999	.000000	1.066000	.000000
5 SS2D	.000000	59.999999	.000000	1.000000	.000000
6 GWS3D	.000000	59.999999	.000000	.000000	1.000000
7 SS3D	.000000	59.999999	.000000	.000000	1.000000
8 GWS4D	.000000	180.000000	.000000	.000000	.000000
9 SS4D	.000000	180.000000	.000000	.000000	.000000
10 DIVD	.000000	14.400000	.000000	.000000	.000000
11 DIVW	.000000	35.699999	.000000	.000000	.000000
12 IRRD	.000000	.000000	.000000	.000000	.000000
13 IRRW	.000000	.000000	.000000	.000000	.000000
14 GWS1W	.000000	4.500000	-1.000000	.000000	.000000
15 SS1W	.000000	59.999999	.000000	.000000	.000000
16 GWS2W	.000000	.000000	.000000	-1.000000	.000000
17 SS2W	.000000	59.999999	.000000	.000000	.000000
18 GWS3W	.000000	.000000	.000000	.000000	-1.000000
19 SS3W	.000000	59.999999	.000000	.000000	.000000
20 GWS4W	.000000	.000000	.000000	.000000	.000000
21 SS4W	.000000	180.000000	.000000	.000000	.000000
22 CONT	.000000	10.000000	-.085000	-.036000	.000000
23 CONMAX	.000000	-9.500000	.085000	.036000	.000000

19 JUN 67 CONJUNCTIVE USE MODEL TWO .000.004.00

CASE FIG. 4. MATRIX TABLEAU (CONTINUED)

Label	GWD4	PUIRD1	PUIRD2	PUIRD3	PUIRD4
Cost	7.530000	-5.000000	-7.500000	-10.000000	-12.500000
Row Label					
1 BEN1	7.530000	-5.000000	-7.500000	-10.000000	-12.500000
2 GWS1D	.000000	1.000000	.000000	.000000	.000000
3 SS1D	.000000	.000000	.000000	.000000	.000000
4 GWS2D	.000000	.000000	1.000000	.000000	.000000
5 SS2D	.000000	.000000	.000000	.000000	.000000
6 GWS3D	.000000	.000000	.000000	1.000000	.000000
7 SS3D	.000000	.000000	.000000	.000000	.000000
8 GWS4D	1.000000	.000000	.000000	.000000	1.000000
9 SS4D	1.000000	.000000	.000000	.000000	.000000
10 DIVD	.000000	.000000	.000000	.000000	.000000
11 DIVW	.000000	.000000	.000000	.000000	.000000
12 IRRD	.000000	1.000000	1.000000	1.000000	1.000000
13 IRRW	.000000	.000000	.000000	.000000	.000000
14 GWS1W	.000000	.000000	.000000	.000000	.000000
15 SS1W	.000000	.000000	.000000	.000000	.000000
16 GWS2W	.000000	.000000	.000000	.000000	.000000
17 SS2W	.000000	.000000	.000000	.000000	.000000
18 GWS3W	.000000	.000000	.000000	.000000	.000000
19 SS3W	.000000	.000000	.000000	.000000	.000000
20 GWS4W	-1.000000	.000000	.000000	.000000	.000000
21 SS4W	.000000	.000000	.000000	.000000	.000000
22 CONT	.000000	.000000	.000000	.000000	.000000
23 CONMAX	.000000	.000000	.000000	.000000	.000000

CASE FIG. 4. MATRIX TABLEAU (CONTINUED)

Label	PUEXD1	PUEXD2	PUEXD3	PUEXD4	PERCD1
Cost	-4.000000	-5.000000	-6.000000	-7.000000	.000000
Row Label					
1 BEN1	-4.000000	-5.000000	-6.000000	-7.000000	.000000
2 GWS1D	1.000000	.000000	.000000	.000000	1.000000
3 SS1D	.000000	.000000	.000000	.000000	.000000
4 GWS2D	.000000	1.000000	.000000	.000000	-1.000000
5 SS2D	.000000	.000000	.000000	.000000	.000000
6 GWS3D	.000000	.000000	1.000000	.000000	.000000
7 SS3D	.000000	.000000	.000000	.000000	.000000
8 GWS4D	.000000	.000000	.000000	1.000000	.000000
9 SS4D	.000000	.000000	.000000	.000000	.000000
10 DIVD	.000000	.000000	.000000	.000000	.000000
11 DIVW	.000000	.000000	.000000	.000000	.000000
12 IRRD	.000000	.000000	.000000	.000000	.000000
13 IRRW	.000000	.000000	.000000	.000000	.000000
14 GWS1W	.000000	.000000	.000000	.000000	.000000
15 SS1W	.000000	.000000	.000000	.000000	.000000
16 GWS2W	.000000	.000000	.000000	.000000	.000000
17 SS2W	.000000	.000000	.000000	.000000	.000000
18 GWS3W	.000000	.000000	.000000	.000000	.000000
19 SS3W	.000000	.000000	.000000	.000000	.000000
20 GWS4W	.000000	.000000	.000000	.000000	.000000
21 SS4W	.000000	.000000	.000000	.000000	.000000
22 CONT	-1.000000	-1.000000	-1.000000	-1.000000	.000000
23 CONMAX	1.000000	1.000000	1.000000	1.000000	.000000

CASE FIG. 4. MATRIX TABLEAU (CONTINUED)

Label	PERCD2	PERCD3	IRRIGD	IRRIGW	CFD
Cost	.000000	.000000	45.000000	10.000000	-8.200000
Row Label					
1 BEN1	.000000	.000000	45.000000	10.000000	-8.200000
2 GWS1D	.000000	.000000	-.250000	.000000	-.300000
3 SS1D	.000000	.000000	.000000	.000000	.000000
4 GWS2D	1.000000	.000000	.000000	.000000	.000000
5 SS2D	.000000	.000000	.000000	.000000	.000000
6 GWS3D	-1.000000	1.000000	.000000	.000000	.000000
7 SS3D	.000000	.000000	.000000	.000000	.000000
8 GWS4D	.000000	-1.000000	.000000	.000000	.000000
9 SS4D	.000000	.000000	.000000	.000000	.000000
10 DIVD	.000000	.000000	.000000	.000000	1.000000
11 DIVW	.000000	.000000	.000000	.000000	.000000
12 IRRD	.000000	.000000	-1.000000	.000000	.700000
13 IRRW	.000000	.000000	.000000	-1.000000	.000000
14 GWS1W	.000000	.000000	.000000	-.500000	.000000
15 SS1W	.000000	.000000	.000000	.000000	.000000
16 GWS2W	.000000	.000000	.000000	.000000	.000000
17 SS2W	.000000	.000000	.000000	.000000	.000000
18 GWS3W	.000000	.000000	.000000	.000000	.000000
19 SS3W	.000000	.000000	.000000	.000000	.000000
20 GWS4W	.000000	.000000	.000000	.000000	.000000
21 SS4W	.000000	.000000	.000000	.000000	.000000
22 CONT	.000000	.000000	-.200000	-.250000	1.000000
23 CONMAX	.000000	.000000	.200000	.250000	-1.000000

19 JUN 67 CONJUNCTIVE USE MODEL TWO .000.007.00

CASE FIG. 4. MATRIX TABLEAU (CONTINUED)

Label	ARTRED	SSTOR	CFW	ARTREW	GWW1
Cost	-15.000000	-3.500000	-7.000000	-14.000000	.000000
Row Label					
1 BEN1	-15.000000	-3.500000	-7.000000	-14.000000	.000000
2 GWS1D	-1.000000	.000000	.000000	.000000	.000000
3 SS1D	.000000	.000000	.000000	.000000	.000000
4 GWS2D	.000000	.000000	.000000	.000000	.000000
5 SS2D	.000000	.000000	.000000	.000000	.000000
6 GWS3D	.000000	.000000	.000000	.000000	.000000
7 SS3D	.000000	.000000	.000000	.000000	.000000
8 GWS4D	.000000	.000000	.000000	.000000	.000000
9 SS4D	.000000	.000000	.000000	.000000	.000000
10 DIVD	1.000000	-1.000000	.000000	.000000	.000000
11 DIVW	.000000	1.000000	1.000000	1.000000	.000000
12 IRRD	.000000	.000000	.000000	.000000	.000000
13 IRRW	.000000	.000000	.700000	.000000	.000000
14 GWS1W	.000000	.000000	-.300000	-1.000000	1.085000
15 SS1W	.000000	.000000	.000000	.000000	1.000000
16 GWS2W	.000000	.000000	.000000	.000000	.000000
17 SS2W	.000000	.000000	.000000	.000000	.000000
18 GWS3W	.000000	.000000	.000000	.000000	.000000
19 SS3W	.000000	.000000	.000000	.000000	.000000
20 GWS4W	.000000	.000000	.000000	.000000	.000000
21 SS4W	.000000	.000000	.000000	.000000	.000000
22 CONT	1.000000	.100000	1.000000	1.000000	-.085000
23 CONMAX	-1.000000	-.100000	-1.000000	-1.000000	.085000

