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THE TRANSITION FROM GROUND-WATER MINING TO INDUCED RECHARGE IN GENERALIZED HYDROGEOLOGIC SYSTEMS

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ABSTRACT

The water rights system of prior appropriation can be extended to ground water by recognizing two components of the ground-water account: stored ground water and induced recharge of surface water. Ground-water storage provides a transient source of water which gradually converts to surface-water depletion. The timing of the transition to reliance on induced recharge of surface water is highly variable from case to case. The shape of the transition curve is calculated for five examples of generalized aquifer types using the three-dimensional model program of McDonald and Harbaugh (1984). The five example aquifer types are similar to those originally described by Lohman (1972) and include a perennial stream, an ephemeral stream, a closed basin, an extensive Tertiary aquifer, and an artesian basin. Few ground-water developments could be treated either as solely a mining or as a fully-recharged case during reasonable planning horizons. The ultimate limit on ground-water withdrawal is controlled by the magnitude of the surface water supply in the area of influence of the development and by the vertical permeability of the aquifer. For a particular wellfield layout, the limit on development is equal to the yield of the induced-recharge phase of the transition curve. This phase applies at times ranging from years to millennia depending on the geometry and diffusivity of the aquifer. The impacts on water rights depend on these factors and should be simulated for an explicit location, rate, and planning horizon.

INTRODUCTION

Hydrologic information becomes a central part of the process of water rights administration when a water-short user calls for his share of the supply or when water is transferred to a new use. Causal hydrologic models serve in these cases to link a proposed action to its hydrologic effects.

Administration of ground water has been governed by the concepts of tributary and nontributary ground water, safe yield versus mining, and the idea of impairment of a ground-water supply. Hydrology as a science, however, has not been markedly successful in communicating to the water policy community some basic principles, such as mass-balance. A water policy study team advising the New Mexico legislature concluded that "This concept and its ultimate impact on the environment... is little understood by hydrologists and lay people alike" (DuMars and others, 1986).

In hydrology, "mass balance" denotes the idea that inputs to the hydrologic system from all sources are equal to outputs. This balance applies for the system as a whole and for each of its parts, on every scale of time, and equally to water and its dissolved constituents. Changes in storage within the system (surface water and ground water) may be either positive or negative, but storage must be counted in the mass balance. The impact on water policy is in the recognition that there is no entirely new source available when ground water is developed.

This paper outlines the physical implications of applying a mass-balance analysis to the water rights rule of prior appropriation in several generalized hydrologic systems of surface water and associated ground water. The systems are those described by Lohman (1972) as "Examples of Aquifers and Their Development." The principles underlying the system of prior appropriation are fully compatible with the physical understanding of hydrogeologic systems. Wide application of the priority system to both surface water and ground water supplies will enhance protection for existing rights, and can expedite the transfer of water to new uses. Administration of the priority system will be considerably aided by adjudication to establish marketable and enforceable rights, by administrative adoption of an economic standard for impairment, and by use of comprehensive hydrologic models to identify the effects of a proposed change in the pattern of water use.

THE HYDROGEOLOGIC SYSTEM

Ground water is the extensive volume of water in the saturated parts of the earth's crust. It has an upper boundary at the water table or at the saturated land surface, but, being a global feature, it has no absolute lateral boundaries or bottom boundaries. As a system, it is not delineated by rock types, permeability variations, or chemical quality. Ground-water flow systems may cross aquifer boundaries and may be local, regional or continental in scale (Bredehoeft and others, 1982).

Surface water consists of overland runoff of snow melt or rain, and baseflow. Baseflow is the discharge from the ground-water system. Surface water is located outside of the upper boundary of the ground-water system. Neither is viewed as a closed system, however, and water is exchanged where surface and ground water contact the saturated land surface.

As to the size of each resource, about 70 percent of the annual output of the world-wide hydrological cycle is discharged as runoff, and 30 percent is discharged through the ground-water component (Lvovitch, 1975). Surface streams typically flush through a complete cycle of their contents dozens of times each year, whereas the much larger volume contained in ground-water flow systems is cycled out more slowly, commonly on a time-scale of centuries.

WATER SYSTEM YIELD

The variable flow of a surface water system is illustrated by the hydrograph in Figure 1. The ladder of priority, wherein senior rights to divert and use the water are held by the first appropriator, is superimposed. The figure reflects the general pattern of development of arid lands, wherein the reliable baseflow of streams was diverted early for irrigation. Ancient irrigation was in place even before United States' occupation in the American southwest (Follett, 1898). Reclamation projects later stored the winter and peak flows and claimed much of the remaining yield from the river systems. Ground-water development followed in the 20th century and has reduced the baseflow of many streams.

The original goal in operation of the priority system is clear: protecting the earliest diversions during natural variation of the supply. Even artificially stored reservoir water may be distributed in order of priority. The practical matter of scheduling variable instantaneous flows to meet a variable demand at a large number of diversion points in the order of priority is not so readily tractable (Eheart and Lyon, 1983), but the objective at least is clear.

The degree of effect on a stream due to ground-water development varies in each case. The effects on some streams are insignificant, while other stream reaches have changed from perennial to intermittent flow because the regional water table has declined below the stream bed (Osterkamp and

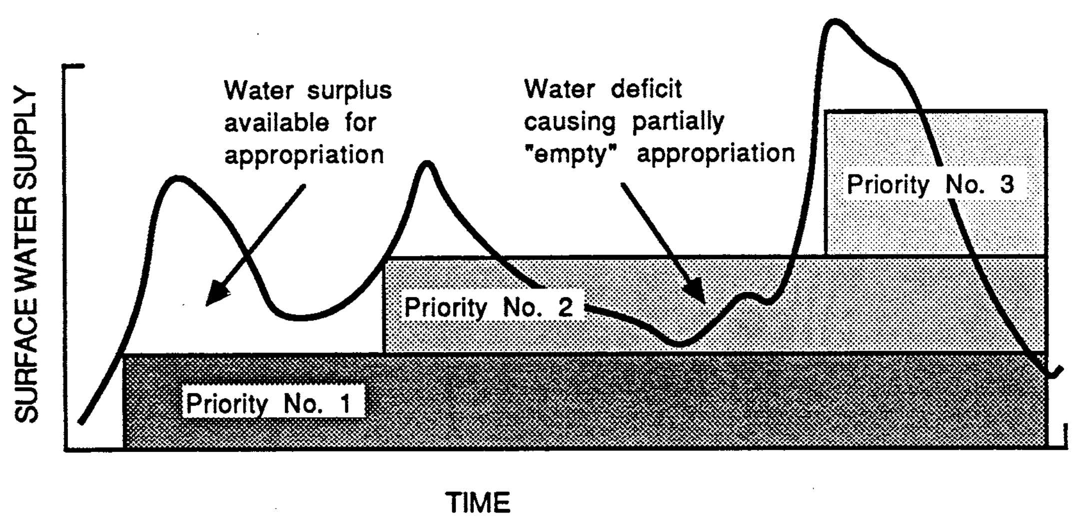


FIGURE 1 - THE PRIORITY APPROPRIATION SYSTEM SUPERIMPOSED ON A GENERALIZED SURFACE WATER HYDROGRAPH

Hedman, 1979). Figure 2 contrasts three cases of differing rates of effects on the yield from a stream system due to ground-water development. With wells nearby the surface streams, the total system yield may be expanded in the short term. The system then rapidly adjusts to a new equilibrium with no net gain in system yield. At greater distances from the surface water bodies, the spacing of the wells and the ground-water hydraulics may allow major expansion of the total supply for centuries. In all cases, the eventual reduction in surface water supply as a result of ground-water development creates an issue in water rights administration.

Ground-water diversions are at a physical advantage under a lax water accounting system. Wells have constant access to water within the economic limitations of the particular purpose of use, whereas many senior surface rights with equal administrative standing may be left physically water short.

