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FUTURE QUANTITY AND QUALITY OF COLORADO RIVER WATER

BY RAYMOND A HILL March, 1965

Lee Ferry
(See Discussion
by Dominy

The undepleted or virgin flow of Colorado River at Lee Ferry was found by the Special Master in the action, State of Arizona versus State of California, to have been as shown in Table 1.

Measurements of the actual flow of Colorado River at Lees Ferry, near Lee Ferry, were not commenced, however, until approximately the beginning of the Water Year 1921–1922, so that authentic records of the historical flow at Lee Ferry are available only for that water year and subsequent years. The estimates of much greater average flows in the river prior to 1922 could be substantially in error; hence, the magnitude of the average virgin flow for the period 1909–1956 and for the period 1914–1956 are questionable.

In testimony in 1958, before the Special Master in the action, Arizona versus California, the writer noted that, although the flow of Colorado River at Lee Ferry in recent years has been considerably below normal, the dependable undepleted supply at this point was no more than 13,700,000 acre-ft per yr, involving complete regulation of inflow to reservoirs for long periods, such as the historical period from 1926 to 1956 and thereafter until the reservoirs might refill.

TABLE 1.—AVERAGE ANNUAL VIRGIN FLOW FOR SELECTED PERIODS

Period	Acre-ft per yr
1909–1956	15,211,000
1914–1956	14,920,000
1922–1956	14,008,000
1930–1956	13,085,000

Upper Basin Depletions.—The actual supply of water in Colorado River at Lee Ferry under historical conditions, approximately 12,000,000 acre-ft per yr, was that remaining after depletions of the natural supply in the Upper Basin. These amounted to 1,854,000 acre-ft per yr on the average during the period of actual measurements of flow at Lee Ferry, less in the early years and more in recent years. It is generally recognized that depletions caused by projects in operation or authorized prior to 1949 for construction in the Upper Basin will soon increase this amount to 2,548,000 acre-ft per yr. Hence, if all of these projects had been in existence in 1922, the average available supply in Colorado River at Lee Ferry would have been approximately 700,000 acre-ft per yr smaller than it was historically. This leaves a total of 11,300,000 acre-ft per yr as the average supply available in the Colorado River at Lee Ferry under 1960 conditions of development.

There must also be deducted the depletions that will be caused by participating projects of the Colorado River Storage Project that are now under construction in the Upper Basin. In addition there will be losses by evaporation from the reservoirs of the Colorado River Storage Project. The magnitude

2 Rifkind, Simon H., Report of December 5, 1960, to the Supreme Court of the United States, State of Arizona v. State of California, et al., 364 U. S. 940, 1961, p. 118

7,500,000 acre-ft per yr apportioned to the Upper Basin by the Colorado River Compact of 1922; actually, the total in the year 1990 amounts 75% of the quantity of water so apportioned. It would be imprudent to assume any lesser rate of development of the Upper Basin.

Under 1990 conditions of development, the average supply of water in Colorado River available for release at Glen Canyon Dam plus the small natural inflow between that dam and Lee Ferry will be little more than 8,000,000 acre-ft per yr, as shown in Table 4.

It is not to be presumed that development in the Upper Basin will be terminated in 1990. On the contrary, it is to be expected that the Upper

TABLE 3.—PROJECTED PERMANENT DEPLETIONS IN UPPER BASIN

Location	Quantities, in thousands of acre-ft			
	1965	1970	1980	1990
Arizona—Existing Uses	11	11	11	11
Colorado Depletion	1702	1961	2676	3112
New Mexico Depletion	119	306	560	642
Utah Depletion	676	880	1073	1198
Wyoming Depletion	271	386	535	666
Total Projected Depletions	2779	3526	4855	5629

TABLE 4.—DEPENDABLE SUPPLY UNDER 1990 CONDITIONS[a]

Average Historical Flow at Lee Ferry (Minimum 10-year period of record)	11,833,000
Average Historical Depletion for same period	1,854,000
Undepleted Flow at Lee Ferry	13,687,000
Projected Depletions under 1990 Conditions	5,629,000
Future Dependable Supply under 1990 Conditions of Development in Upper Basin	8,058,000

[a] All quantities in acre-feet per year.

Basin States will use all means within their power to apply to beneficial use the remainder of the water supply physically available to them, subject only to compliance with the provisions of Article III (c) and (d) of the Colorado River Compact, which are:[3]

"(c) It is agreed as a matter of international comity, the United States of America shall hereafter recognize in the United States of Mexico any

[3] Ibid., p. 117.

it will be possible to control the river completely by regulation in L
Powell, formed by Glen Canyon Dam. Lake Mead will presumably be held
a lower average level than has been customary. The resulting savin
evaporation loss, however, will be more than offset by increased diversi
for use in Arizona, Nevada, and Utah between Lee Ferry and Hoover Da
Consequently, the supply of water entering Lake Havasu, the first major po
of diversion in the Lower Basin, will not differ materially in the future fr
the flow of Colorado River at Lee Ferry.