CASE FIG. 4. MATRIX TABLEAU (CONTINUED)

Label	GWW2	GWW3	GWW4	PUIRW1	PUIRW2
Cost	2.510000	5.020000	7.530000	-6.000000	-8.000000
Row Label					
1 BEN1	2.510000	5.020000	7.530000	-6.000000	-8.000000
2 GWS1D	.000000	.000000	.000000	.000000	.000000
3 SS1D	.000000	.000000	.000000	.000000	.000000
4 GWS2D	.000000	.000000	.000000	.000000	.000000
5 SS2D	.000000	.000000	.000000	.000000	.000000
6 GWS3D	.000000	.000000	.000000	.000000	.000000
7 SS3D	.000000	.000000	.000000	.000000	.000000
8 GWS4D	.000000	.000000	.000000	.000000	.000000
9 SS4D	.000000	.000000	.000000	.000000	.000000
10 DIVD	.000000	.000000	.000000	.000000	.000000
11 DIVW	.000000	.000000	.000000	.000000	.000000
12 IRRD	.000000	.000000	.000000	.000000	.000000
13 IRRW	.000000	.000000	.000000	1.000000	1.000000
14 GWS1W	.000000	.000000	.000000	1.000000	.000000
15 SS1W	.000000	.000000	.000000	.000000	.000000
16 GWS2W	1.036000	.000000	.000000	.000000	1.000000
17 SS2W	1.000000	.000000	.000000	.000000	.000000
18 GWS3W	.000000	1.000000	.000000	.000000	.000000
19 SS3W	.000000	1.000000	.000000	.000000	.000000
20 GWS4W	.000000	.000000	1.000000	.000000	.000000
21 SS4W	.000000	.000000	1.000000	.000000	.000000
22 CONT	-.036000	.000000	.000000	.000000	.000000
23 CONMAX	.036000	.000000	.000000	.000000	.000000

19 JUN 67 CONJUNCTIVE USE MODEL TWO .000.009.00

CASE FIG. 4. MATRIX TABLEAU (CONTINUED)

Label	PUIRW3	PUIRW4	PUEXW1	PUEXW2	PUEXW3
Cost	-12.000000	-15.000000	-3.000000	-4.000000	-5.000000
Row Label					
1 BEN1	-12.000000	-15.000000	-3.000000	-4.000000	-5.000000
2 GWS1D	.000000	.000000	.000000	.000000	.000000
3 SS1D	.000000	.000000	.000000	.000000	.000000
4 GWS2D	.000000	.000000	.000000	.000000	.000000
5 SS2D	.000000	.000000	.000000	.000000	.000000
6 GWS3D	.000000	.000000	.000000	.000000	.000000
7 SS3D	.000000	.000000	.000000	.000000	.000000
8 GWS4D	.000000	.000000	.000000	.000000	.000000
9 SS4D	.000000	.000000	.000000	.000000	.000000
10 DIVD	.000000	.000000	.000000	.000000	.000000
11 DIVW	.000000	.000000	.000000	.000000	.000000
12 IRRD	.000000	.000000	.000000	.000000	.000000
13 IRRW	1.000000	1.000000	.000000	.000000	.000000
14 GWS1W	.000000	.000000	1.000000	.000000	.000000
15 SS1W	.000000	.000000	.000000	.000000	.000000
16 GWS2W	.000000	.000000	.000000	1.000000	.000000
17 SS2W	.000000	.000000	.000000	.000000	.000000
18 GWS3W	1.000000	.000000	.000000	.000000	1.000000
19 SS3W	.000000	.000000	.000000	.000000	.000000
20 GWS4W	.000000	1.000000	.000000	.000000	.000000
21 SS4W	.000000	.000000	.000000	.000000	.000000
22 CONT	.000000	.000000	-1.000000	-1.000000	-1.000000
23 CONMAX	.000000	.000000	1.000000	1.000000	1.000000

19 JUN 67 CONJUNCTIVE USE MODEL TWO .000.010.00

CASE FIG. 4. MATRIX TABLEAU (CONTINUED)

Label	PUEXW4	PERCW1	PERCW2	PERCW3	*B1
Cost	-6.000000	.000000	.000000	.000000	.000000
Row Label					
1 BEN1	-6.000000	.000000	.000000	.000000	.000000
2 GWS1D	.000000	.000000	.000000	.000000	34.500000
3 SS1D	.000000	.000000	.000000	.000000	59.999999
4 GWS2D	.000000	.000000	.000000	.000000	59.999999
5 SS2D	.000000	.000000	.000000	.000000	59.999999
6 GWS3D	.000000	.000000	.000000	.000000	59.999999
7 SS3D	.000000	.000000	.000000	.000000	59.999999
8 GWS4D	.000000	.000000	.000000	.000000	180.000000
9 SS4D	.000000	.000000	.000000	.000000	180.000000
10 DIVD	.000000	.000000	.000000	.000000	14.400000
11 DIVW	.000000	.000000	.000000	.000000	35.699999
12 IRRD	.000000	.000000	.000000	.000000	.000000
13 IRRW	.000000	.000000	.000000	.000000	.000000
14 GWS1W	.000000	1.000000	.000000	.000000	4.500000
15 SS1W	.000000	.000000	.000000	.000000	59.999999
16 GWS2W	.000000	-1.000000	1.000000	.000000	.000000
17 SS2W	.000000	.000000	.000000	.000000	59.999999
18 GWS3W	.000000	.000000	-1.000000	1.000000	.000000
19 SS3W	.000000	.000000	.000000	.000000	59.999999
20 GWS4W	1.000000	.000000	.000000	-1.000000	.000000
21 SS4W	.000000	.000000	.000000	.000000	180.000000
22 CONT	-1.000000	.000000	.000000	.000000	10.000000
23 CONMAX	1.000000	.000000	.000000	.000000	-9.500000

The actual optimization using the Simplex procedure can then be described as a method which proceeds in systematic steps from an initial basic feasible solution to adjacent basic feasible solutions, and finally in a finite number of steps to an optimal basic feasible solution. The value of the objective function at each step (iteration) is better (or at least not worse) than at the preceding step. Because the value of the objective function is improved (or at least not worsened) at each step, the number of iterations needed before an optimal solution is arrived at is, in general, small relative to the total number of existing basic solutions.

If at any stage the Simplex method comes to an extreme point which has an edge leading to infinity (unbounded convex set) and if the objective function can be increased (or decreased) by moving along that edge, an unbounded solution is indicated.

An example of the computer output for the conjunctive use model is given to illustrate the results which can be obtained with the solution to each problem. The results from the optimization consist of several parts, which are explained below.

The section of output which is labeled "Primal Output" contains the number of iterations required to reach the optimal solution and the optimal value of the objective function. For the case under consideration 36 were iterations and $11,342,965 was the de-coded value of the objective function. The primal output also contains for each variable in the optimal solution its label, its cost and its activity level (optimal value). For example the solution tells us the following:

1. All of the groundwater is pumped from the first two groundwater levels (SS1 and SS2) which had original quantities 59.999 (decoded as 60,000 A.F.) stored in each.
2. The optimal amount of irrigation water to be used is 220.849 or decoded it is 220,849 A.F.
3. The total amount of water pumped from the first groundwater level (PUIRD1) is 104,742 A.F. which includes the quantity initially in storage as well as the amount recharged to that level from seepage losses, etc.
4. The optimal amount of water which is delivered through canals (CFD) is 50,099 A.F. of this amount 35,699 A.F. comes from surface storage (SSTOR).

Each item of the list will not be explained in detail. These examples, however, together with the computer output enableone to interpret the remainder of the primal output for this particular model.

The section of output which is labeled "Dual Output" consists of non-basic slack variables (those variables which do not enter the optimal solution), the cost coefficients (which are zero unless prices were assigned to slacks), and the shadow prices.