Ground Water

The administration of ground water in the priority system is not straightforward because the source of ground water has two components: ground-water storage and induced recharge of surface water. Development of aquifer storage interjects an additional source of water into the otherwise well ordered surface water scheme. Ground-water storage is relatively large. Variation in supply from wells is not a consideration until the decline in water level becomes an economic problem. Diversions from wells,

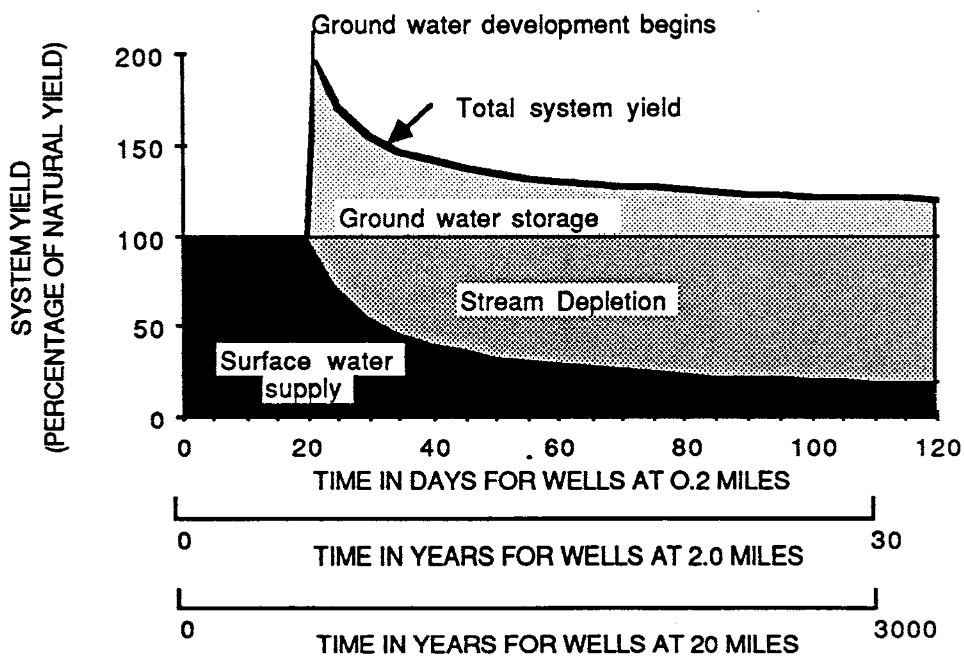


FIGURE 2 - EFFECT ON SYSTEM YIELD WITH THREE WELLFIELDS AT 0.2, 2.0, AND 20 MILES FROM A SURFACE STREAM

however, are physically linked to surface depletions in the form of induced recharge from the surface streams (Theis, 1940). Theis noted that "All water discharged by wells is balanced by a loss of water somewhere. Some ground water is always mined... further discharge by wells will be made up at least in part by an increase in the recharge [and] in part by a diminution in the natural discharge." In the 1980s, three-dimensional numerical models of the complete hydrogeological system have been put to use for water rights purposes (Hearne, 1980). These models provide a predictive tool explaining the connection between wellfield withdrawal and surface water depletion at particular sites.

The timing of effects on adjacent streams caused by ground-water withdrawal depends upon the aquifer diffusivity and the distance from the wells to the surface water body. Aquifer diffusivity is a physical constant for a given aquifer which describes the rapidity with which a transient change in head will be transmitted throughout the system. It has horizontal and vertical components and is expressed as the ratio of the permeability-thickness product to storativity. Permeability is a measure of the rate of ground-water movement under standard conditions, and storativity is a measure of the effective water content in the earth's crust. The dimensions of diffusivity are $Length^2/Time$. The major factor in determining the rate of effects on surface supplies is the distance of withdrawals from the surface sources. For radial flow of ground water, a 10-fold increase in distance from the surface water body causes a 100-fold delay in the response time, whereas a change in diffusivity is linearly proportional to the response time.

Surface streams commonly lie in contact with different sedimentary units than those rock layers in which wells are perforated. Hydrologic stresses propagated from one rock unit to the other must cross vertical layering in permeability (hydraulic conductivity) and storage properties. Thus, the three-dimensional aspect of diffusivity and distance becomes important for accurate simulation of effects on rivers or on water levels at various depths in the aquifer. Commonly, the vertical component of ground-water flow is retarded relative to horizontal flow in sedimentary rocks. In other cases, response time may be accelerated through vertical fractures in fine-grained or crystalline rocks. Most large-capacity wellfields, however, produce from layered sedimentary rocks where the three-dimensional aspects of flow serve to delay the effects on adjacent surface water bodies.

Depletion of Surface Water by Wells

When a serviceable hydrogeologic model is available, the effect of ground-water usage can be quantified in terms of the availability of the surface supply to serve prior water demand. The yield of a surface system is not viewed as a simple average annual supply, reliably available, and apportioned to a fixed number of claimants. The priority system would have no purpose if the yield of the system was constant each year and reliable at all times. The priority system deals with the variable duration of surface water flow. The flow-duration curve is a standard hydrologic approach showing the percent of time that flows of certain magnitudes are available from a stream system. Water rights cannot be exercised when there is no flow to divert. The percentage of time when water claims are "empty" is illustrated by superimposing the ladder of priority on the flow-duration curve (Figure 3A).

The flow-duration curve for a stream reach can be adjusted to show the effect on future flow availability when ground-water depletions subtract from the baseflow of the stream. Depletions grow with time, so several adjusted curves may be needed. The starting and ending points of an illustrative adjusted duration curve reflecting the depletion of 150 units of flow are shown on Figure 3B. With the ladder of priority superimposed on the adjusted flow-duration curves, the hydrologic effects on water rights become clear. Ground-water development initially expands the basin yield, as shown by the hachures on Figure 3B, but eventually the baseflow of surface streams adjusts to restore the original net basin yield. The loss from surface water availability is shown by the black interval on Figure 3B. Although all surface water flow is affected, the supply of water available to serve priority number one experiences the largest percent reduction. Users of the ground water source, in contrast, receive the full benefit of their continuously available supply. The effect is to move supplies from early surface diversions to later ground water users.

Typical streams in the western United States are water short when compared to the total size of water claims (NM Bureau of Mines and Mineral Resources, 1965). Even the earliest priorities may not be fully served each year. The order of priority of water claims establishes their utility and, thereby, their value. Later priority implies access to a lesser duration of flow and a correspondingly larger fraction of empty water claims. Many late priority water claims are seen to be predominantly empty. The senior users may represent the only water claims with a substantially full natural supply. Even the very senior surface water users can be affected by diversions from ground water, which are ultimately a diversion from the stable baseflow of nearby streams relied upon most by the original surface water user.

The losses borne by the surface water system are offset by the new supply of water developed from ground-water storage (Figures 2 and 3). In some cases, return flow from ground-water withdrawal directly increases the local stream flow (Hearne, 1980). With ground water development, the total system yield available to support beneficial uses increases until surface water depletion approaches the magnitude of the ground-water development. The duration of the net benefit may be months or millenia, depending upon two factors: diffusivity and distance. Table 1 shows the variable time period for ground-water pumpage to be balanced in part by surface water sources as predicted in some recent three-dimensional ground-water models. As shown in the last column (surface water depletion), the expanded yield of the total system comes at the eventual cost of a reliable supply for surface water diversions.