FUTURE QUALITY OF WATER

Reasonably frequent complete chemical analyses of the water in Colora
River at Lees Ferry, a short distance upstream from Lee Ferry, have be
kept for many years. These data, for the 20 yr from October, 1940,
September, 1960, adjusted by proportion to equate the sums of cations a

TABLE 5.—SALTS IN COLORADO RIVER AT LEES FERRY—AVERAGES FROM
OCTOBER, 1940, TO SEPTEMBER, 1960

Ions	Milligram equivalents per liter	Tons-equivalent per year	Reacting values
Calcium (Ca^{++})	3.78	60,800	43.4%
Magnesium (Mg^{++})	1.99	32,100	22.9%
Sodium and Potassium (Na^{+} + K^{+})	2.93	47,100	33.7%
Total Cations and Anions	8.70	140,000	100.0%
Bicarbonate (HCO_3^{-})	3.02	48,500	34.6%
Sulphate (SO_4^{--})	4.35	70,000	50.0%
Chloride and Nitrate (Cl^{-} + NO_3^{-})	1.33	21,500	15.4%

Average Flow: 11,821,000 acre-ft per yr

Tons equivalent: 8.70 x 11,821,000 = 140,000

735

Acre-Ft per ton-equivalent: .85

TDS (Dry Weight): 515 parts per million

0.70 tons per acre-ft

anions are summarized in Table 5 and the average composition of the salts
is given in Table 6.

Use has been made throughout this study of milligram equivalents per
liter (epm) in lieu of parts per million. Likewise tons-equivalent (Te) have
been used in lieu of tons to avoid the confusion caused by the unequal weights
of atoms. In any water containing salts, there must be one positive ion (cation)
for each negative ion (anion) although the actual combining weights of the
common ions differ widely. For example, if 68 milligrams of calcium sulphate
were dissolved in a liter of pure water (68 ppm), there would then be one
milligram equivalent of calcium and one milligram equivalent of sulphate
in the solution because the combining weight of calcium is 20 and the com-
bining weight of sulphate (SO_4) is 48.

Similar data for the flow of Colorado River and its tributaries entering Lake Havasu show an average of 11,284,000 acre-ft of water and an average salt burden of 164,900 tons-equivalent during the same 20 yr. These data are summarized in Table 7 and the average composition is given in Table 8.

It is apparent from Tables 6 and 8 that the average salinity of the waters entering Lake Havasu was 24% more than the salinity of the water passing Lees Ferry, but that there were considerably greater changes in the concentration of some ions. The milligram equivalents per liter of calcium and magnesium increased only approximately 15%; the concentration of sodium and potassium and that of sulphate both increased approximately 40%, and the chlorides more than 60%. On the other hand, there was a 17% decrease in the

TABLE 7.—SALT BURDEN OF COLORADO RIVER AT LAKE HAVASU
(Quantities in Thousands)

Water year	Discharge, in acre-ft	Tons-equivalent			Total cations or anions	Tons-equivalent		
		Ca	Mg	Na + K		HCO_3	SO_4	$Cl + NO_3$
1940–41	11,825	86.4	38.5	70.6	195.5	41.8	118.0	35.7
–42	17,468	120.5	55.3	101.3	277.1	61.8	162.9	52.4
–43	11,691	74.3	36.2	65.6	176.1	41.2	101.1	33.8
–44	13,898	84.6	42.4	77.6	204.6	49.0	115.9	39.7
–45	12,447	72.8	39.0	70.2	182.0	43.9	101.7	36.4
1945–46	10,962	64.1	34.2	62.7	161.0	38.8	89.4	32.8
–47	10,416	61.0	32.4	59.3	152.7	36.7	84.7	31.3
–48	12,581	72.9	37.6	69.3	179.8	43.6	99.4	36.8
–49	12,917	72.0	36.8	67.3	176.1	43.9	96.7	35.5
–50	12,224	63.9	34.0	61.7	159.6	41.1	87.4	31.1
1950–51	8,656	47.4	25.6	47.6	120.6	29.5	66.3	24.8
–52	13,872	74.4	41.0	75.7	191.1	46.5	106.0	38.6
–53	12,786	65.2	34.9	62.5	162.6	41.5	89.7	31.4
–54	9,815	54.4	31.3	53.9	139.6	33.6	77.3	28.7
–55	9,333	55.7	32.7	59.6	148.0	31.7	83.5	32.8
1955–56	7,375	48.0	27.9	52.7	128.6	25.0	73.6	30.0
–57	7,412	48.2	27.1	51.3	126.6	25.2	72.1	29.3
–58	11,738	69.8	37.4	64.3	171.5	39.2	95.3	37.0
–59	9,458	51.7	27.0	46.7	125.4	29.5	71.0	24.9
1959–60	8,808	47.9	25.5	46.5	119.9	27.5	67.2	25.2

milli-equivalents of bicarbonate. These tables also disclose that there was an apparent loss of 10,000 tons-equivalent of bicarbonate between Lees Ferry and Lake Havasu, but that there was a gain in the tons-equivalent of all other ions.