Shadow prices represent marginal costs of introducing unit amounts of the non-optimal slack variables into the optimal solution. These data are an indication of the profit (or cost) of raising or lowering the constraint values (the RHS values); they show how relaxed specifications can increase or decrease profit. For example, consider the shadow price of 153.94 associated with DIVD (the slack variable associated with the amount of streamflow available in the dry season). If the amount of streamflow available (14,400 A.F.) were reduced to 14,399 A.F. the profit of $11,342,965 would be reduced by $153.94.

The "Reduced Cost" output consists of non-basic variables (again, those which do not enter into the optimal solution) their cost coefficients, and the reduced costs. The reduced costs are the amounts by which the costs associated with the non-basic variables would have to be reduced before these variables would become eligible for entry into the optimal solution.

For example, if the cost of CFW (the canal flow in the wet season) were changed from $-7.00 to $-25.98 ($-7.00 less the reduced cost $18.98) this variable would be able to enter the basis and be replaced by another variable.

The "Dual Ranges" are the ranges of feasibility of the RHS elements of the non-basic variables. They are directly related to the shadow prices obtained in the Dual.

The original RHS element of DIVD is 14.4 (decoded to 14,400 A.F.). The value of this element

PRIMAL OUTPUT

CASE ITERATION 39 OBJECTIVE VALUE 18387.579000

	LABEL	COST	ACTIVITY	LABEL	COST	ACTIVITY
E	BEN1	.000000	18387.579000	SS1D	.000000	59.999999
	SS2D	.000000	59.999999	SS3D	.000000	59.999999
	SS4D	.000000	180.000000	SS1W	.000000	59.999999
	SS2W	.000000	59.999999	SS3W	.000000	59.999999
	SS4W	.000000	180.000000	CONT	.000000	61.139998
	PUIRD1	-5.000000	177.729990	PUIRD2	-7.500000	59.999999
	PUIRD3	-10.000000	59.999999	PUIRD4	-12.500000	180.000000
	IRRIGD	45.000000	512.799990	IRRIGW	10.000000	9.000000
	CFD	-8.200000	50.099999	SSTOR	-3.500000	35.699999
	GWW4	7.530000	.000000	PUIRW1	-6.000000	9.000001
	PERCW1	.000000	-.000000	PERCW2	.000000	-.000000

END PRIMAL OUTPUT

DUAL OUTPUT

CASE ITERATION 39 OBJECTIVE VALUE 18387.579000

	LABEL	COST	SHADOW PRICE		LABEL	COST	SHADOW PRICE
E	BEN1	.000000	.000000	Z	GWS1D	.000000	53.333332
	SS1D	.000000	.000000	Z	GWS2D	.000000	50.833333
	SS2D	.000000	.000000	Z	GWS3D	.000000	48.333333
	SS3D	.000000	.000000	Z	GWS4D	.000000	45.833333
	SS4D	.000000	.000000		DIVD	.000000	48.633332
	DIVW	.000000	45.133332	Z	IRRD	.000000	-58.333333
Z	IRRW	.000000	-14.000000	Z	GWS1W	.000000	8.000000
	SS1W	.000000	.000000	Z	GWS2W	.000000	8.000000
	SS2W	.000000	.000000	Z	GWS3W	.000000	8.000000
	SS3W	.000000	.000000	Z	GWS4W	.000000	7.530000
	SS4W	.000000	.000000		CONT	.000000	.000000

END DUAL OUTPUT

REDCST OUTPUT

CASE ITERATION 39 OBJECTIVE VALUE 18387.579000

LABEL	COST	REDUCED COST	LABEL	COST	REDUCED COST
Z GWS1D	.000000	53.333332	Z GWS2D	.000000	50.833333
Z GWS3D	.000000	48.333333	Z GWS4D	.000000	45.833333
DIVD	.000000	48.633332	DIVW	.000000	45.133333
Z IRRD	.000000	-58.333333	Z IRRW	.000000	-14.000000
Z GWS1W	.000000	8.000000	Z GWS2W	.000000	8.000000
Z GWS3W	.000000	8.000000	Z GWS4W	.000000	7.530000
GWD1	.000000	53.599998	GWD2	2.510000	43.678332
GWD3	5.020000	35.313332	GWD4	7.530000	30.773333
PUEXD1	-4.000000	57.333333	PUEXD2	-5.000000	55.833333
PUEXD3	-6.000000	54.333333	PUEXD4	-7.000000	52.833333
PERCD1	.000000	2.500000	PERCD2	.000000	2.500000
PERCD3	.000000	2.500000	ARTRED	-15.000000	10.299999
CFW	-7.000000	39.933333	ARTREW	-14.000000	51.133333
GWW1	.000000	8.680000	GWW2	2.510000	5.778000
GWW3	5.020000	2.980000	PUIRW2	-8.000000	2.000000
PUIRW3	-12.000000	6.000000	PUIRW4	-15.000000	8.530000
PUEXW1	-3.000000	11.000000	PUEXW2	-4.000000	12.000000
PUEXW3	-5.000000	13.000000	PUEXW4	-6.000000	13.530000
PERCW3	.000000	.470000	Z *B1	.000000	18387.579000

END REDCST OUTPUT

DUAL RANGE OUTPUT

CASE ITERATION 39 OBJECTIVE VALUE 18387.579000

		- - - - - - LIMITS OF RANGE		- - - - - -	
LABEL	ORIG. ACT.	LABEL	INCREMENT	LABEL	INCREMENT
DIVD	14.400000	CONT	-83.372723	CFD	50.099999
DIVW	35.699999	CONT	-73.367997	SSTOR	35.699999
GWD1	.000000	IRRIGW	-4.500000	SS1D	59.999999
GWD2	.000000	IRRIGW	-4.500000	PERCW1	.000000
GWD3	.000000	IRRIGW	-4.500000	PERCW1	.000000
GWD4	.000000	GWW4	-.000000	PUIRD4	180.000000
PUEXD1	.000000	CONT	-83.372724	PUIRD1	133.297500
PUEXD2	.000000	CONT	-83.372724	PUIRD2	59.999999
PUEXD3	.000000	CONT	-83.372724	PUIRD3	59.999999
PUEXD4	.000000	CONT	-83.372724	PUIRD4	180.000000
PERCD1	.000000	PUIRD2	-59.999999	PUIRD1	177.729990
PERCD2	.000000	PUIRD3	-59.999999	PUIRD2	59.999999
PERCD3	.000000	PUIRD4	-180.000000	PUIRD3	59.999999
ARTRED	.000000	PUIRD1	-253.899990	CFD	50.099999
CFW	.000000	IRRIGW	-4.500000	SSTOR	35.699999
ARTREW	.000000	IRRIGW	-4.500000	SSTOR	35.699999
GWW1	.000000		-9999.000000	IRRIGW	4.147465
GWW2	.000000	PERCW1	-.000000	IRRIGW	4.343629
GWW3	.000000	PERCW1	-.000000	IRRIGW	4.500000
PUIRW2	.000000	PERCW1	-.000000	PUIRW1	9.000001
PUIRW3	.000000	PERCW1	-.000000	PUIRW1	9.000001
PUIRW4	.000000	IRRIGW	-4.500000	GWW4	.000000
PUEXW1	.000000	CONT	-122.279996	IRRIGW	4.500000
PUEXW2	.000000	PERCW1	-.000000	IRRIGW	4.500000
PUEXW3	.000000	PERCW1	-.000000	IRRIGW	4.500000
PUEXW4	.000000	CONT	-61.139998	GWW4	.000000
PERCW3	.000000	PERCW1	-.000000	IRRIGW	4.500000