GROUND-WATER MINING

Ground-water mining remains under discussion in the current water policy literature (Western States Water Council, 1984; Edison Electric Institute, 1984; DuMars, 1986; Holzschuh, 1987). Ground-water mining is generally described as the opposite of safe-yield management and as appropriate for unrechargeable or nontributary ground-water basins. Some ground-water systems have low diffusivity, are located relatively far from surface water bodies and, therefore, have a low potential for inducing recharge. Such ground-water systems warrant special consideration in water

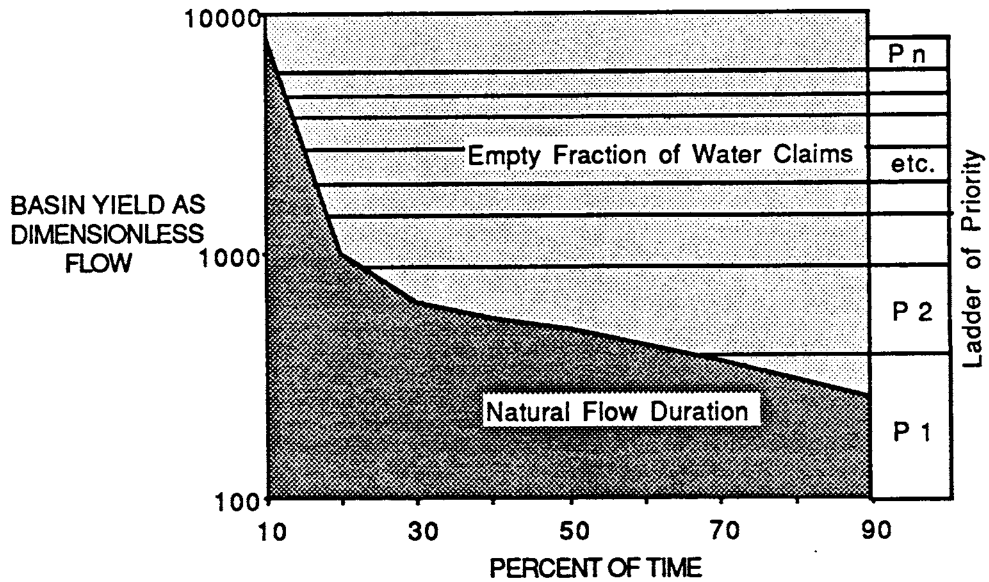


FIGURE 3 A - THE PRIORITY SYSTEM APPORTIONS THE NATURAL FLOW TO A SEQUENCE OF WATER CLAIMS.

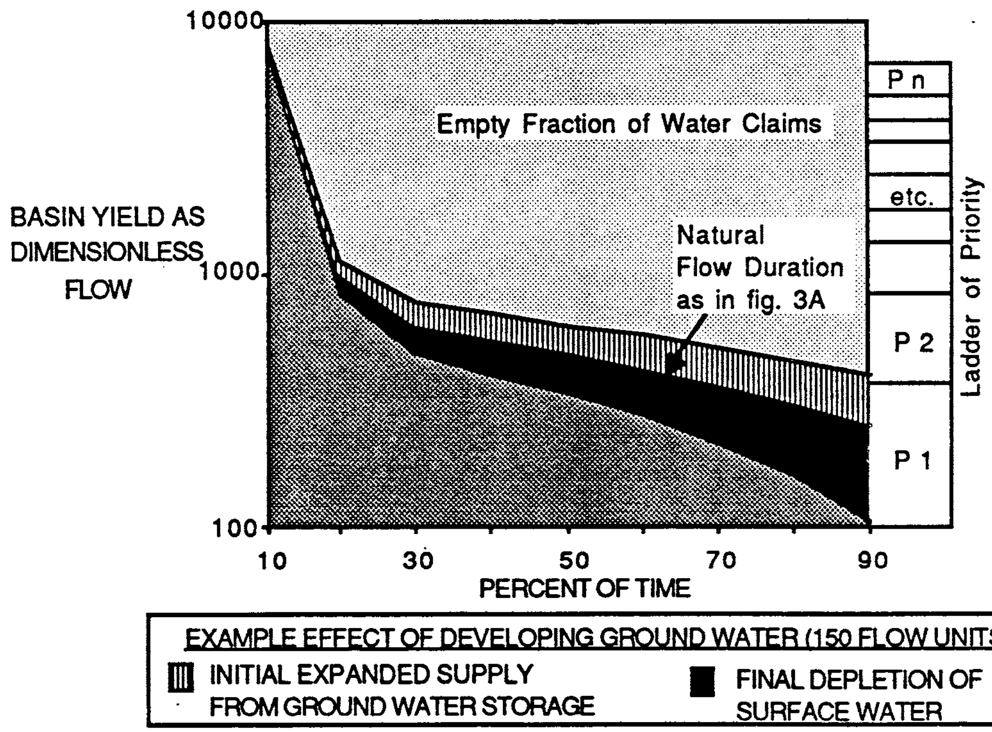


FIGURE 3 B - GROUND WATER DEVELOPMENT INITIALLY EXPANDS THE SUPPLY. BALANCE IS RESTORED BY DEPLETION OF BASEFLOW.

TABLE 1

Sources of Water (Surface Water Depletion and Ground-Water Storage) Supporting Ground-Water Withdrawals as Predicted by 3-D Ground-Water Models in New Mexico

Author	Distance to Surface Water (Miles)	Geologic Units	Time Period (years)	Wellfield Drawdown (feet)	Source of Water (Percent of Withdrawal) Ground-Water Storage	Surface Water Depletion
Billings (1984)	1 to 7	Permian Limestone	11	30	37.6	62.4
Faust et al. (1984)	4 to 20	Tertiary Volcanics	34	600	54.3	45.7
Hearne (1980)	1 to 10	Tertiary Sedi- ments	50	300	88.8	11.2
HGC (1982)	15 to 20	Jurassic Sedi- ments	30	2300	98.4	1.6
HGC (1983)	12	Permian Sedi- ments	50	138	96.8	3.2
Lyford et al. (1980)	40	Jurassic and Cret. Sed.	47	3900	99.2	0.8
Peterson et al. (1984)	12	Tertiary sediments	100	200	49.6	50.4
Kernodle et al. (1987)	1 to 8	Tertiary Sediments	72	60	25	75

policy questions due to their relative isolation from external water bodies. As shown below and in Table 1, however, essentially all ground-water withdrawal can deplete surface water to some degree in the long term. It would be hydrologically inaccurate and economically inefficient to ignore the transition period and to assume that ground water is only of two types: 100 percent mined or 100 percent recharged by surface water (Martin, 1986).

Every ground-water development, whether from a local river bed or a continental-scale flow system, begins with 100 percent of withdrawals being derived from storage. The timing of the change from storage depletion (mining) to induced recharge from surface water bodies is key to the water policy question. The shape of the transition curve for a two-dimensional system is shown in Figure 4 in nondimensional form based on Glover's (1974) tabulation. As is demonstrated in Bredehoeft and others (1982) and in the following sections of this report, the general shape of the growth curve is retained in systems with appreciably different boundaries and parametric values. The management category of mineable, nontributary or unrechargeable water is a reasonable one to apply to wellfield areas that would not progress beyond the earliest stages of the Figure 4 curve (98 percent storage) within a reasonable planning horizon. Two of the modeling studies in Table 1 (both in Jurassic sediments of the San Juan Basin) fall in this category and demonstrate that some ground-water resources can be developed properly as mineable water.

The rate at which dependence on ground-water storage converts to dependence on surface water depletion is highly variable and is peculiar to each case. Table 2 illustrates a broad range of effects. The initial and final phases of the growth curve on Figure 4, representing mining and induced recharge, are separated in time by a factor of nearly 10,000; for example, one week of mining implies a transition to steady recharge 8,000 weeks or 160 years later. The curve is disproportionally steep in the early transition toward induced recharge. In example C on Table 2, storage provides 90 percent of the source of water after two weeks and only 10 percent after 6.5 years. The progression to full reliance on indirect recharge, above 98 percent, is extremely slow. The distinct category of ground-water mining depends entirely upon the time frame. All ground-water developments initially mine water, and finally do not.

Natural Recharge

The distinction between natural recharge and induced recharge also complicates water rights administration. Natural recharge is that water moving through the ground-water system under the boundary conditions imposed by natural topography and climate. Induced recharge is surface water added to the natural ground-water system in response to artificial boundary conditions imposed at wellfields, drains, recharge basins, reservoirs, etc. Induced recharge and ground-water storage are credited as the two sources of water to balance artificial ground-water withdrawals. Natural recharge balances natural discharge and does not enter the artificial water account.