It was impossible for bicarbonates to have been lost by precipitation or otherwise without an equal number of tons-equivalent of some positive ion having likewise been lost between Lees Ferry and Lake Havasu. Furthermore, the true loss was necessarily greater than an average of 10,000 tons-equivalent per yr, because tributary streams brought in large amounts of bicarbonate. No precise calculation can be made, but the difference between the salt burden of Colorado River at Lees Ferry and that at Lake Havasu can be accounted for in the manner shown in Table 9.

The salts contributed by tributary streams, such as Little Colorado River and Virgin River, are not known accurately but were approximated from observed differences between the chemical composition of the waters of Colorado River at Lees Ferry and at the gaging station at Grand Canyon. The values given in Table 9 are averages for the 20 yr from October, 1940, to September, 1960. The records for individual years indicate that there

TABLE 8.—SALTS IN COLORADO RIVER AT LAKE HAVASU[a]

Ions	Milligram equivalents per liter	Tons-equivalent per year	Reacting values
Calcium (Ca)	4.35	66,800	40.5%
Magnesium (Mg)	2.27	34,800	21.1%
Sodium and Potassium (Na + K)	4.13	63,300	38.4%
Total cations and anions	10.75	164,900	100.0%
Bicarbonate (HCO_3)	2.52	38,500	23.4%
Sulphate (SO_4)	6.05	93,000	56.4%
Chloride and Nitrate ($Cl^- + NO_3$)	2.18	33,400	20.2%

[a] Averaged from October, 1940, to September, 1960.
Average flow: 11,284,000 acre-ft per yr.
Acre-Feet per Ton-equivalent: .69
TDS (Dry Weight): 855 parts per million
0.39 tons per acre-ft

TABLE 9.—CHANGES IN SALT BURDEN OF COLORADO RIVER—LEES FERRY TO LAKE HAVASU

Item	Ca	Mg	Na + K	Total (+) (−)	HCO_3	SO_4	$Cl + NO_3$
Lees Ferry Supply	80.8	32.1	47.1	140.0	48.5	70.0	21.5
Tributary Inflow	7.0	2.0	9.0	18.0	8.0	4.0	6.0
Total Inflow	87.8	34.1	56.1	158.0	56.5	74.0	27.5
$CaCO_3$ Precipitated	−18.0			−18.0	−18.0		
Net Solution	+17.0	+0.7	+7.3	+24.9		+19.0	+5.9
Lake Havasu Supply	86.8	34.8	63.3	164.9	38.5	93.0	33.4

[a] Average flow from October, 1940, to September, 1960. All values in thousands of tons-equivalent per year.

[illegible] increase in the rate of precipitation of calcium carbonate [illegible] the year [illegible] amounts of salts dissolved by solution from the bed of Lake Mead (since 1941, when Lake Mead was first filled,

watershed above Lees Ferry. The total quantity of salt brought into the river by all its tributaries will be little changed by future upstream developments which will involve only a few hundred thousand acres.

Transmountain diversions from Colorado River and its tributaries will necessarily be made near the headwaters of the streams in which the salt content is relatively low. The amounts of such projected diversions out of the watershed of Colorado River and their salt burden is given in Table 11.

The net result, assuming for the moment no other change in conditions in the Upper Basin, will be to increase the unit concentration of salts in Colorado River at Lees Ferry from 8.7 milligram equivalents per liter to 9.2 milli-equivalents.

Such transmountain diversions, however, are only a small part of the total depletions that will result from the development of the Upper Basin. Many new irrigation projects are under construction or are being planned for construction. Water diverted to these lands will carry salts that must be removed by

TABLE 12. EFFECT OF UPPER BASIN DEVELOPMENTS IN 1990 ON QUALITY OF WATER AT LEES FERRY (Quantities in Tons-equivalent)

	Ca	Mg	Na + K	Total (+) (−)	HCO_3	SO_4	$Cl + NO_3$
Historical average 1940–1960	60,800	32,100	47,100	140,000	48,500	70,000	21,500
Deduct T/C transmountain diversions	−2,100	−940	−1,086	−4,126	−1,923	−1,747	−456
Add T/C domestic and industrial imports	100	100	400	+1,800	—	300	300
Change in composition by irrigation use	−950	−237	+1,187	0	−1,187	+831	+356
1990 conditions	57,850	31,023	47,601	136,474	45,390	69,384	21,700

natural or artificial drainage in order to prevent any accumulation of salts that might render the land unsuitable for crops.

Experience has demonstrated that there is a tendency for less soluble salts, such as calcium carbonate, to be precipitated and be left in the soils and for more soluble salts, such as sodium chloride, to be picked up by the water passing through the soils in irrigated areas. There is also considerable evidence in the history of long established projects that there is a tendency for more salt to be removed from an irrigated valley in early years than is brought into it with the irrigation water.

