Management of Groundwater

CHAPTER 9

Maximum development of groundwater resources for beneficial use involves planning in terms of an entire groundwater basin. Recognizing that a basin is a large natural underground reservoir, it follows that utilization of groundwater by one landowner affects the water supply of all other landowners. Management objectives must be selected in order to develop and operate the basin. These involve not only geologic and hydrologic considerations but also economic, legal, political, and financial aspects. Typically, optimum economic development of water resources in an area requires an integrated approach that coordinates the use of both surface water and groundwater resources. After evaluation of total water resources and preparation of alternative management plans, action decisions can then be made by appropriate public bodies or agencies.

Concepts of Basin Management

The management of a groundwater basin implies a program of development and utilization of subsurface water for some stated purpose, usually of a social or economic nature.[9] In general, the desired goal is to obtain the maximum quantity of water to meet predetermined quality requirements at least cost.* Because a groundwater basin can be visualized as a large natural underground reservoir, it follows that extraction of water by wells at one location influences the quantity of water available at other locations within the basin.

Groundwater is extracted from the ground just as are other minerals such as oil, gas, or gold. Water typically carries a special constraint: it is regarded as a renewable natural resource. Thus, when a water well is drilled, people presume that production of water will continue indefinitely with time. In effect, this can only occur if there exists a balance between water recharged to the basin from surface sources and water pumped from within the basin by wells.

Development of water supplies from groundwater begins typically with a few pumping wells scattered over a basin. With time more wells are drilled and the rate of extraction increases. As wells become more numerous, development of the basin reaches and exceeds its natural recharge capability. Continued development thereafter without a management plan could eventually deplete the groundwater resource.

By regulating inflow to and outflow from the basin, an underground reservoir can be made to function beneficially and indefinitely just as a surface water reservoir.[3,14] The increasing demand for water in the United States and throughout the world has produced the realization that the vast underground reservoirs formed by aquifers constitute invaluable water storage facilities; proper management of them, therefore, has become a matter of considerable interest.[1,8,50] Some of the pros and cons of subsurface and surface reservoirs are summarized in Table 9.1.

Forecasts of future water demand suggest that mismanagement—or lack of management—of major groundwater basins cannot be permitted if adequate ongoing water supplies are to be provided. The management objective consists of providing an economic and continuous water supply to meet a usually growing demand from an underground water resource of which only a small portion is perennially renewable.

Equation of Hydrologic Equilibrium

To manage a groundwater basin, knowledge of the quantity of water that can be developed is a prerequisite. Determination of the available water within a basin requires evaluation of the elements

*As Bear and Levin[4] succinctly stated: "The basic idea is to regard the aquifer as a system which has to be operated in an optimal manner."

TABLE 9.1 Advantages and Disadvantages of Subsurface and Surface Reservoirs (after U.S. Bureau of Reclamation[51])

Subsurface Reservoirs	Surface Reservoirs
Advantages	Disadvantages
1. Many large-capacity sites available	1. Few new sites available
2. Slight to no evaporation loss	2. High evaporation loss even in humid climate
3. Require little land area	3. Require large land area
4. Slight to no danger of catastrophic structural failure	4. Ever-present danger of catastrophic failure
5. Uniform water temperature	5. Fluctuating water temperature
6. High biological purity	6. Easily contaminated
7. Safe from immediate radioactive fallout	7. Easily contaminated by radioactive material
8. Serve as conveyance systems—canals or pipeline across lands of others unnecessary	8. Water must be conveyed
Disadvantages	Advantages
1. Water must be pumped	1. Water may be available by gravity flow
2. Storage and conveyance use only	2. Multiple use
3. Water may be mineralized	3. Water generally of relatively low mineral content
4. Minor flood control value	4. Maximum flood control value
5. Limited flow at any point	5. Large flows
6. Power head usually not available	6. Power head available
7. Difficult and costly to investigate, evaluate, and manage	7. Relatively easy to evaluate, investigate, and manage
8. Recharge opportunity usually dependent on surplus surface flows	8. Recharge dependent on annual precipitation
9. Recharge water may require expensive treatment	9. No treatment required of recharge water
10. Continuous expensive maintenance of recharge areas or wells	10. Little maintenance required of facilities