Natural recharge is already generally appropriated at its downstream discharge point as the reliable baseflow of springs, wetlands and rivers. Natural recharge is a spurious part of the wellfield water budget and is irrelevant to the magnitude of an artificial ground-water development.

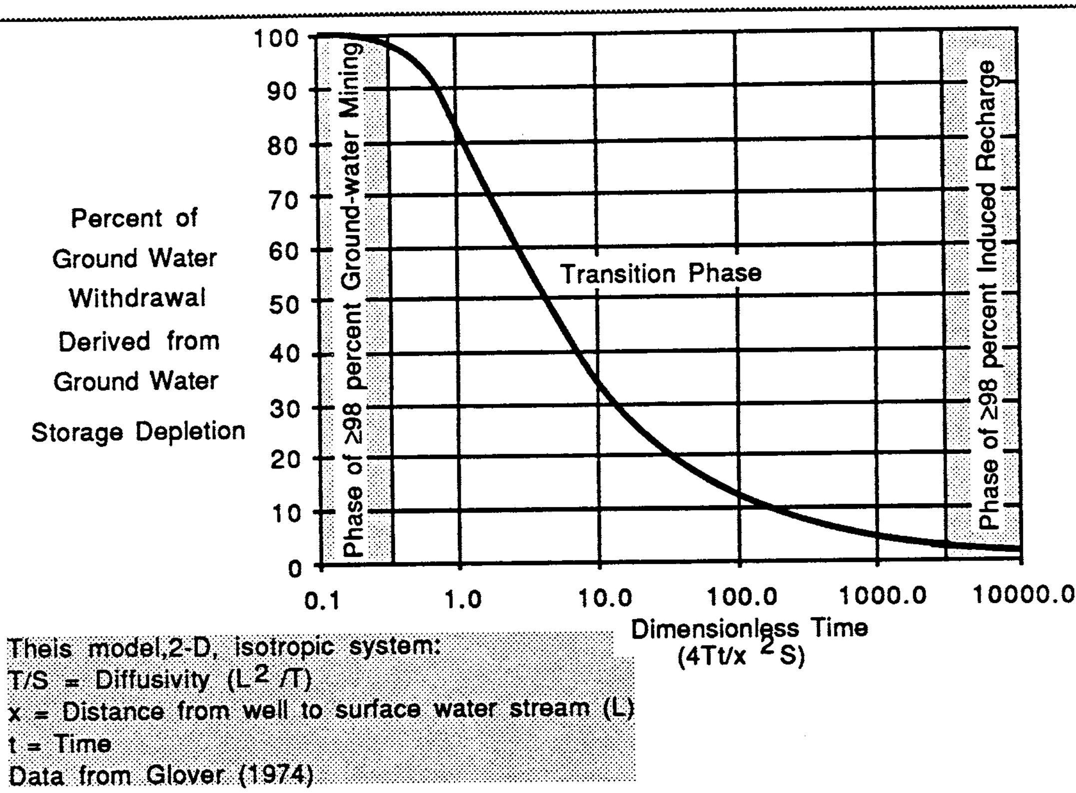


FIGURE 4 - TRANSITION OF SOURCES OF WATER TO WELLS FROM RELIANCE UPON GROUND WATER STORAGE TO INDUCED RECHARGE OF SURFACE WATER

Freeze and Cherry (1979), in commenting on ground water resource evaluation, stated that: "Some authors have suggested that the safe yield of a ground-water basin be defined as the annual extraction of water that does not exceed the average annual ground-water recharge. This concept is not correct." Bredehoeft (1982a) noted that: "Perhaps the most common misconception in ground-water hydrology is that a water budget of an area determines the magnitude of possible ground-water development."

GROUND-WATER PLANNING POLICY

There is no valid generic rule, such as pumping the natural recharge, that will lead to a desirable economic or stable (non-depleting) level of ground-water development. Subject to local permeability and storage conditions, such a rule can cause either greatly excessive and increasing drawdown or costly constraints on resource usage regardless of the rate of natural recharge. The effects of concern to water policy are primarily aquifer drawdown and surface water depletion. Both are related to pumping rate, aquifer diffusivity, location, and time of pumpage. The natural recharge rate is not related to any of the parameters controlling drawdown and depletion, the primary water policy concerns. Despite the irrelevance to hydrologic effects, a ground-water policy based ostensibly on a steady

TABLE 2

Example Rates of Transition from
Ground Water Mining to Induced Recharge

Sources of Water	Example Rates of Change on Transition Curve of Figure 4[a]			
	A[b]	B	C	D
Mining Phase	1 second	1 day	1 week	1 year
90 percent storage	2 seconds	2 days	2 weeks	2 years
50 percent storage	12 seconds	12 days	3 months	12 years
10 percent storage	6 minutes	11 months	6.5 years	340 years
Induced Recharge Phase	2 hours	23 years	160 years	8350 years

(a) Based on Glover (1974) model.

(b) The hydrologic parameter T/Sx^2 (aquifer diffusivity/ distance squared) ranges over 7 orders of magnitude in examples A-D.

state with use balanced by recharge remains attractive to policymakers as in Santa Fe, New Mexico, where the quantitative approach "gave the Plan scientific credibility and public political acceptance" (Wilson, 1983). Water policies should be publicly understood and accepted, but public purposes are not served by adopting an attractive fallacy that the natural recharge rate represents a safe rate of yield.

A suitable hydrologic basis for a ground-water planning policy aimed at determining the magnitude of possible development would be a curve as in Figure 4 coupled with a projected pattern of drawdown for the system under consideration. The level of ground-water development is calculated using specified withdrawal rates, wellfield locations, drawdown limits and a defined planning horizon. Ground-water models are capable of generating the response curve for any case by simulating the management or policy alternatives in these terms. A specified withdrawal rate, well distribution, and drawdown of water levels to an economic or physical limit are used in the model to project the sources of water from ground-water storage and from surface water depletion throughout the area of response. The area of response is not known in advance of such a projection. Wells outside topographic drainage boundaries can be a source of significant stream depletion of surface water inside the drainage basin. The planning horizon must be defined to assess which phase of the transition curve will apply during the period of the plan or policy. The withdrawal rate selected in this way relies first on aquifer storage and secondly on the potential for induced recharge. Induced recharge, of course, implies the reduction of supplies for existing uses of the captured surface water.

Ground water withdrawn from the mineable category (>98 percent from storage) does not cause any significant surface water effect. In such a case, priority to mineable ground water becomes an economic right to protection from later depletion of aquifer water levels. Priority in access to stored ground water appears to have no other significance than economic protection. Neither private property interests nor the public trust are enhanced by a reservation of "dead storage" excluded from the resource base.

Example Calculations of Effects of Wellfield Development

Lohman (1972) discussed safe yield and the sources of water derived from wellfields using a series of five example aquifer types. He discussed in conceptual terms the setting, sources of water, operation of the systems in terms of mass-balance, and the limitations on each. His conceptual model is extended below to illustrate quantitatively the rate of change of water sources in the types of systems that he discussed. The three-dimensional aquifer model program of McDonald and Harbaugh (1984) is used to calculate the drawdown and depletion rates for five example flow systems following Lohman's description. The aquifers are:

1. Valley of Large Perennial Stream in Humid Regions.
2. Valley of Ephemeral Stream in SemiArid Region.
3. Closed Desert Basin.
4. Southern High Planes
5. Artesian Basin.