The least adverse effect that can be expected in the case of Upper Basin irrigation projects is that there will be no increase in the total amount of salt reaching Lees Ferry and that the upstream agricultural developments will only change the relative composition of the dissolved solids in the river water. The writer's estimate of the magnitude of such changes is based on

Future Salt Burden at Lake Havasu.—If there should be no precipitation of calcium carbonate in Lake Powell nor any solution of other salts from the bed of that reservoir, nor any change in conditions below Lees Ferry, the future salt burden of Colorado River at Lake Havasu would be equal to the sum of the tons-equivalent of the several ions listed in Table 12 and the net gains between Lees Ferry and Lake Havasu shown in Table 9. The total salt burden so computed for 1990 conditions, given in Table 13, would be a little less than it was historically.

On the other hand, if there should be precipitation of calcium carbonate and solution of other salts at Lake Powell to the same extent as has been the case at Lake Mead, but with no change in conditions below Lees Ferry, the future salt burden of Colorado River at Lake Havasu would be greater than it was during the 20 yr from October, 1940, to September, 1960. The resulting amounts of each principal ion so computed are given in Table 14.

Although the precipitation of calcium carbonate in Lake Mead is not a unique phenomenon, it may not occur in Lake Powell where climatic conditions

TABLE 14.—SALT BURDEN OF COLORADO RIVER AT LAKE HAVASU IN 1990 ASSUMING PRECIPITATION AND SOLUTION OF SALTS IN LAKE POWELL

Ion	Unadjusted burden at Lake Havasu (Table 13), in Te	Potential effect of reservoir, in Te	Resulting burden at Lake Havasu, in Te
Ca	63,850	− 1,000	62,850
Mg	33,723	+ 700	34,423
Na + K	63,801	+ 7,200	71,001
Total (+) or (−)	161,374	+ 6,900	168,274
HCO_3	35,390	−18,000	17,390
SO_4	92,384	+19,000	111,384
Cl + NO_3	33,600	+ 5,900	39,500

are considerably different. There is also less probability of solution of calcium sulphate and other soluble salts from the bed of Lake Powell than has been the case at Lake Mead. Only time will tell the effect of Lake Powell, but it is most probable that the future salt burden of Colorado River at Lake Havasu will be greater than the 161,374 tons-equivalent computed as shown in Table 13 and less than the 168,274 tons-equivalent determined in Table 14. It may reasonably be assumed, however, that the pickup of salts in Lake Powell will induce any further reduction in the rate that salts are picked up by solution in the waters of Lake Mead.

Historically, the waters of Colorado River at Lake Havasu contained an average of 10.76 milligram-equivalents per liter of dissolved solids (655 parts per million) and the average salt burden was 164,900 tons-equivalent per year (10,060,000 tons dry weight). The future salt burden should average approximately 165,000 tons-equivalent (10,080,000 tons dry weight) per year under 1990 conditions of development in the Upper Basin.

This quantity of salt must be carried, however, by only approximately 8,000,000 acre-ft of water each year. Hence, the unit concentration of the dissolved solids will be correspondingly greater under 1990 conditions of development than it has been historically, as shown in Table 15.

These unit concentrations are not such as to preclude the use of Colorado River water for irrigation although the leaching requirement will be relatively high. The usableness of the water for domestic and industrial purposes will be impaired, however, because the hardness will be almost 450 ppm and the sulphates will exceed 400 ppm. Furthermore, if the Upper Basin States are successful in their endeavor to use all the water apportioned to them under the Compact of 1922, the inflow to Lake Havasu would be less than 8,000,000 acre-ft per yr and the concentration of salts even more adverse.

The foregoing has dealt only with the probable quality of the water that will be available for diversion from Lake Havasu by The Metropolitan Water District of Southern California and through the proposed Central Arizona

TABLE 15.—PROBABLE AVERAGE SALT CONCENTRATION AT LAKE HAVASU UNDER 1990 CONDITIONS

Ion	Milli-equivalents per liter	Reacting values, in percentage	Parts per million
Calcium	5.80	38.6	116
Magnesium	3.12	20.9	38
Sodium + Potassium	6.06	40.5	142
Bicarbonate	2.76	18.4	168
Sulphate	9.00	60.1	432
Chloride + Nitrate	3.22	21.5	115
Sum of Ions	14.98	100.0	1011
Loss on Evaporation	–	–	85
Calculated Dry Weight	–	–	926

Project. The water now diverted from Colorado River further downstream for use in California and Arizona and Mexico has a higher salt content than the average supply taken from Lake Havasu because of intervening consumptive uses. The same relation may prevail in the future, or the effect of depletions in the Upper Basin may be more pronounced at such points of diversion of water from Colorado River below Lake Havasu.