END DUAL RANGE OUTPUT

PRIMAL RANGE OUTPUT

CASE ITERATION 39 OBJECTIVE VALUE 18387.579000

		- - - - - - LIMITS OF RANGE	- - - - - -		
LABEL	COST	LABEL	INCREMENT	LABEL	INCREMENT
BEN1	.000000		-9999.000000	ARTRED	1.000000
SS1D	.000000	GWD1	-53.599998		9999.000000
SS2D	.000000	GWD2	-43.678332		9999.000000
SS3D	.000000	GWD3	-35.313332		9999.000000
SS4D	.000000	GWD4	-30.773333		9999.000000
SS1W	.000000	GWW1	-8.680000		9999.000000
SS2W	.000000	GWW2	-5.778000		9999.000000
SS3W	.000000	GWW3	-2.980000		9999.000000
SS4W	.000000	PERCW3	-.470000	PUIRW4	8.530000
CONT	.000000	PERCW3	-.940000	PUEXW4	13.530000
PUIRD1	-5.000000	PERCD1	-2.500000	ARTRED	14.714285
PUIRD2	-7.500000	PERCD2	-2.500000	PERCD1	2.500000
PUIRD3	-10.000000	PERCD3	-2.500000	PERCD2	2.500000
PUIRD4	-12.500000	GWD4	-30.773333	PERCD3	2.500000
IRRIGD	45.000000	GWD4	-23.080000		9999.000000
IRRIGW	10.000000	PERCW3	-.235000	PUIRW4	4.265000
CFD	-8.200000	ARTRED	-10.299999		9999.000000
SSTOR	-3.500000	CFW	-39.933333		9999.000000
GWW4	7.530000	PUIRW4	-8.530000	PERCW3	.470000
PUIRW1	-6.000000	PERCW3	-.235000	PUIRW4	8.530000
PERCW1	.000000	GWD3	-35.313332	PERCW3	.470000
PERCW2	.000000	GWD3	-35.313332	PERCW3	.470000

END PRIMAL RANGE OUTPUT

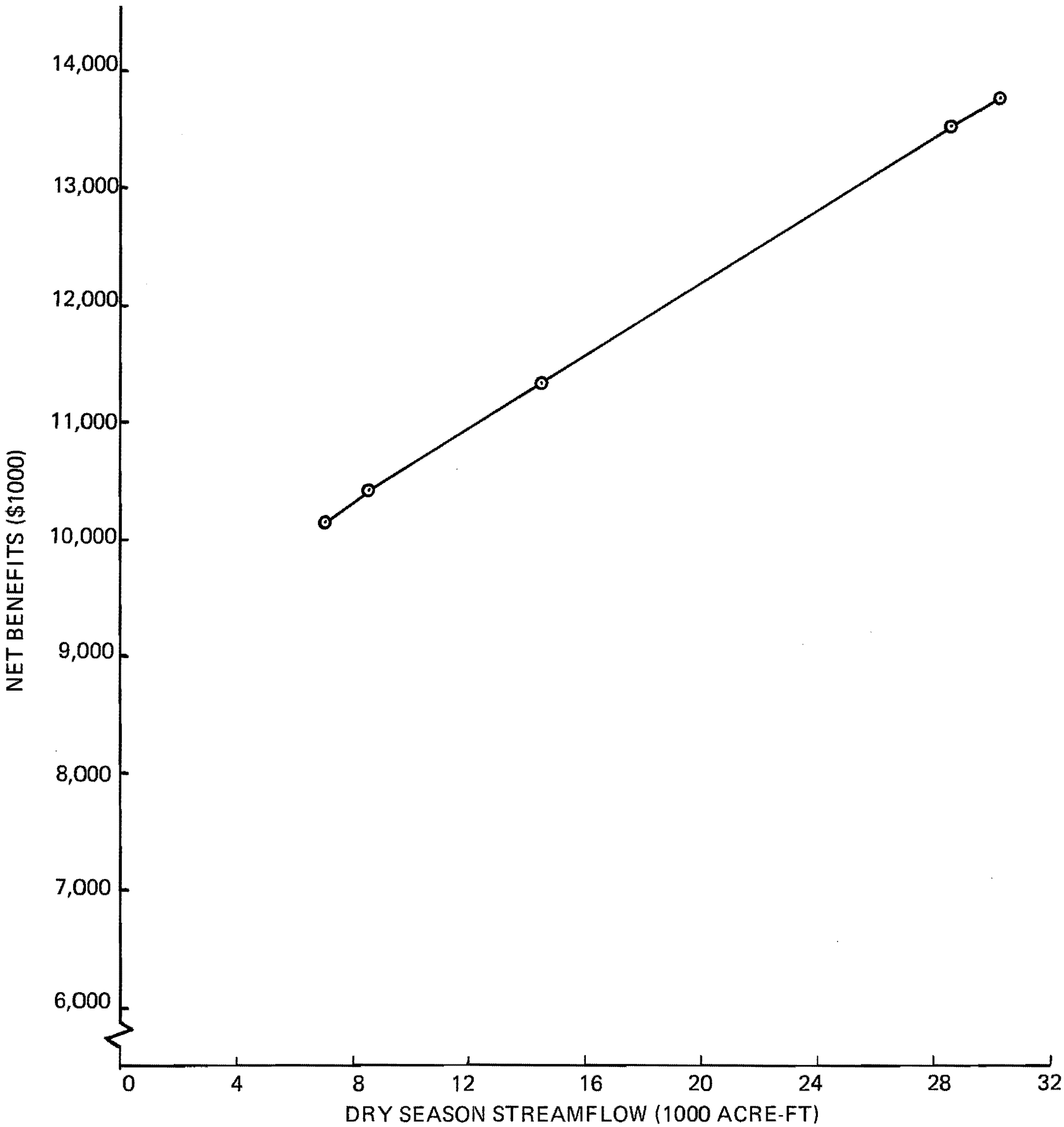

Fig. 5. Results of parametric analysis of dry season streamflow.

may be reduced to -14.1681. If further reduction is attempted the variable GWD3 will leave the optimal solution. Similarly the RHS of DIVD may be increased to 6.0136 without requiring a basis change. Increase beyond this point will cause variable SS3W to leave the optimal solution.

The allowable range given in this output is a measure of the sensitivity to change. A variable with a large range is relatively insensitive, and a variable with a small range is highly sensitive.

The "Primal Ranges" are the ranges of optimality of the objective coefficients corresponding to the variables in the optimal solution. These ranges are directly related to the optimal activity levels obtained in the Primal Output. The allowable range given for each objective coefficient in the primal ranges is a measure of the sensitivity of these coefficients to change.

The objective function coefficient of variable CFD (canal flow in dry season) which is -8.20 may vary between -18.50 and + ∞(∞ represented by 9999.0) without destroying optimality. A value less than 18.50 will cause variable ARTRED to enter the basis. Similar interpretation may be applied to the other coefficients listed in this output.

One of the major problems in developing an appropriate linear-programming model is the gathering of accurate and reliable numerical values for the coefficients in both the objective function and the constraint system, and for the right-hand side. Since these values are estimated and thus subject to error, it is necessary to consider the behavior of a particular solution when the coefficients and requirements (right-hand side) are allowed to vary. This is the subject matter of parametric linear programming and is an important part of the overall sensitivity analysis.

In carrying out the sensitivity analysis we may wish to vary the coefficients of the constraint matrix, the objective function cost and benefit coefficients, or the constants of the right-hand side of the constraints. The first ot these variations cannot be carried out efficiently without resolving the entire problem. The other two, however, by using parametric programming algorithms can be carried out without resolving the problem. These variations provide an efficient means of sensitivity analysis which, in turn, allows for a great amount of flexibility in consideration of alternative decisions.

Cost ranging and right-hand side ranging are also part of the sensitivity analysis. These items have been discussed in previous sections of this paper.

Parametric analyses have been carried out for several of the RHS values as well as for several of the objective coefficient values. Rather than present examples of the entire computer output for these values a short summary of the parametric output for one RHS value and for one objective coefficient is presented.

Parametric analysis of the RHS element DIVD (streamflow available during the dry season) shows that when DIVD is varied from an initial value of 14,400 A.F. between the limits of 6,963 A.F. and 30,200 A.F. the net benefits respond as shown in Figure 5. Within this range several changes take place in the optimum model. For example as streamflow is increased from the initial value of 14,168 A.F. to 28,568 A.F. The groundwater storage in GW3 is depleted and pumping from GW4 during the dry season begins. Also as streamflow is decreased from 14,400 A.F. to 8,386 A.F. pumpage from GW3 during the wet season ceases and pumpage from GW2 during the wet season decreases.

Project Continuation

Further work outlined for the current project on optimization of the groundwater surface water system will include a further sophistication of the water resources system model, by addition and study of sociological and legal constraints to the hydrologic constraints of the model, and by the use of non-linear relationships and stochastic variables.

Further expansion of the hydrological model will include water supply sources in addition to local surface waters and precipitation. Additional water demands with corresponding benefits will also be included in the model. These will include demands for municipal and industrial waters.