Lohman's figures 43 through 47 are reproduced in Figure 5 for illustration of the geometry of each aquifer system. Additional input required for the three-dimensional simulations, particularly withdrawal rates and anistrophy, is illustrated on Figures 6A through 10A. In each case a wellfield was specified in the model to produce at practical rates from each system. Withdrawal was simulated at a constant rate except at the Southern High Plains example where a constant drawdown with declining yield was simulated. The sources of water to each system are also outlined. Generally, the surface sources were simulated as an amount available to be captured from perennial streams, springs, or from reduction of evapotranspiration. The example aquifers do not represent any specific field conditions, but are intended to demonstrate the general behavior of a variety of generalized ground-water systems under development.

Calculated curves displaying the transition from full reliance on aquifer storage to full reliance on induced recharge of surface waters are given in Figures 6B through 10B. The shape of the curves is generally reminiscent of that on Figure 4 for a two-dimensional radial flow system. The curves show the importance of selecting a suitable planning horizon when evaluating the effect of a ground-water withdrawal. As seen on Table 3, the phase during which more than 98 percent of the withdrawals are derived from aquifer storage ranges from 9 hours to 41 years after initiation of withdrawals in these five examples. The 98 percent induced recharge phase ranges from 4 to 9,400 years. The results suggest that a ground-water policy based either on equilibrium condition or on a mining

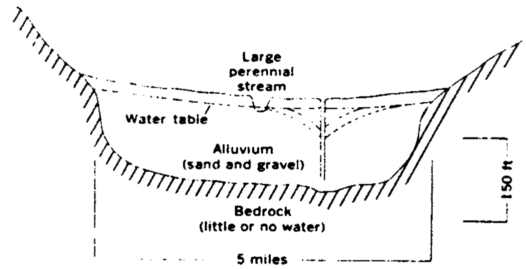


FIGURE 43.—Development of ground water from valley of large perennial stream in humid region.

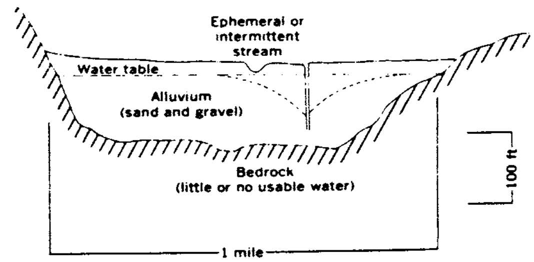


FIGURE 44.—Development of ground water from valley of ephemeral stream in semiarid region.

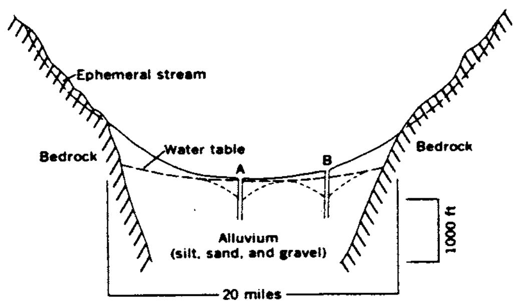


FIGURE 45.—Development of ground water from bolson deposits in closed desert basin.

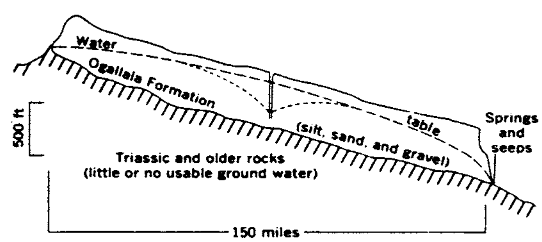


FIGURE 46.—Development of ground water from southern High Plains of Texas and New Mexico.

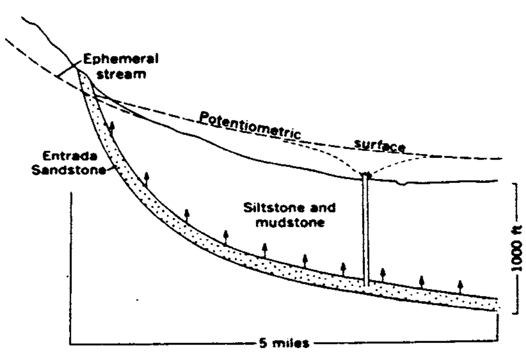
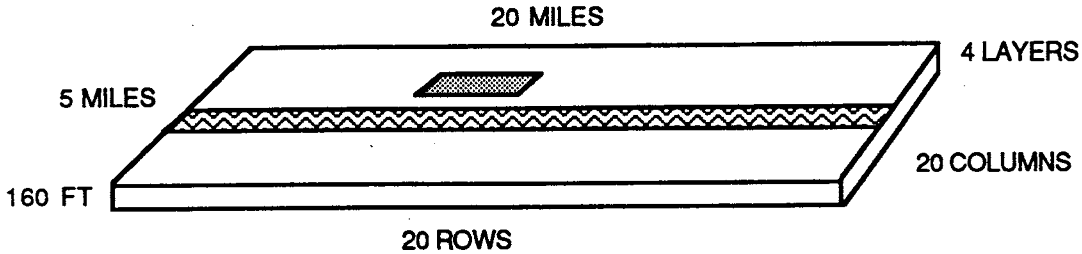


FIGURE 47.—Development of ground water from the Grand Junction artesian basin, Colorado.

FIGURE 5 - LOHMAN'S (1972) FIVE EXAMPLES OF AQUIFERS AND THEIR DEVELOPMENT



AQUIFER PROPERTIES:

K = 200 feet/day
Anisotropy = 0.005
Sy = 0.10
Ss = 0.0000025
Layers = 40 feet x 4

WITHDRAWAL:

Net from 6 model cells in layer 3 produce 18 cfs (13,000 AFY).

SOURCES OF WATER:

1. Aquifer storage; Max drawdown 9.25 ft. at 10 years.
2. Perennial stream, 0.25 mile wide throughout a 20 mile reach (1,170,000 AF available).

Wellfield

Surface water source

FIGURE 6A - LARGE PERENNIAL STREAM AQUIFER MODEL

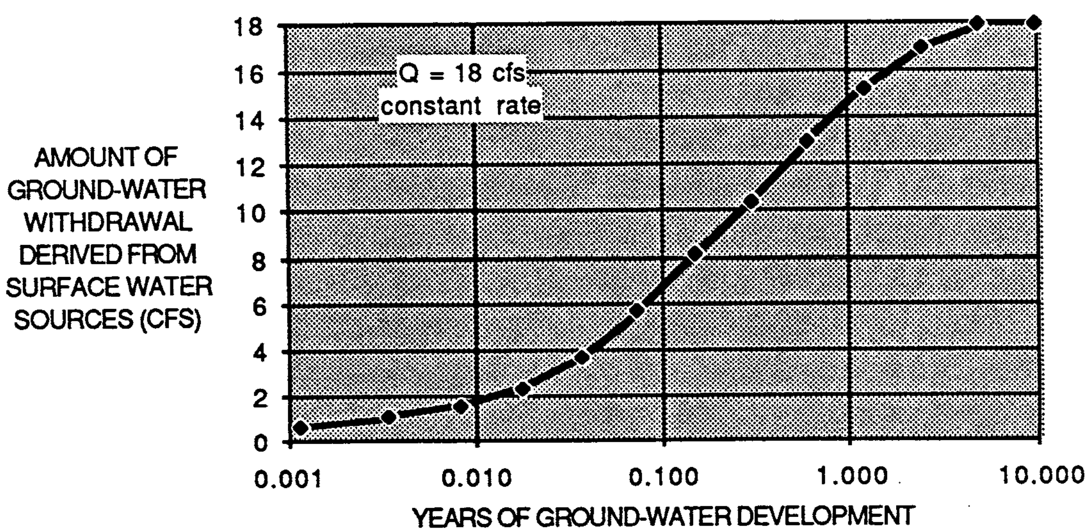
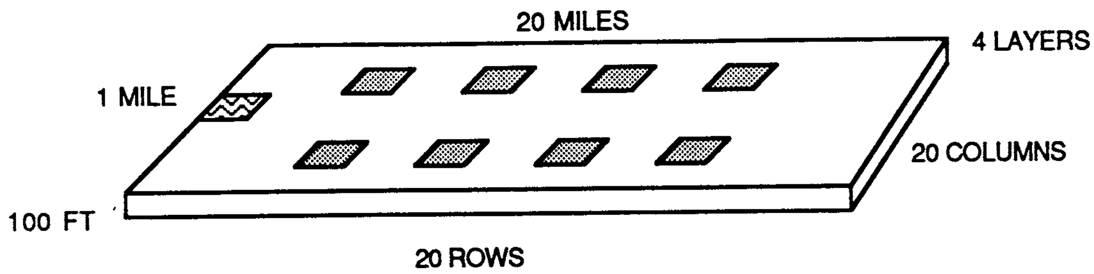


FIGURE 6B - LARGE PERENNIAL STREAM AQUIFER SYSTEM TRANSITION FROM RELIANCE ON AQUIFER STORAGE TO SURFACE-WATER DEPLETION



AQUIFER PROPERTIES:

K = 200 feet/day
Anisotropy = 0.01
Sy = 0.10
Ss = 0.000002
Layers = 25 feet x 4

WITHDRAWAL:

Net from 8 model cells in layer 3 produce 3.52 cfs (2548 AFY).