CONCLUSIONS

Sufficient data are available with respect to the quantity and quality of the waters of Colorado River and to the nature and extent of developments underway in the Upper Basin to warrant the following general conclusions

1. The gross water supply available in Colorado River for use in the Lower Basin and in Mexico will shrink during the next 30 yr from an average of 11,800,000 to approximately 8,000,000 acre-ft per yr;

2. the total salt burden of Colorado River at Lake Havasu, now averaging approximately 165,000 tons-equivalent (roughly 10,000,000 tons) per yr, will not change materially unless there is a net pickup of salts from new irrigation projects in the Upper Basin;

3. the concentration of salts in the waters of Colorado River at Lake Havasu will increase progressively from the present level of 10.75 milligram equivalents per liter (655 parts per million) to approximately 15.0 milli-equivalents (926 ppm) before the end of this century, even if there should be no net pickup of salts from new irrigation projects in the Upper Basin.

tain diversions, will decrease the flow of water into the lower basin mainstream, they will not significantly decrease the total salt burden. On the contrary, the pickup of salts from irrigated soils and industrial and domestic uses in the basin would lead to increase the total salt burden at Lake Mead.

The increase in salt concentrations in the lower mainstream is of major significance in estimating water requirements for leaching and salt balance in the desert areas of Arizona and California. Much of the data cited by the United States Salinity Laboratory at Riverside, California, and by other irrigation engineers to leaching and salt balance requirements. Previously revised estimates will be considerably higher than those that have been used in the past. This is important, particularly in the Imperial and Coachella Valleys of California, in which the water required for leaching and salt balance must be diverted from the Colorado River but is not returned to the river because the bulk of the irrigated lands are below sea level. In other areas, such as the Palo Verde Valley, which is adjacent to the Colorado River, the probability of increased leaching requirements, although important, is of lesser significance because greater requirements for salt balance would mean thereby a greater circulation of water through the project area and back to the river.

In January, 1965, the United States Dept. of the Interior published its second progress report "Quality of Water, Colorado River Basin"[11] in directed by P.L. 485 of the 84th Congress. The report includes projections of the future quantities and qualities of flow in the mainstream at various points throughout its length. Although the Interior Department studies evidently are based on different considerations and methods from those of the author, the results appear to be comparable. For example, the Interior Department report estimates that a decrease of approximately [illegible] acres a yr from the historical flow below Hoover Dam will be accompanied by an increase of roughly 20% in the mineral concentration of the water at that point. The author estimates that a decrease of 3,800,000 acres [illegible] will cause an increase in mineral concentration of approximately 40%.

The United States Public Health Service is currently (1966) conducting intensive investigations in the Colorado River Basin, including investigation of water quality. However, results of these investigations probably will not be published for at least another year.

It is now universally agreed that the only effective solution to the many problems connected with the Colorado River is the development of a regional program, and [illegible] the development and execution of a regional program, that [illegible] only additional developments within the Basin but of primary importance, will include some method of augmenting the water supply of the Basin from other sources. Because the only other major sources available would provide water of considerably better chemical quality than that of the Colorado River, the inevitable result would be [illegible] from the Lower Colorado, as well as to [illegible].

Legislation now (1965) pending in the Congress (S 1019 by Senator Kuchel and Senator Murphy and companion bills in the House of Representatives) is to authorize the Lower Colorado River Basin project and the development of a regional plan to supplement the Colorado River supply, is generally endorsed by official state agencies and civic groups throughout the [illegible]. Opinion is almost unanimous that plans should be made immediately to implement a regional plan that will result in augmentation of the water supply of the Colorado. When this is accomplished, many of the vexing water problems on the

Colorado, including problems of water quality, could become more acaden than real.

FLOYD E. DOMINY,[7] AFF. ASCE.—In the recently (1965) completed pro ress report[8] on the quality of water in the Colorado River Basin, the US used the 21-yr period, January 1, 1941 to December 31, 1961, to reflect estimates of future quality of water. However, instead of attempting to estim the time when upstream depletions would affect the future water quali estimates were made of the depletion effects of a group of authorized and pr posed projects. An intermediate calculation was also made to adjust historical conditions to present conditions. This was termed the "present mo fied condition" and was based on the assumption that new developments dur the 1941 to 1961 period were in operation for the full period.

To determine future quantity of water in the Colorado River, assumptio must be made on the magnitude of future upstream depletions and on the oper tions of existing, authorized, and future reservoirs. Records of streamflow the Colorado River are available for a longer period of time than are recor of dissolved solids.

The author based his estimates on future quantity of water in the Colora River on the 30-yr period, 1927 to 1956, inclusive. His estimate of the futu quality of water was based on records of dissolved solids for the 20-yr perio October 1, 1940 to September 30, 1960. Adjustments were made by him for t effects of upstream depletion, etc.

Table 16 compares the historic and future conditions for the Lees Fer gage and the inflow to Lake Havasu as estimated by the USBR and the autho Some apparent differences may be explained by the following facto

1. The assumed depletions were greater as used by the author than tho used by the USBR. The USBR study was confined primarily to existing a authorized projects, however, the author assumed future potential, but as y unauthorized, projects would be developed.

2. The author assumed no pickup of dissolved solids; that is, leaching salines from the substrata to be caused by future irrigation. The US presented alternative calculations, (a) assuming no pickup from irrigation a (b) assuming a pickup of 2 tons of dissolved solids for each acre of new la irrigated.