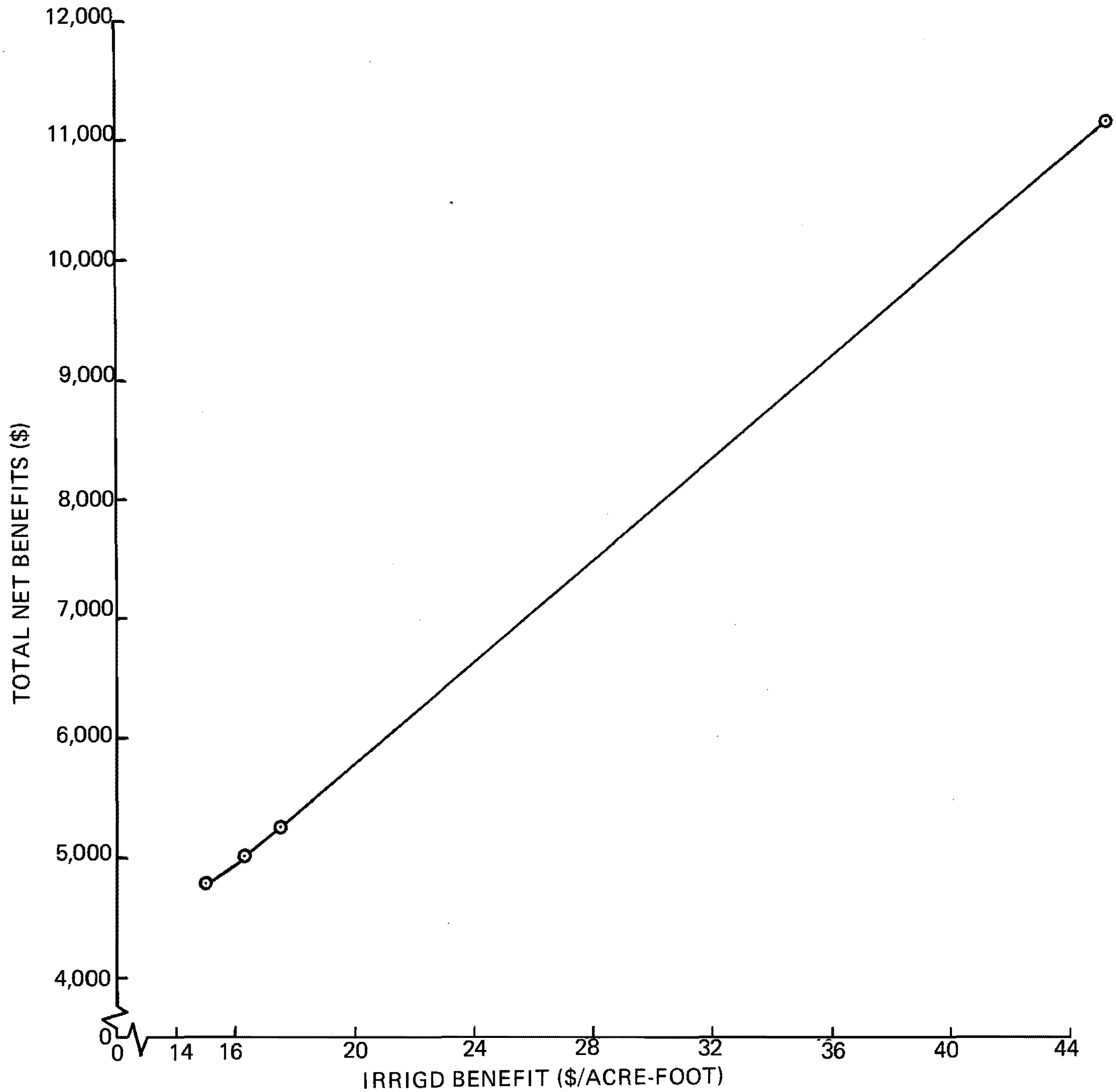

Fig. 6. Results of parametric analysis of cost coefficients associated with variable IRRIGD.

Improvements will be made in the representation of the groundwater aquifers and of the surface water storage and distribution system along with their appropriate relationships. Present analyses are based upon average annual values, while future work may include monthly values over a period of several years.

The effects of different sociological and legal constraints will be studied even though it is difficult to quantify such constraints. Once these constraints are quantified, sensitivity analysis should prove to be a valuable tool in determining the economic effects from these restraints.

In order to more nearly represent the actual physical situation, stochastic variables and non-linear relationships must be in the model. Stochastic linear programming and/ or non-linear programming can then be used to carry out the optimization.

As has been shown, much can be learned from the optimization of the simple synthetic system thus far studied in this project. But to be of greater value to the water engineers and planners, the methods discussed in this paper must be applied to an actual water resources system in a real basin. The final step of the current project will be to carry out an actual application.

The results of parametric analysis on the cost coefficient associated with the variable IRRIGD (a benefit coefficient from irrigation during the dry season) are shown in Figure 6. As before, when the cost coefficient is allowed to vary from $45.00 to $15.05 several changes take place in the optimum model. As the irrigation benefit is reduced, the pumping scheme changes and irrigation demands are met by a different combination of pumping and canal flows. Also, more of the water previously available for irrigation is by-passed and sent downstream.

Conclusions

The previous discussion of linear programming optimization of conjunctive use of surface and groundwater has shown that linear programming optimization, with accompanying post-optimal analysis, provides a powerful tool to the water resource system designer for obtaining optimal designs and studying alternatives. The value of the objective function at each level provides a "thermometer" by which the effects of various changes can be gauged or evaluated. The best design level for each variable is given as part of the linear programming solution and all levels, of course, will satisfy all of the constraints and reflect the effects of the economic parameters as well. Thus the linear programming solution will determine simultaneously an optimal design and optimal levels or values for the quantities of all inputs and outputs of the system, taking account of hydrologic, engineering, and economic considerations in one fell swoop.

In addition to these advantages of the linear programming solution, marginal values are given for those activities or variables which do not enter the solution. This shadow price information, together with the sensitivity analysis results give valuable information to the planner which can be used to map out trade-offs between available sources of uses of water. The information can also be used as a pricing guide for a planning agent. The sensitivity analysis information can also indicate which coefficients should be studied in more detail.

Thus, in spite of the restrictions placed upon the model by linearity requirements, if a model can be developed which represents the physical characteristics much information is made available to the planner who is attempting to optimize conjunctive use of groundwater and surface water.

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DEVELOPING GROUNDWATER ALONG THE WASATCH FRONT, UTAH

by

C.E. Jacob[1]

When Mr. Criddle was calling the roll he didn't mention New Mexico, but I guess it's because we only touch on a corner. I'm not officially representing the state, but I would like to bring greetings from New Mexico – the "Land of Enchantment."

After the discussion that has taken place this afternoon I may have to tear up my notes. But I would like to say a few things in the next fifteen minutes, perhaps with the advantage of having the last word here. I'm very much interested in the preceding paper and in this panel discussion on law. In my opinion the two are very closely related. I was going to ask the question whether intentional conjunctive use of groundwater reservoirs has begun yet in Utah. I take it that it really hasn't on any scale, comparable to what is practiced in California, for example, where there is at least a 30-year history of this practice.

The interpretation of the doctrine of priority of right as it applies to confined groundwater reservoirs will probably have to be modified in Utah – I say probably rather than certainly, and I mean by legislative enactment in order to readily enable the use of groundwater reservoirs conjunctively with surface water reservoirs.

There is a lag in law which reflects the lag in technology. May I say something in defense of the legal profession, because I've had a long and enjoyable contact in and out of court with lawyers. We seem sometimes to smile at the concepts that appear in case law about the mode of occurrence of water. This is a natural and logical development, and it took place with the aid and abetting of people in other professions – geology, hydrology, and engineering. The distinctions that were made among naturally occurring subsurface waters – if you look at them from the standpoint of proof in court – reflect the uncertainties, and even today we have uncertainties. There is still a great deal of inference in testimony that is given as to what occurs underground. I was recently asked to advise a governor of an eastern seaboard state as to whether the water in a given limestone reservoir is water that is "percolating, oozing, and seeping" and so on, or whether it is water that flows in a "well defined channel." And, of course, the conventional answer now is that it is generally water that is seeping and percolating. But because of the uncertainity of our knowledge 50 years ago or 80 years ago, in the last part of the nineteenth century, it is very easy to see how these concepts got into case law.