SOURCES OF WATER:

1. Aquifer storage; Max drawdown 87 ft. at 1000 years.
2. Ephemeral stream with a 1 mile reach (26,500 AF available).

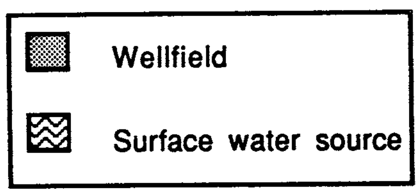


FIGURE 7A - EPHEMERAL STREAM AQUIFER MODEL

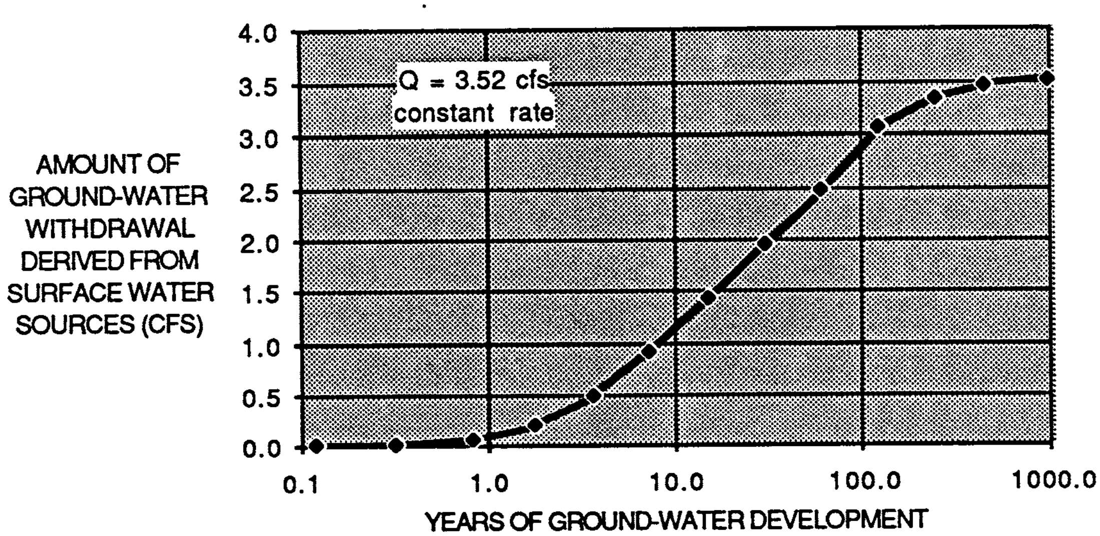


FIGURE 7B - EPHEMERAL STREAM AQUIFER SYSTEM TRANSITION FROM RELIANCE ON AQUIFER STORAGE TO SURFACE-WATER DEPLETION

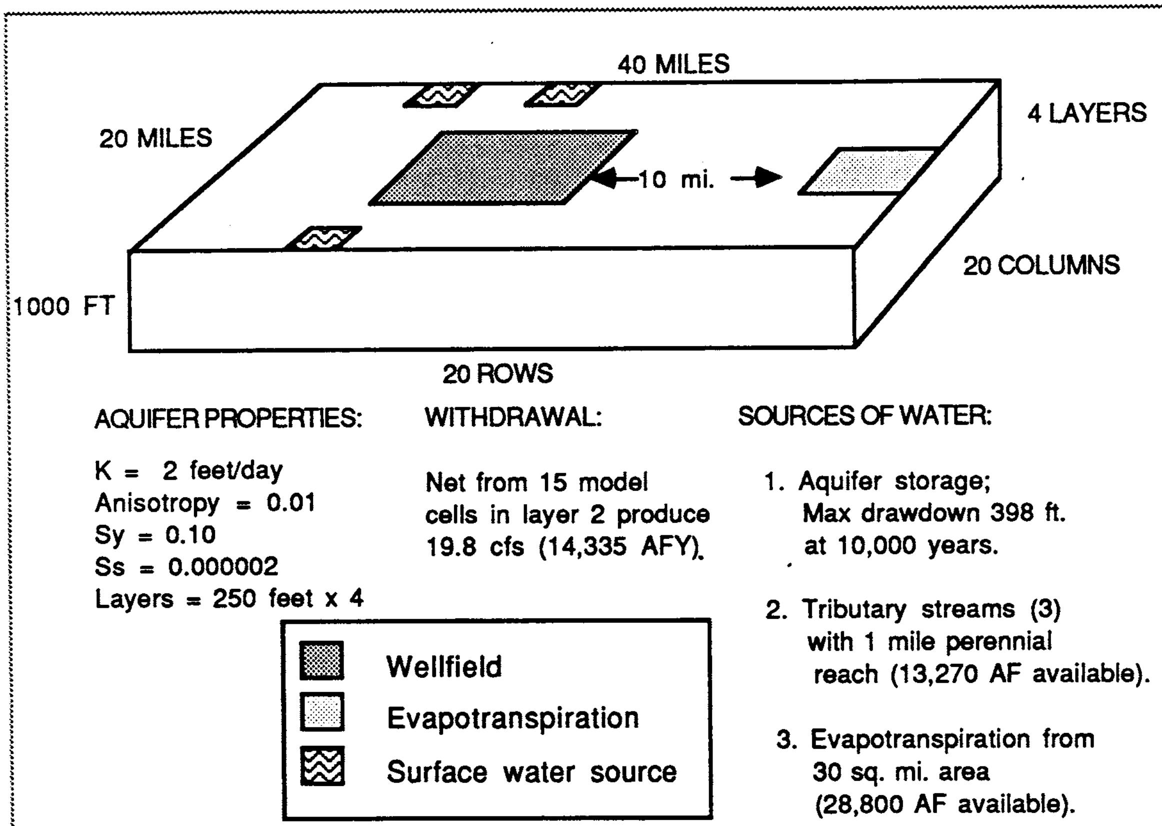


FIGURE 8A - DESERT BASIN AQUIFER MODEL

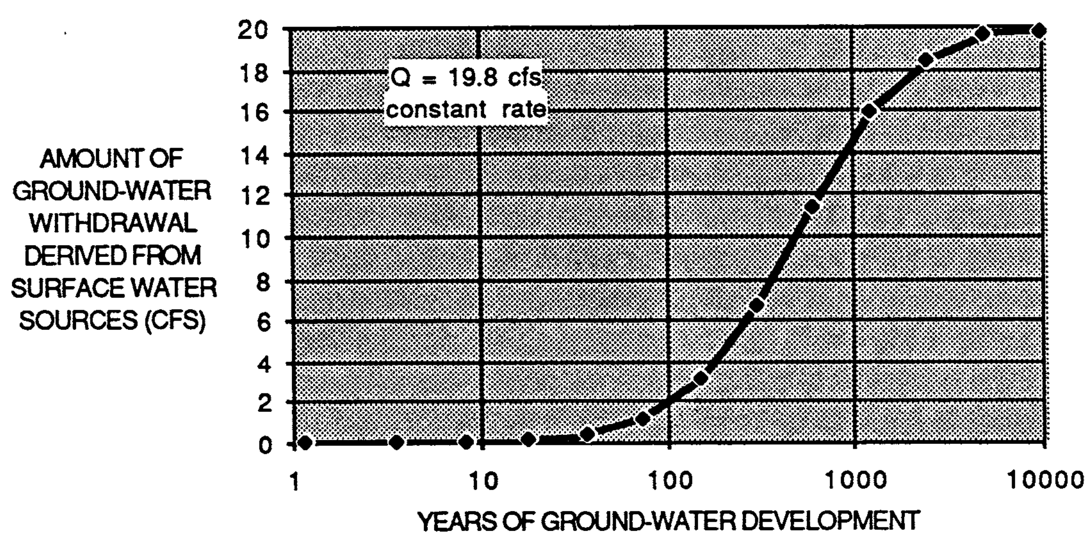


FIGURE 8B - DESERT BASIN AQUIFER SYSTEM TRANSITION FROM RELIANCE ON AQUIFER STORAGE TO SURFACE-WATER DEPLETION

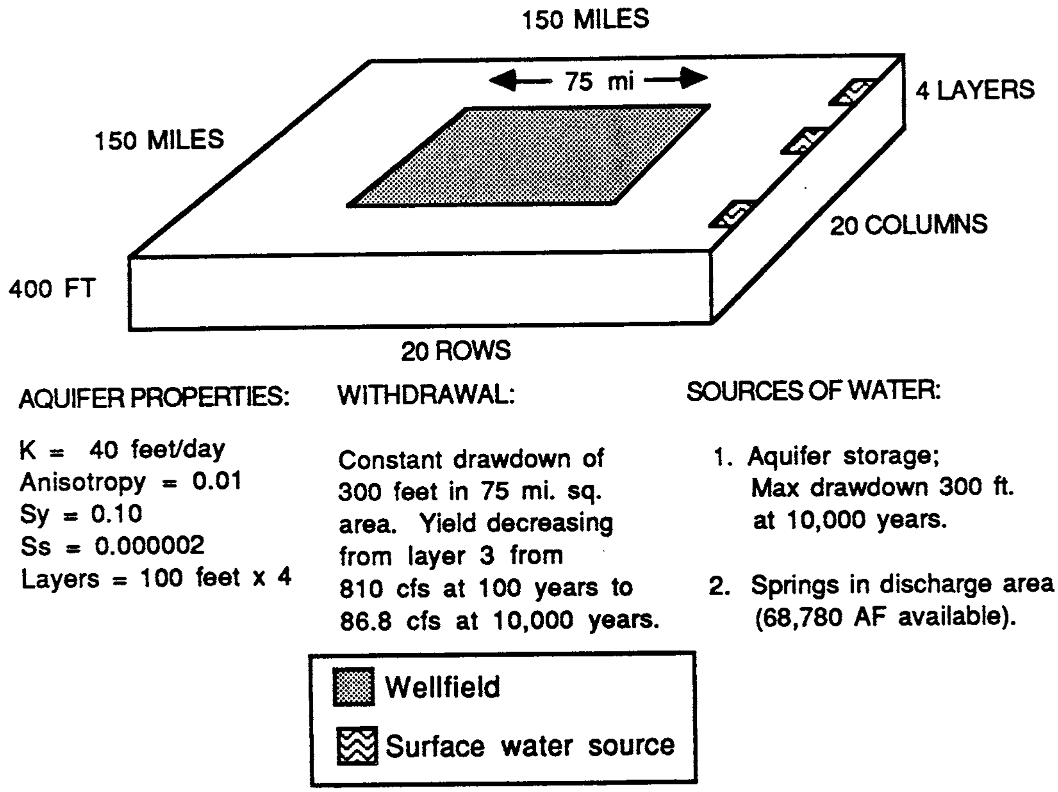


FIGURE 9A - SOUTHERN HIGH PLAINS AQUIFER MODEL

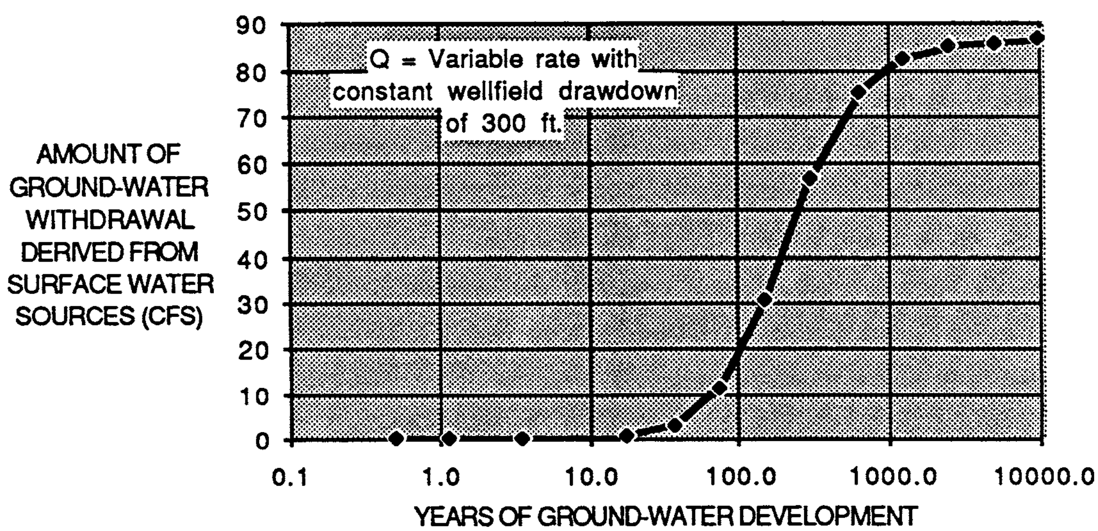


FIGURE 9B - SOUTHERN HIGH PLAINS AQUIFER SYSTEM TRANSITION FROM RELIANCE ON AQUIFER STORAGE TO SURFACE-WATER DEPLETION

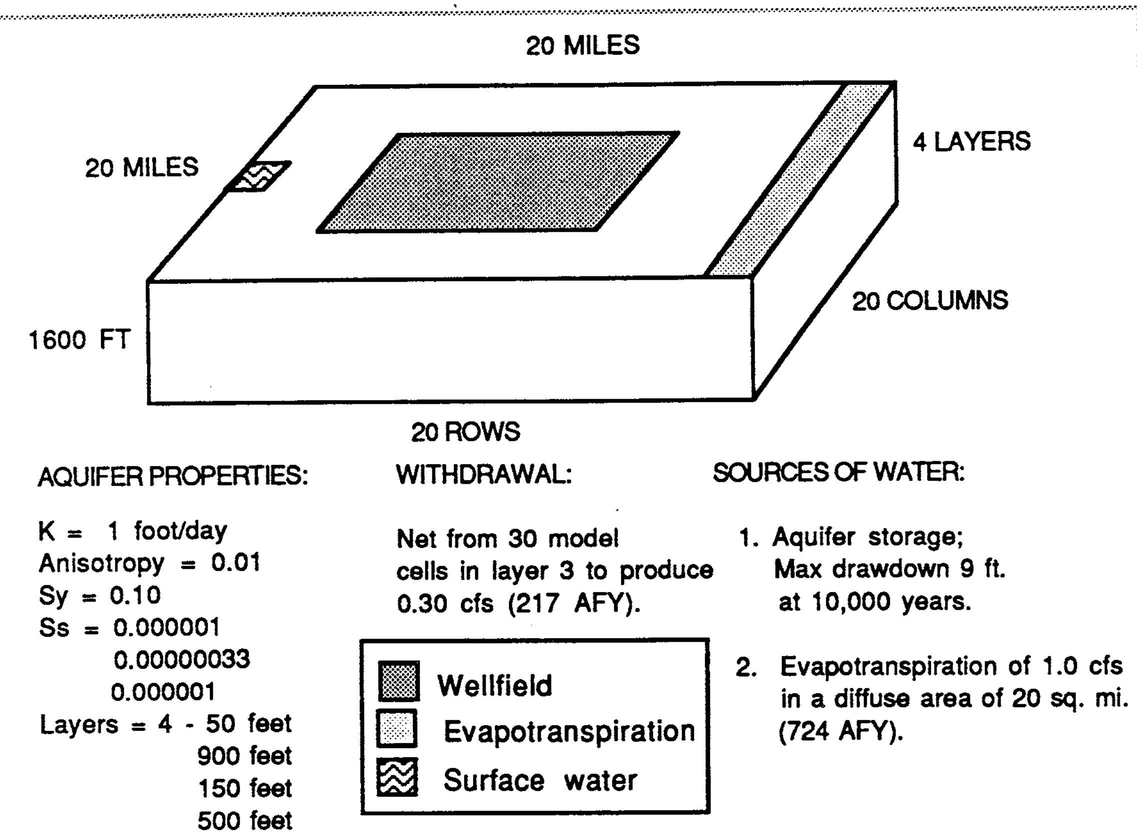


FIGURE 10A - ARTESIAN BASIN AQUIFER MODEL

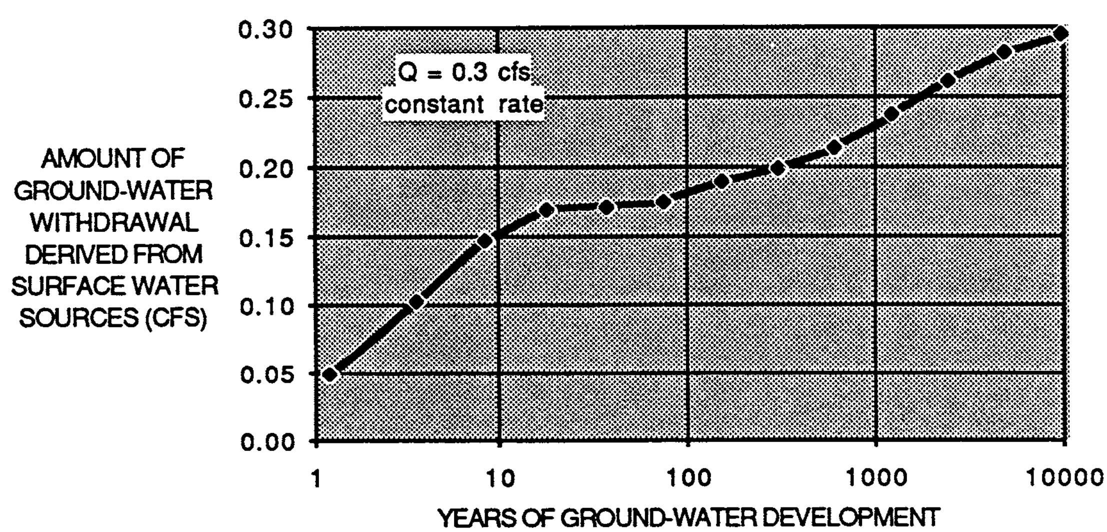


FIGURE 10B - ARTESIAN BASIN AQUIFER SYSTEM TRANSITION FROM RELIANCE ON AQUIFER STORAGE TO SURFACE-WATER DEPLETION

TABLE 3

Duration of Sources of Water from Storage
and From Induced Recharge
in Five Example Aquifer Systems

Aquifer System	Duration of Storage Phase[a]	Time of Induced Recharge Phase
Large Perennial Stream	9 hours	4 years
Ephemeral Stream	310 days	375 years
Desert Basin	41 years	4,700 years
So. High Plains	33 years	2,900 years
Artesian Basin	1 year	9,400 years

(a) The storage phase is defined as the period when >98 percent of withdrawals are derived from aquifer storage. The induced recharge phase is the period when <2 percent of withdrawals are derived from aquifer storage.

strategy should be thoroughly examined for its physical and economic effects through the years. Both arid and humid regions may require this type of information before the effects of a water plan are fully understood.

Validity of Hydrologic Models

Hydrologists participate in the western water rights system to provide the hydrologic models needed by the fact-finders and the parties in each case. Cases are known in which alternative models by professional hydrologists have predicted results not merely different in the size of effects from a proposed withdrawal of water, but different in direction, i.e., a consumptive use that increases the water supply instead of depleting the net supply (Faust and others, 1984). Hydrologists are admitted to the process as expert witnesses to serve the court or the administrator's need for sound information, and are required to advise upon which outcome applies and to what degree before the administrative system can be effective.