3. Hill assumed no deposition or pickup of salts by reason of the futu operation of Lake Powell. The USBR assumed that 5% of the dissolved soli would be deposited in Lake Powell. In this connection, the writer agrees w the observation on page 28: "Only time will tell the effect of Lake Powel This matter will be studied in greater detail in the future when additio records become available based on observation with future operations of La Powell."

The USBR did not attempt to analyze the differences in the chemical comp sition of the dissolved solids. Their studies were based on total dissolv solids. The calculations summarized in Tables 9, 12, 13, 14, and 15 are inte esting. The methodology is a contribution to the knowledge of the possib changes in the chemical composition of dissolved solids. From an over- viewpoint, there appear to be other differences between the USBR study and t author's presentation.

[7] Commr. of Reclam., Bur. of Reclam., U.S. Dept. of the Interior, Denver, Colo.

[8] "Quality of Water, Colorado River Basin," Progress Report, Bur. of Reclam., U. Dept. of the Interior, Denver, Colo., January, 1965.

1. Near the bottom of page 20 and the top of page 21, the author discusses compact provisions that will limit the Upper Basin use of water and define the future dependable flow at Lees Ferry. Table 4 shows the "Dependable supply under 1990 conditions" at Lees Ferry of 8,058,000 acre-ft per yr. The obligation of the Upper Basin to deliver water at Lees Ferry to meet the Mexican obligation has not been clearly defined. In a report dated May 18, 1961, entitled "Limitations on Lower Basin Uses of Water due to Shortage of Colorado River Supply," the author implies that because of the quoted compact limitations the average flow at Lees Ferry would not be less than the sum of 7,500,000 acre-ft under Article III(d) and 750,000 acre-ft under Article III(c), a total of 8,250,000 acre-ft per yr.

TABLE 16.—COMPARISON OF USBR STUDY AND HILL STUDY

	USBR study averages for 21 yr 1941-1961		Hill study averages for 20 yr 1941-1960	
	Water, 1,000 acre-ft	T.D.S. ppm	Water, 1,000 acre-ft	T.D.S. ppm
Historic Flows				
Colorado at Lees Ferry	11,584	543	11,821	515
Colorado into Lake Havasu[a]	11,084	665	11,284	655
Present Level Flows[b]				
Colorado at Lees Ferry	11,296	562	—	—
Colorado into Lake Havasu[a]	10,796	690	—	—
Future Flows[c]				
Colorado at Lees Ferry	9,464	630 663	8,060	735
Colorado into Lake Havasu[a]	8,786[d] d	822 865	8,000	926

[a] Estimated as sum of Colorado below Parker Dam and diversions by Metropolitan Aqueduct.

[b] Historic flows corrected to reflect completion of projects that were authorized prior to Colorado River Storage Project.

[c] Bureau made allowance for depletion effects of authorized projects and proposed Marble Canyon and Bridge Canyon Reservoirs. Hill made allowance, also, for potential future projects which he assumed would be completed by year 1990.

[d] Assumes salt pickup of 2 tons per acre of new land irrigated.

2. The historic conditions summarized in Table 6 show a net average annual decrease of approximately 537,000 acre-ft between Lees Ferry and inflow to Lake Havasu for the 20-yr period, October, 1940 to September 30, 1960. Hill's estimates for future conditions show only a minor difference between the flows at Lees Ferry and the inflow to Lake Havasu (8,060,000 acre-ft compared to 8,000,000 acre-ft). The brief explanation from the bottom of page 21 to the top of page 22 is inadequate to account for this marked difference between the historic net loss and the estimated future net loss between Lees Ferry and inflow into Lake Havasu shown in Hill's study. Storage withdrawals would be needed to attain the inflow to Havasu indicated by Hill.

rent paper to extend the Lees Ferry data by including the water quality figures he calculated for the earlier paper. In 1955, it was necessary to estimate the quality of water data for several years in which records were not taken at Lees Ferry. A complete record is available at the downstream Grand Canyon station during this period, and, for part of the time, complete records are available at the Green River station on the Green River, at the Cisco station on the Colorado River, and at the Bluff station on the San Juan River, the sum of which measures 96% of the Lees Ferry discharge. The correlations between the station and upstream and downstream data are good and the derived figures for the missing years are reliable within a small range of error. The writer has carefully reexamined the earlier data in the light of later records and has made some changes in the values derived in 1955, including a small adjustment to evaluate and include the nitrate ion.

To make the two sets of data parallel, it was necessary to change the values presented in Table 4, that vary from the recorded data in that Hill had the yearly values smoothed to correspond with a discharge-quality curve relationship and had adjusted the values in tons equivalent for each year to equate the sums of the major anions and cations. Although the smoothed figures achieve an average over the period, they vary substantially from the recorded values in individual years. The figures presented in the following table show the quality of water record of the Colorado River at Lees Ferry on the basis of recorded values.