I would say this also, that there are many people who are testifying as experts today – many of them are mature men who testify as experts in the courts of this land – whose testimony does not reflect the present knowledge, the forefront of hydrological knowledge. There is a lag in our profession also. And it may take about 20 or 30 years to bring up the body of the profession to the forefront of present research. So we should be careful in criticizing the legal profession. There are reasons for this. It is because of human inertia. It's also because of the great lag of our educational institutions behind the state of the art. That, of course, is being rectified, fortunately, in water-resources research. But for a long time there was a lag behind the advances in the state of the art as practiced by those in the forefront of developing the ideas, and it was reflected in our educational institutions. Fortunately as I said, this gap is being closed, and fortunately, I think, the gap between the two professions also

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is being closed. Meetings of this kind, and interchanges of papers in law journals and engineering journals would be most desired to get these ideas settled.

Again I say it's really basically up to the state legislature — this is my impression — to spell out the matter more clearly in Utah. I say this as a person who grew up here and who has had an exposure to many systems of law, both here and abroad, for administering water rights. There have been conflicting Supreme Court decisions which were divided opinions in this state on this very crucial point regarding continued groundwater reservoirs. So there needs to be, I think, a legislative enactment to clarify, and I don't think it needs to be very lengthy to do that.

Well, conjunctive use of groundwater and surface water reservoirs undoubtedly will be practiced in groundwater development along the Wasatch front. I'm not up-to-date on all of the recent developments in the state. I don't have an inventory of the groundwater pumpage. I know it's probably presumptive of me to come in from outside and try to speak on this subject, but it is an important topic. And I recognize that the Utah Water and Power Board and the State Engineer's Office, in conjunction with the U.S. Geological Survey, are carrying out investigations — comprehensive studies, for example, of the Jordan Valley — in which water budgets will be drawn up, and meaningful inventories, I hope, will be published. But I'm sure they will have to be refined because this is the nature of hydrology. Nothing is final. There is a great deal of work yet to be done.

I would like to give you a few ideas. I'm not going to talk directly to the subject of the technology of the development, but just throw out some ideas. These might in a sense appear anticlimactic after Dr. Clyde's and Mr. Milligan's talk about the methodology they're following. A great deal of needless effort has been spent in the field looking at groundwater reservoirs somewhat as a person would look at the grain of wood in the top of the pulpit here, even though he was probably only interested in the structural properties overall. He could get lost if he wanted to study this wood in every detail. There is a great deal of study done of geological reservoirs — and they are geological, and the geological knowledge is important — but a great deal of wasted effort is spent, in my opinion, not only here but abroad, getting lost in needless detail. If one would take the approach of systems analysis, analyzing a groundwater basin as a dynamic system, he'd immediately begin to see the relevance or the irrelevance of certain bodies of data. In other words, the minute we begin to attempt a comprehensive analysis of the dynamic system as a whole, we begin to see the weaknesses in our instrumentation, for example. And this is a great flaw. In subsurface hydrology, much more so than in surface water hydrology — this, in my impression, is the present state of the art — there is a great need for improving instrumentation. There are economic reasons why we are unable generally to get the kind of data out of groundwater basins that we should have. There are limitations, obviously. But when we begin to try to study the system as a dynamic whole then these things show up. Until we do that, they do not show up.

I might say that hydrology is practiced in different ways in different places. In a neighboring state, not immediately contiguous to Utah, a large basin is now in the process of ajudication. In the first go-around, on the engineering committee in the procedure of reference, in which they are finding the facts and interpreting them, they actually used 20-year old hydrology in doing that — 20 or 25-year old hydrology. They tried to set up a water budget by analyzing the items individually in that budget and trying to make them balance, and then if they didn't balance, to cut and fill and again cut and fill, failing to realize that the groundwater basin operates on certain physical principles and there are certain changes that are impossible dynamically. There are certain combinations of storage changes and inflow-and-outflow changes that just can't happen physically even though you think the "bank account" says so.

Now I might say, parenthetically, that not only is storage important, but so is interflow — groundwater interflow, that is lateral inflow to an area or outflow from an area. Interflow between basins is very difficult to measure. It is extremely difficult to measure interflows accurately. And this will always be a limitation.

In regard to the remark made about the compact between the states of Utah and Idaho, there have been other state compacts on streams, some of which have included groundwater return flow but most of which probably have not included it. It would be difficult to implement a compact between two states that had very diverse doctrines about the fundamental meaning of the rights adhering to groundwater. There is a very good example of this, internationally, and there is very little precedent internationally between nations, or treaties that I know of, or international case law that clarifies this on an international scale. We drew up a treaty with Mexico on the division of waters in the Colorado Basin in about 1946. That treaty said nothing about groundwater. You will remember the recent controversy in the Yuma area over the salinity of the Colorado that was rectified by a salinity bypass channel. This completely overshadowed for a time an equally important issue between our two countries on the groundwater underflow that occurs beneath the border. And that is a very difficult thing to measure. There is a great deal of inference in the interpretation of the data. We may agree upon the data, but reasonable men may have very different opinions about the interpretation of the data. So to measure groundwater underflow is a difficult thing. If we program these things, for example on analog computers, we sometimes purposely avoid boundaries. We may make the system as large as the geology may dictate or allow. We thus treat the groundwater basin as an effectively infinite system and merely study the transient in the system, because of our inability accurately to measure groundwater interflows.

Well, maybe it was wise that there wasn't any specification on groundwater in this treaty. Maybe bycontrivance the two countries agreed to a standoff to have it that way. Now we're impressed that the Mexican government would like to have a supplemental treaty — impressed also that if the thing were not settled out of court they would to to the World Court on this matter. Presently it's being kept under cover and being settled, but this merely points up the very important interrelationship between the state of the art of hydrology as it is practiced, even in advanced phases, and the application of these ideas to legal and social problems, as for example between states and between nations.

Now just a few words about groundwater systems. If we analyze a system on the basis of a water balance, that is, that "the inflow is equal to the outflow plus the storage gain," we can set up some very interesting relationships, for example between ratios of parameters. If we analyze the behavior of a system in response to natural impulses — and every ground reservoir is subjected to them continually, and to artificial impulses — we can do a great deal, more than is generally done by traditional groundwater hydrology, to come quite quickly and relatively cheaply to a meaningful water balance. If we can't reach that water balance, we can at least find out the kind of instrumentation we need to sharpen it, and by successive approximations get reasonably good answers. Whereas the traditional approach led into many bypaths — and I say this without any ill will because I have spent 30 years in this field and have been subjected to all kinds of approaches, to quantitative solutions of subsurface hydrology — now use these tools of linear programming, non-linear programming, systems analyses, and whatever other techniques are useful to express water balances by analogy, that is whether in a digital or mathematical model or whether in an electronic analog model or a passive network. These, of course, are things that are only as good as the data that is fed into them.

Now just a word about how this applies to the Wasatch Front. I understand the estimates are that about 10 percent of the total inflow into Great Salt Lake is groundwater inflow. The day may come when we're pressed to salvage that. That is, after we've imported our share of Colorado River water and used it wisely, and increased our efficiency in the reuse of water as far as can be accomplished in these valleys, we may then come down — I'm not trying to predict how soon it will be — to the time when we may desire to salvage as much of this natural loss as we can, that is, the remaining 10 percent. Now this will probably be the last loss that there will be a concerted drive to salvage in an organized way.

There are other places in the country where they've been forced to do this much earlier, as you realize, especially in coastal areas where there is, just as there is in the Great Salt Lake basin, a balance between saline waters and fresh waters. In certain areas, particularly in the Gulf Coastal Plain, the Atlantic Coastal Plain, and other coastal plains of the world, there have been overdrafts locally, and there has been the need to try to achieve some kind of balance, an operational balance, with which one could live to extend the useful life of reservoirs. This is done through some kind of purposeful management, and the lives of these reservoirs can be extended many times over what usually happens with lack of management. By management I don't mean necessarily socializing the water industry, but I do mean adequate legal controls and wise administration and management under the laws that are set up for that purpose.

Now, suffice it to say that anytime you have a balanced system of this kind and you attempt to divert the lighter fluid that discharges into a lake or into a desert salt pan you have, of course, very serious problems. These are problems of avoiding the dispersion or the mixing of the bad water with the good water. The state of the art is rapidly advancing to where physical controls can be exercised. Fortunately, when you have brines you have much higher density contrasts than you do with merely sea water-fresh water contrast, and you inherently have much greater dynamic stability, other things being equal. The mineralized thermal springs along the Wasatch Front should probably be concentrated eventually and re-injected underground. And this itself is a very wise move in that it conserves reservoir energy in the stratified system. Both by decreasing the volume occupied by that fluid and by the enhancement of the density, the stability is increased.