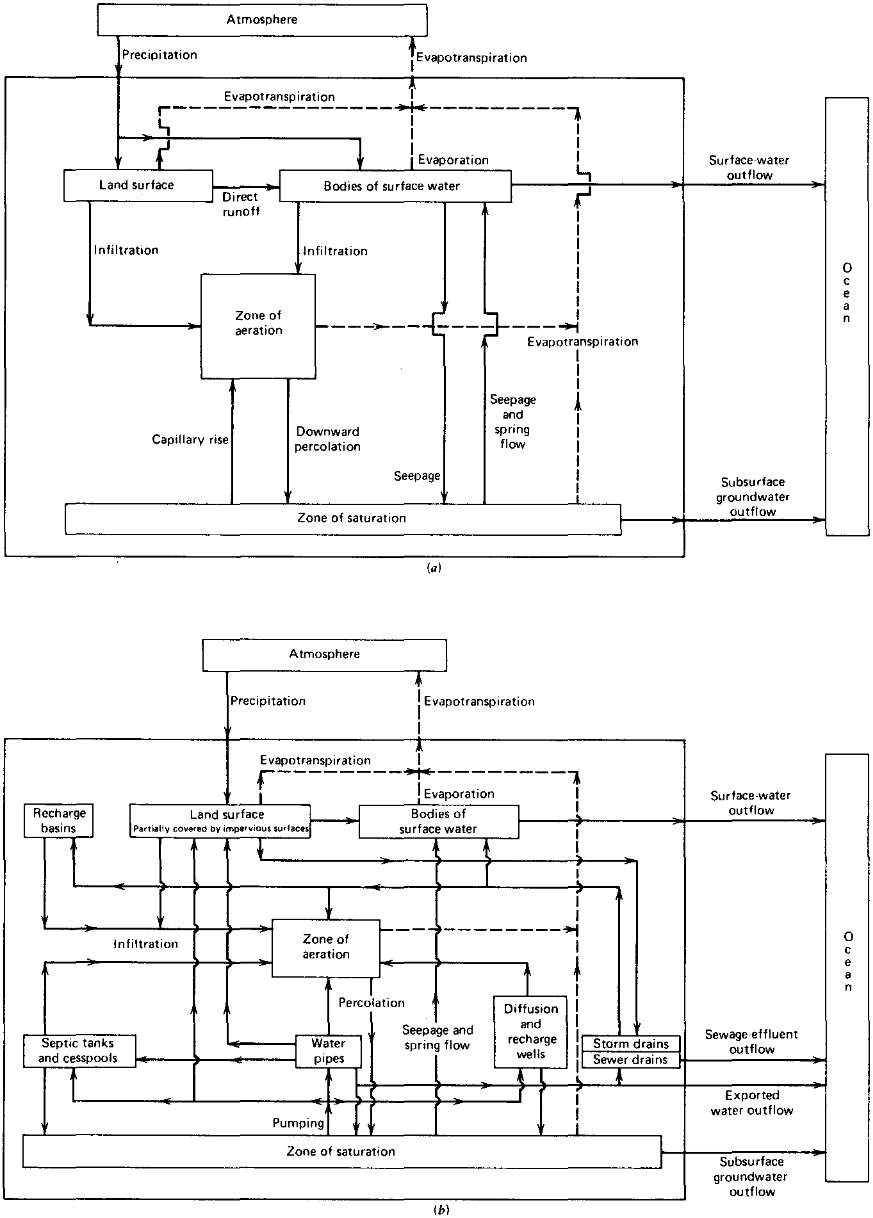

Fig. 9.1 Flow diagram of a hydrologic system. (*a*) Natural conditions. (*b*) Urban and suburban development. Solid lines represent flow of liquid water; dashed lines represent movement of water vapor (after Franke and McClymonds[20]).

constituting the hydrologic cycle. A flow diagram of the hydrologic system for a basin under natural conditions is shown in Fig. 9.1*a*, while the more complex system for a basin containing urban and suburban development is depicted in Fig. 9.1*b*.

In terms of the hydrologic cycle for a particular groundwater basin, a balance must exist between the quantity of water supplied to the basin and the amount leaving the basin. The equation of hydrologic equilibrium provides a quantitative statement of this balance. In its most general form it may be expressed as in Eq. 9.1.

$$\begin{bmatrix}\text{surface inflow + subsurface inflow + precipitation} \\ \text{+ imported water + decrease in surface storage} \\ \text{+ decrease in groundwater storage}\end{bmatrix} = \begin{bmatrix}\text{surface outflow + subsurface outflow + consumptive use} \\ \text{+ exported water + increase in surface storage} \\ \text{+ increase in groundwater storage}\end{bmatrix} \tag{9.1}$$

In this form the equation includes all waters—surface and subsurface—entering and leaving a basin. There are many situations in which it is possible to eliminate certain items from the equation because they are negligible or because they do not affect the solution. For example, a confined aquifer may have a hydrologic equilibrium independent of overlying surface waters; therefore, items of surface flow, precipitation, consumptive use, imported and exported water, and changes in surface storage can be omitted from the equation.