The conflicts in prediction of hydrological effects arise both from disputed understanding of hydrologic parameters and boundaries (Corps of Engineers, 1984; Williams, 1986) and from the assumptions behind the stresses simulated by the models (Konikow, 1986). For example, simulating an historically empty right as though it were a fully exercised one results in greatly different predicted effects on the hydrologic system. In all cases, the diversion scenario and the timing of ground water effects is important. No single point on the transition curves presented herein represents the entire period of interest for water rights purposes. The hydrologist must make explicit the history of diversions and the planning period for future diversions. Hydrogeological information based on accurate models of actual conditions is required for administration of the priority system in general.

CONCLUSION

Water rights administration is concerned with ensuring that the property interests of prior appropriators are protected when supplies are short, and has the parallel goal of expediting the transfer of water to higher economic purposes. The newer, more economically and socially productive purposes of use, such as municipal, industrial, power generation, recreation, etc., commonly bid against the historical use of irrigated agriculture for a limited water supply. During administrative review of this competitive process, hydrologists are asked to explain the factual basis underlying the effects of proposed new uses or changes in use. The proper outcome of the process is a flow of water to the more socially beneficial uses, and a counterbalancing flow of value to the displaced prior users. The exchange is brought about correctly through a marketplace transaction. Adjudication of the priority and amount of water right ownership helps to establish marketable title to water and to facilitate water rights administration.