Conjunctive use undoubtedly will be practiced here. I would like to say that in a sense it is already practiced. Not directly but indirectly. Conjunctive use is practiced in groundwater surface-water reservoir systems in most of the western states where we practice irrigation, because when we have seepage losses from canals, and we have wells, especially on a mixed project where we have surface water and groundwater both being used, we are really practicing conjunctive use. The system is usually not optimized in the way it's accomplished by the developments that occur in many places. There is no optimization of the joint resource. But in this sense conjunctive use is already practiced in the state of Utah. It's practiced to a greater extent in other nearby states intentionally. This, I think, reinforces what Mr. Criddle had to say about the fact that, generally speaking, the groundwater stream is just a parallel stream or branch of the main stream of the hydrologic cycle. There are many side loops, and we shouldn't overlook these. There are many important closed loops, and there are some we're not sure about, that is whether they're closed or not, in the hydrologic cycle. And these do add complications. But generally speaking, even in desert areas and in arid intermontane basins, there is a very close association between surface water and groundwater even when there are no perennial streams. I have recently been working in Arabia, and even in that country, where there is only one perennial stream that I know about, in the whole peninsula, a close association between surface water (when it occurs) and groundwater still exists. And you cannot master subsurface hydrology in those desert areas without surface hydrology.

The mining of water will be practiced on a long-range basis, and this of course requires some predictive skill which we don't have yet in meteorology and hydrology. The long-range utilization of the secular change of the groundwater budget in desert areas needs to be considered, and laws need to be passed and social changes need to be made that will permit the wise mining of water. In Texas, Arizona, and California it has been wise that mining has been permitted. Utah has a little different situation and a different history in the development and management of groundwater resources. Yet the full conjunctive use of waters will entail the mining of groundwater. Even if we're permitted to import as much water as we need into the Great Basin, someday, I think, we will see the need for mining in order to fully optimize the joint groundwater and surface-water resource.

GROUNDWATER IN THE STATE WATER PLAN

by

Jay R. Bingham[1]

"He digged the hard rock with iron and made wells for water."
—Ecclesiastes

(Groundwater Development Is Not New)

Total resource

A recent and very conservative survey estimated that the nearly 60 known and probable groundwater reservoirs in Utah contain enough water in the first 1,000 feet below the surface to fill the combined Lake Mead, Lake Powell, and Flaming Gorge Reservoirs eleven times. Not all of this vast store of water underground in Utah is available to wells, for most of it occurs in sediments such as silt and clay which are too fine-grained to yield water. But the analysis does indicate that the coarse-grained aquifers in the upper 500 feet of the reservoirs probably contain between 48 million and 72 million acre-feet of water available to wells.

In 1964, the total yield of groundwater from all of Utah's reservoirs was 650,000 acre-feet, according to the U.S. Geological Survey, as reported in Utah Water and Power Board Cooperative Investigation Report No. 3, published in March, 1966.

Factors preventing use

The development of Utah's groundwater resources in the past has largely depended upon the initiative of individual water users, which is in the American tradition of personal freedom and enterprise. But this method has its drawbacks, because such development is often haphazard and generally quite expensive, inefficient, and wasteful. Groundwater reservoirs were discovered by trial-and-error methods rather than with the guidance of comprehensive investigations by competent hydrologists. A man drilled a well on his property at a spot where, for practical considerations, the water could best be distributed by gravity through ditches to his growing crops. This, of course, is good common sense, but all too frequently nature had failed to provide the site chosen with an adequate water supply, and a costly failure resulted.

Well costs have risen greatly (like everything else) until today a typical 16-inch diameter well, 500 feet deep, fully equipped with pump and motor, represents a capital outlay of about $25,000, a sum often too high for an individual water user to afford, especially when the risk of a "dry hole" is always a possibility.

From the standpoint of water planning, perhaps the most serious problem that hampers and often prevents the full use of the water stored underground is the problem of the "interference" of a new well in a given basin with already existing wells which are often small diameter (2" or 3") flowing wells for domestic use and stock watering. Several of Utah's neighboring states, have recognized the basic hydrologic fact that pumping from a well is bound to cause a lowering of the pressure where artesian conditions exist or a lowering of the static levels in nonflowing wells.

In many of Utah's groundwater reservoirs, especially in the western part of the state where the basins are not adjacent to major water-producing mountain ranges, the annual recharge is relatively

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small and if pumpage was kept in balance with these small yearly increments, the large quanity of water known to be in storage in these reservoirs would remain dormant and go unused. Under these conditions what should the state's policy be? May not mining water in these areas be fully justified?

Laws should be changed or clarified to allow drawing down water levels to dry up flowing wells and phreatophyte vegetation that depends on over-flowing groundwater aquifers for its water supply.

Principles of good management

In developing a state water plan, serious consideration must be given to devising better methods for making more of this vast water resource available to the people of the state. Ideally, a groundwater reservoir should be managed like a surface water reservoir, drawing upon its stored water heavily in dry years and allowing it to be refilled in wet years. Thus groundwater is an insurance policy against drought!

1. Groundwater is part of total hydrologic system and should be considered as such. It is inseparable from the surface water.
2. Groundwater reservoirs should be operated as a part of the total water resource system, just as surface reservoirs are.
3. Groundwater reservoirs should be managed such as to provide an insurance policy against drought.
4. Where groundwater is being mined, encouragement should be given to maximizing water use efficiency and also to utilize the water to maximize the economic return from its use. This may require altering the cropping patterns and finding new markets for the products.
5. In areas where there is a difference in quality of groundwater, the uses being made of the water should be commensurated with the need. In other words, high quality (potable) water should not be used for industry which can get along with poorer quality water. This also holds for surface water.

Benefits of good management

By increasing water use efficiency and maximizing economic return, the life of the groundwater basin can be extended.

An example of the benefits of improved efficiency exists near Milford where water use is presently based on pumping. In this area, they are mining the groundwater, or in other words, they are using more than the annual recharge to the basin. This results in a lowering of the groundwater table. The Agricultural Research Service is presently making an economic and efficiency study of this area. They have found that over the last few years, the water use efficiency study of the area around Milford has averaged about 55 percent, or, in other words, they are consumptively using 55 percent of the water that they deliver to raise their crops. This, by the way, is an extremely good efficiency rate compared to most of the state. The studies also indicate that under present economic conditions, the economic pump lift is 249 feet and that under present conditions with the present rate of water use, this economic pump lift will be reached in 82 years. The study points out, however, that by merely increasing the efficiency 7 percent, which is reasonable to expect, that the economic pump lift can be increased by 50 feet and the water table can be drawn down to 290 feet. This would lengthen the life of the groundwater basin by another 25 years under the present usage. By increasing the efficiency, however, less water would be pumped so the life of the groundwater basin would be extended still farther.

Water yields can be increased by drying up flowing wells which in turn brings about greater crop production and cash income.

Larger, deeper wells sponsored by groups of individuals make the cost of development and cost of water for each individual less expensive than a "go it alone" development.

Where do we go from here?

Major groundwater recharge areas should be determined and measures should be taken to protect these areas from uses which would circumvent them from performing their function, investigation potentials and feasibility of artificial recharge. A strong information and education program should be initiated with water users to inform them of the pricniples and benefits of good management.

CHANGING CONDITIONS IN WATER RESOURCE PLANNING

by

E.O. Larson[1]

Most everything pertaining to the use of our water supplies is continually subject to change in one way or another as time goes on. Multiple use, competition for the same water, determination of the feasibility of projects, water quality, and pollution have become especially involved in these changes, over the years. Here in the United States our history covers only a small span of years compared to other countries that have centuries of history. Iran, for example, claims 4,000 years of documented history and some say they even claim 2,000 years beyond that. Even so, much history has been made in the United States in the nature and extent of the uses of water supplies and in the laws and policies governing these uses. In the early days, in most areas, development started with plenty of water, scarcity showing up mostly in the Western States.