Each item of the equation represents a discharge, a volume of water per unit of time. Any consistent units of volume and time can be adopted. The water year, extending from October 1 to September 30, is preferable to the calendar year. The equation can be applied to areas of any size, although for meaningful results a hydrologic entity, such as an aquifer, a groundwater basin, or a river valley, is best.

The equation of hydrologic equilibrium in theory must balance. In practice, if all items can be evaluated, it will rarely balance exactly. This may be attributed to inaccuracies of measurements, lack of adequate basic data, or incorrect approximations. The amount of unbalance should not exceed the limits of accuracy of the basic data. In order to achieve a balance, adjustments should be made in items subject to large error. If the unbalance exceeds the limits of accuracy of the basic data, further investigation is necessary. Application of the equation requires good judgment, adequate hydrologic data, and careful analysis of the geology and hydrology of the particular area.

With the equation the quantity of water available from a groundwater basin can be determined under existing conditions as well as under any specified future conditions. Also, any one unknown item can be determined if all others are known. This last application can be misleading, however, for inaccuracies in one or more of the known quantities may exceed the magnitude of the unknown quantity.

Groundwater Basin Investigations

Ideally, before groundwater is developed in a basin, an investigation of the underground water resources should be made. In practice this rarely occurs; instead, a study is usually initiated either after extensive development with a view toward further development or after overdevelopment when a problem threatening the water supply appears imminent. Investigations are seldom concerned with simply locating groundwater supplies. More commonly the concerns involve evaluating the quantity and quality of groundwater resources already known to exist or determining the impact of human plans or activities on the quantity and quality of groundwater. Figure 9.2 illustrates the sequence of activities preceding the start of a groundwater management investigation.

Groundwater management studies are usually undertaken by local government agencies. Four levels of study are generally recognized, although not all are required.[2] In brief these include:

1. *Preliminary Examination*—Based largely on judgment by experienced personnel, this study identifies the management possibilities of meeting a defined need for a specified area.

2. *Reconnaissance*—This study considers possible alternatives in the formulation of a water management plan to meet a defined need for an area, including estimates of benefits and costs. The investigation draws on available data and generally necessitates a minimum of new data collection.

3. *Feasibility*—This study requires detailed engineering, hydrogeologic, and economic analyses together with cost and benefit estimates to ensure that the selected project is an optimum development. The sequence of activities normally involved in a feasibility investigation is outlined in Fig. 9.3. Typically, the investigation concludes with a report recommending approval and funding for the project.

4. *Definite Project*—This investigation involves planning studies necessary for defining specific features of the selected project. The completed report forms the basis for starting final design and preparation of plans and specifications.

The following section briefly outlines the types of data and the tasks involved in the physical portion of a reconnaissance or feasibility study for groundwater management.