The system of prior appropriation is fully compatible with the hydrogeologic view of regional ground-water and surface water systems. The variability of surface water supply is reflected both by the flow-duration curve and by the ladder of priority.

Ground-water appropriations consist of water from two sources: ground-water storage and induced recharge from surface water. Natural recharge does not enter the water account for artificial ground-water diversions. The duration of flows serving surface water claims is changed by ground-water development. The total basin yield is expanded by ground water development until baseflow is eventually depleted to restore hydrologic balance. In the process, benefits are generally shifted from senior (surface water) to junior (ground-water) users. The consequent induced depletion of surface water must be correctly appraised to compensate those with prior rights. Basin-wide three-dimensional hydrogeologic models developed since 1980 are adequate for this purpose. The development of five example aquifer systems has been simulated herein to illustrate the rates of surface depletion to be expected. The full effects of aquifer development may require decades or thousands of years to approach equilibrium.

The prior appropriation system serves to protect existing property interests while expediting transfer of water to socially beneficial ends. Basin adjudication, objective standards of evaluation, and accurate hydrologic models are needed to provide predictable and equitable outcomes of water rights issues.

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William P. Balleau is a graduate of the University of New Mexico (B.A. Geology, 1968) and has worked as a ground-water geologist in Kenya, through the US Peace Corps, in Australia for the West Australian Geological Survey, and as a consultant based in Connecticut before returning to New Mexico. From 1978 to 1985, he was the Bureau of Indian Affairs hydrologist in Albuquerque involved in projecting the effects of ground-water developments in basin-wide adjudications of water rights. He has been an associate of the consulting firm of Leggette, Brashears & Graham, Inc. and manager of the southwestern regional office since 1985. This paper is a product of his interest in integrating water policy with hydrologic analysis.

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