It will be noted from Table 17 that the sums of the three major cations and the three major anions as reported by the USGS do not balance. The weighted values of the cations are consistently higher than those of the negative ions by a fraction of 1%, probably resulting from the presence of minor ions not included in the tabulation. It is simple, however, to balance the two groups, as Hill has done, for purposes of analyzing changes in water quality.

Coincidentally, the quality data cover almost the same period of time, excepting 1929, as that of the 30 yr of minimum discharge in the river.

Table 18 averages the data for the years 1930-1960, with the cations and anions adjusted by proportion to equate the sums. The 31-yr period shows a somewhat smaller river discharge and a consequently greater unit concentration of salts than that for the 20-yr period (Table 6). The proportions of the several constituents are approximately the same in each case.

The assumptions made by the author in translating the effect of changes at Lees Ferry into effect at Lake Havasu appear to be reasonable, with the exception of the adjustments made in Table 11. These adjustments are Hill's estimates of changes that may occur as a result of storing water in Lake Powell for long periods of time and are based on the historical changes in Lake Mead. The writer believes that conditions in the two reservoir basins are different. In 1948-1949, a comprehensive study of Lake Mead was conducted by the Navy in cooperation with the United States Department of the Interior, the United States Department of Commerce, the University of California and others.[12] The report covers a detailed analysis of the physical phenomena and changes that occur in the operation of this large hold-over reservoir. It shows that the Overton Arm, or Virgin River, branch of the reservoir basin contains substantial deposits of sodium chloride and gypsum. Solution from these

[12] Smith, W. O., Vetter, C. P., Cummings, C. B., et al., "Comprehensive Survey of Sedimentation in Lake Mead, 1948-49," U. S. Geological Survey Professional Paper 295, U. S. Government Printing Office, Washington, D. C.

TABLE 18.—AVERAGE SALTS IN COLORADO RIVER AT LEES FERRY, 1930–1960

Ions	Milligram equivalents per liter	Tons—equivalent per year	Reacting values
Calcium	3.65	56,300	42.0%
Magnesium	1.95	30,100	22.5%
Sodium and Potassium	3.09	47,500	35.5%
Total Cations and Anions	8.69	133,900	100.0%
Bicarbonate	2.85	43,900	32.8%
Sulphate	4.47	68,600	51.2%
Chloride and Nitrate	1.37	21,400	16.0%

Average Flow: 11,314,000 acre-ft per yr
Tons—Equivalent: 133,900
Total Dissolved Solids: 0.71 tons per acre-ft

of the salt concentrations at San Marcial by the USGS as a result of its sampling methods in the early years, the results for those years are questionable. The record shows, however, that during a 23-yr period in which time the storage in Elephant Butte Reservoir completed a cycle and returned substantially to its original starting level, the net change within the reservoir basin consisted largely of the deposition of carbonates of calcium and some magnesium. Losses or accretions of other ions appear to be limited.

If, as Howard determined, approximately 6.3% of the dissolved solids entering Lake Mead were precipitated as carbonates, approximately the same percentage can be expected to occur in the basin of Lake Powell. Furthermore, it seems probable that losses or accretions of the other ions in the lake will be limited.

Translated downstream to Lake Havasu, the over-all concentrations of the water should be no greater, and probably less, than those shown in Table 13. The distribution of the ions will be altered by the loss of carbonates by precipitation. Accordingly, the percentages of the more soluble ions, but not the concentrations, will be increased.

The average undepleted flow of the Colorado River at Lees Ferry has been computed as 13,085,000 acre-ft annually for the period 1930–1956 (Table 1). The USBR has subsequently extended the table through the climatic year 1960, the extended average being 13,220,000 acre-ft. The historic discharge of the river during this 31-yr period was 11,314,000 acre-ft giving an annual average depletion of 1,906,000 acre-ft. The undepleted river discharge for the 1914–1960 period is 14,853,000 acre-ft. Using 1930–1960 depletions, this value becomes 12,947,000 acre-ft. Table 18 indicates that the 1930–1960 average concentration of the river at Lees Ferry was 133,900 tons-equivalent. Using Hull's estimate (Table 10) that within this range of river discharge, each 1,000,000 acre-ft increase in flow increases the salt content of the waters by approximately 6,000 tons-equivalent, the long-time salt burden of Colorado River at Lees Ferry will average approximately 133,700 tons-equivalent. Assuming that this value represents the virgin salt contribution of Lees Ferry, it will result in an over-all increase of approximately 2.6% in Hull's estimates.

On the basis of the above discussion, the writer believes that the 1990 average salt concentration at Lake Havasu, with an average annual water supply of 8,000,000 acre-ft, will be approximately 163,400 tons-equivalent, assuming the long-time virgin and salt water production of the basin and assuming that there will be no net pick up of salts from new irrigation projects in the Upper Basin. The water hardness as calcium carbonate will average approximately 435 ppm. These values do not differ greatly from those found by the author. If the water supply is reduced to 7,500,000 acre-ft each year by additional Upper Basin consumptive uses, the concentrations will, of course, be proportionately increased.