Most of the early water developments for domestic, municipal, industrial, and irrigation use of water were made by private irrigation concerns, cities, and towns. Our pioneers built ditches; cities and towns built their own pipe lines; they didn't go to the government for assistance at that time. As our country expanded, the need for flood control, harbor improvements, and related works to be financed and constructed by the Federal Government became apparent. These needed developments were just too big to be done privately. This resulted in the Congressional Acts under which the Corps of Engineers have operated for many years. Later the concept of expanding irrigation in the West by using reimbursable federal funds, with no interest charge, became a reality when the Reclamation Act in 1902 was passed. Since the passage of the Flood Control and Reclamation Acts by Congress, most of the flood control projects have been constructed by the Corps of Engineers and most of the large irrigation projects have been constructed by the Bureau of Reclamation. Under different Congressional Acts, other Federal agencies are constructing water use projects, such as the soil and water conservation projects by the Soil Conservation Service and the wildlife refugees by the Fish and Wildlife Service. In general the Corps of Engineers and the Bureau of Reclamation started out with single-purpose flood control and irrigation projects. In the early days we looked for dam sites for irrigation, we never thought of anything else. On the Upper Colorado River the aim was to find dam sites that could be constructed at the lowest cost per acre-foot of storage capacity. That concept was changed. The new concept was to select dam sites in deep canyons with the highest dams possible to generate power and reduce evaporation losses by having a smaller reservoir water surface area. In planning the Weber Basin Project, the objective was to plan reservoirs for municipal water supply, irrigation, flood control, recreation, fish and wildlife enhancement, and to some extent better water quality.

Concurrently with the growing importance in the use of our surface water supplies, the increase in use of groundwater for municipal, irrigation and industrial uses is becoming very important in many areas – in fact, it has been especially important in California, Arizona, and some other states for a long time. This great diversity of the use of our surface and groundwater supplies, coupled with the ever-increasing water demands from a fast growing population, has brought to light many problems to be solved. I would like to mention two or three of these problems.

First there is the matter of laws, rules, and regulations governing the use of water which vary considerably from state to state – especially between the arid Western States and the Eastern States where they really don't have water laws as we know them in the West. There are also conflicts in the use of groundwater as related to the use of surface water. Many states

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do not have groundwater laws such as we have in Utah, for example. Then there is the overriding conflict which we label "Federal vs. State Rights" in the use of water. This is a subject by itself and I will not attempt to cover it here.

Water laws in most states of the West have been developed over the past hundred years or less; first by local custom and practices; second by court decisions; and third by an enactment of comprehensive water codes. The State water codes are ordinarily divided into at least four parts: (a) general principles of water law; (b) appropriation of public water for beneficial use; (c) distribution of water; and (d) the adjudication of water rights. I mention these divisions as there is no counterpart of the great bulk of this basic water law to be found in the federal statutes. As you are aware, the source of federal authority is our Constitution as expressly delegated and as such may be reasonably implied from the authority expressly granted. And here, of course, is where the controversy exists between federal agencies and the states. Under the Treaty-Making Power Clause, the Mexican Treaty was negotiated. Under the Commerce Clause, which means the regulation of commerce among nations and between states, gives the Government the right to go from one state to the other such as constructing transmission lines across statelinex. Under the General Welfare Clause, the Congress has the power to provide for common defense and general welfare of the United States. Flood control projects and other projects are constructed under this clause. Then there is the Interstate Compact Clause which provides that no state can compact with another state without the consent of the Congress. Under this clause the Bear River Compact, Colorado River Compact, and Upper Colorado River Compact were negotiated and authorized. Another caluse I might mention is the Property Clause which gives the Government the right to make rules and regulations to govern its own property. The clauses I have mentioned are of direct interest to water resource developments by our Federal Government.

The enactment by the various Western States of their Comprehensive Water Codes was to prevent the abuses incident to adjudication by the courts of more rights to the use of water than there was water in the stream. In most states, the legislatures placed the administrative control of appropriation of water in the hands of professional engineers, to determine whether a given water supply is exceeded and when appropriation of water should cease. The task of formulating proposed decrees in statutory adjudication suits has also, in several states, been [given to the State Engineer. In the case of one state, water rights are required through the application method, but the Board of Control handles the statutory adjudications. And in other states, water rights are placed on record by the entry in the district courts of conditional decrees—such as Colorado. And later by the entry of an absolute decree when the works are constructed and you put the water to use. Still in other states, the application system is used with the water adjudication handled by the court.

In theory the state procedure is generally sound, but in practice I'm sure planners are still faced with water rights in excess of the available supply. What I'm trying to point out is that our state laws haven't changed too much and they still differ from one state to the other. I think as time goes on it will be up to some of these states to update their laws before conditions become more controversial than they are now. We have reached the stage where it will be to the public interest to turn down some applications to appropriate water for one use in order that the available water supply can be reserved for a higher use. Another point is that our water right laws in many cases do not cover all aspects of multiple-purpose projects as we know them today. In some states, present laws, rules, and regulations do not prevent padding of water rights—it still goes on. Rights are still granted for more water than can be beneficially used. There are no clear provisions in the law of most states covering the use of holdover storage capacity in reservoirs or the use of reservoir capacity more than once during a water year.

Also the water laws in general are not clear as to the charging of only net evaporation losses from reservoirs—a method of great importance to many reservoirs such as the large reservoirs in the Upper Colorado River Basin.

Another subject of interest is the changes that have taken place over the years in the methods used by Federal agencies in determining the feasibility of irrigation, flood control, and multiple-purpose projects.

For irrigation projects planned before 1945, the finding of feasibility was largely a matter of judgment — based on a knowledge of the soil, topography of the lands to be irrigated, climate, kind of crops and yields, water rights, availability of water, project construction costs, and the ability and willingness of the water users to meet construction and operation and maintenance costs. The methods used by the Corps of Engineers was similar for determining the feasibility of flood control projects.

Beginning about 1945 the methodology changed. The Corps of Engineers, the Bureau of Reclamation, and other Federal agencies, modified their procedures and methods to more clearly evaluate the benefits that could reasonably be expected to result from the construction of a project and then compare the annual benefits with the estimated construction and other costs of the project capitalized on an annual basis. This comparison is designated as the benefit-cost ratio. Discussions by the Bureau of the Budget and Congressional Committees, in seeking better methods for determining the feasibility of flood control, irrigation, and other water resource projects, continued for a few years until 1952 when the Bureau of the Budget issued Circular A-47. This document outlined the details for evaluating annual benefits and comparing them with the annual costs to determine the benefit-cost ration. If the ratio is greater than one-to-one the project is considered feasible. Circular A-47 defined the standards and procedures that would be used by the Executive Office of the President (the Bureau of the Budget), in reviewing Agency projects and budget estimates in order that uniform policies could be applied to the establishment of priority for projects yielding the greatest value to the nation at the minimum necessary cost.

The Bureau of Reclamation, and I am sure the Corps of Engineers, found it impractical or impossible to follow the methodology of Circular A-47 in all respects. Even though the Circular was amended in 1955, it still involved considerable detail work, and many questions still remained unsolved.

Discussions as to the standards and procedures by Congressional Committees continued after the issuance of A-47. As a result, Senate Resolution No. 148 was adopted in January 1955. This resolution sets forth in considerable detail the Senate's concept of proper standards and criteria to evaluate all water use projects to be financed by the Federal Government. I believe this resolution is still being followed; however, its effectiveness seems to be questionable.

In May 1962, the Bureau of the Budget cancelled Circular A-47 and in lieu thereof Senate Document No. 97, dated May 29, 1962, was issued as the new policy. This document with subsequent amendments is still being followed.

Even with the new policies, standards, and procedures some problems remain unsolved in the planning of irrigation, flood control, and multiple-purpose projects. Some of the problems pertaining to outdoor recreation were intended to be solved. Supplement No. 1 was added to Senate Resolution 97 but problems still remain.

Even though the Bureau of the Budget and Congressional Committees have spent considerable time and effort to formulate better policies for evaluating benefits, and allocating costs of irrigation, flood control and other water resource projects, many problems still exist. One important problem to be considered is the need for simpler and less costly procedures for determining the feasibility of projects. The extensive benefits that have resulted from the construction of most water resource projects financed by the Federal Government is the proof that the projects were correctly classed as being feasible when they were planned. However, there is need for rather careful studies to evaluate these extensive benefits that have been realized with the benefits that were evaluated before authorization of the project. Such a study would be expected to reveal the short comings of the older methods and improvements that should be adopted in the present methods used in evaluating benefits, allocating costs and determining the feasibility of a project.

Other important changes that have taken place in recent years are the accelerated increases in population, industrial development, and in the use of our natural resources. This means that more emphasis must be given to the use of water for municipal and industrial purposes, and to pollution control. It further means that we need a new look, both statewide and nationally, in future long-range planning for the use of our remaining water supplies. With the many complications and problems with which we are confronted, the rapid increase in water demands, competition for the limited supplies in many areas, and the continual increase in the pollution of our streams, the challenge is very great. This challenge applies to professional and educational people, the state legislatures, and the Federal agencies who have responsibilities in water resource development.