The writer agrees with Hill's conclusion that the probable 1990 unit concentrations of water at Lake Havasu will not be so great as to preclude use of Colorado River water for irrigation, but will impair its usefulness for municipal and industrial purposes.

The Metropolitan Water District of Southern California indicates that currently (1965) it is successfully treating Colorado River water from Lake Havasu having an average hardness of 350 ppm and, on occasion, as high as 420 ppm. Undoubtedly, as Hill states, these hard waters "fall far below presently accepted standards." Nevertheless, they are being treated and even higher concentrations are subject to successful treatment by large softening plants. With the expected completion of California's State Water Plan years prior to 1990, water through the metropolitan aqueduct will be blended with higher quality water from northern California, thus alleviating the hard water problem.

FEDERAL VERSUS STATE INTERESTS IN WATER DEVELOPMENT[a]

Discussion by William C. Kuhs

WILLIAM C. KUHS,[b] A. M. ASCE.—The authority and responsibility for the planning, development, and control of the water resources of the United States has, under the constitutional form of government, been shared by the state and national governments. The jurisdiction of the federal government in water resource activities derives from several provisions of the Constitution: The Commerce Clause (art. I, § 8, cl. 3), the Property Clause (art. IV, § 3, cl. 2), the War Powers (art. I, § 8, cls. 1 & 11), the Treaty Powers (art. II, § 2, cl. 2 & art. VI, cl. 2), and the General Welfare Clause (art. I, § 8, cl. 1). The author has concentrated on the problems associated with the "Reservation Doctrine" and the "powers of the United States over navigable waters." The federal-state

a March, 1965, by Harvey O. Banks (Proc. Paper 4246).

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problems associated with the Reservation Doctrine stem from the exercise by the federal government of its Property Clause powers. The federal-state problems associated with navigable waters—the "navigational servitude"—stem basically from the exercise by the federal government of its Commerce Clause powers. The writer wishes to limit his discussion to the author's consideration of the Reservation Doctrine.

The Reservation Doctrine.—Congress, under the Property Clause, has the power "to dispose of and make all needful Rules and Regulations respecting . . . Property belonging to the United States . . ." In the exercise of this power, Congress passed legislation (Act of 1866, Revised Stat. §§2239-40 (1875), 43 U.S.C. § 661 (1958); Act of 1870, Revised Sta. § 2340 (1875), 43 U.S.C. § 661 (1958); Act of 1877 (Desert Land Act), 19 Stat. 377 (1877), as amended, 43 U.S.C. § 321 (1958)) which, according to the U. S. Supreme Court in California Ore. Power Co. v. Beaver Portland Cement Co., (295 U. S. 142 (1935)), was intended to effect "a severance of all waters upon the public domain, not theretofore appropriated, from the land itself," (295 U. S. at 158) and making "all nonnavigable waters then a part of the public domain . . . subject to the plenary control of the designated states . . . with the right in each to determine for itself to what extent the rule of appropriation or the common-law rule in respect of riparian rights should obtain." (295 U. S. at 163-64).

However, the "plenary" control by the states of unappropriated, nonnavigable waters upon public lands has been subject to one qualification since 1908. In what may be termed the birth of the Reservation Doctrine, the Supreme Court held in Winters v. United States (207 U.S. 564 (1908)) that the United States, by creation of the Fort Belknap Indian Reservation, had the power to reserve waters on the nonnavigable Milk River in Montana. This case was considered an exception to the governmental policy of recognizing the water laws of each state as controlling nonnavigable streams. The exception was considered necessary for the federal government to fulfill its obligations to the Indians. Four subsequent cases have turned this exception into a rule. In FPC v. Oregon (349 U.S. 435 (1955)), the Supreme Court restricted its holding in Beaver Portland by excluding "reserved lands"—lands owned by the United States that are withdrawn from the operation of the public land laws—from the definition of public domain. The Court determined that the federal government, in creating the reservations involved, had withdrawn the control of the nonnavigable stream (as limited by the purpose for which the reservation was created) from the state of Oregon. Pelton involved a nonconsumptive use of nonnavigable waters. In the Hawthorne case, Nevada v. United States (165 F. Supp. 600 (D. Nev. 1958), aff'd on other grounds, 279 F. 2d 699 (9th Cir. 1960)), the Reservation Doctrine was extended to the consumptive use of unappropriated ground water. In Arizona v. California (373 U.S. 546 (1963)), the Doctrine was extended to consumptive uses of appropriated waters for purposes other than Indian Reservations. The present state of the Reservation Doctrine is best illustrated in Glenn v. United States (Civil No. C-153-61, D. Utah, March 16, 1963) where, in contrast to the complex factual setting in Arizona v. California, the facts were few, simple, and stipulated. Glenn was the holder of a state certificate of appropriation of water issued in 1933. In 1961, the United States, the owner of the Ashley National Forest—an 1897 reservation—diverted the waters that had previously flowed to Glenn's land. The United States' right to divert these waters was not based on a state-created right. At