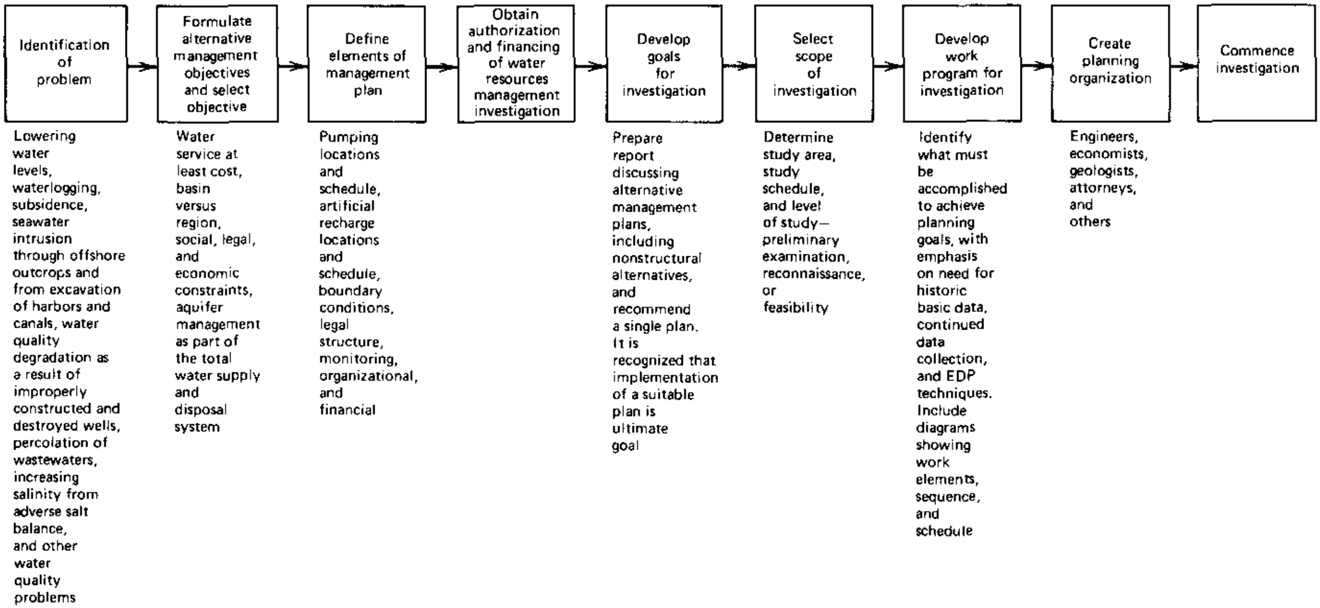

Fig. 9.2 Sequence of activities preceding start of a groundwater management investigation (after Amer. Soc. Civil Engrs.[2]).

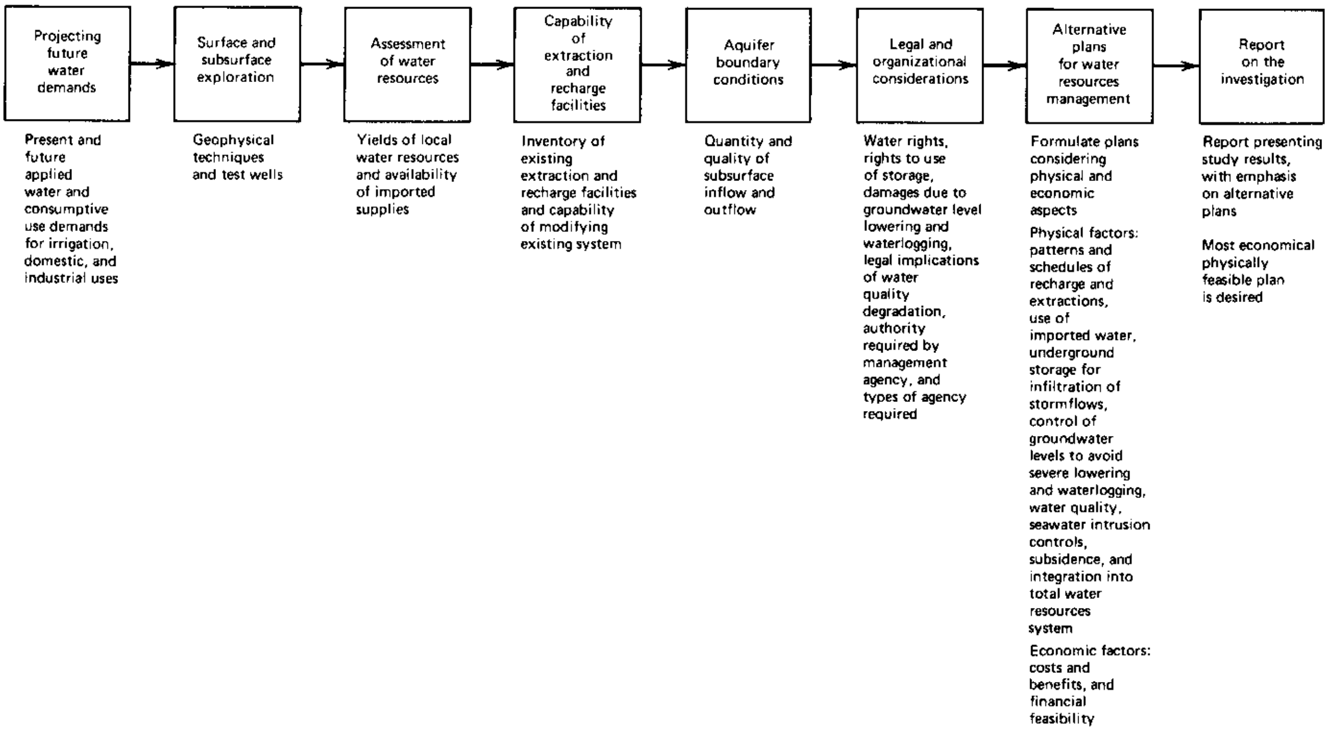

Fig. 9.3 Sequence of activities during a feasibility investigation for groundwater management (after Amer. Soc. Civil Engrs.[2]).

Data Collection and Fieldwork

Topographic Data. Contour maps, aerial photographs, and benchmarks related to a leveling network are basic requirements. They are directly applicable for locating and identifying wells, measuring groundwater levels, conducting crop and land use surveys, and plotting areal data.

Geologic Data. Surface and subsurface geologic mapping provides the framework for the occurrence and movement of groundwater and hence is essential for feasibility studies. Subsurface information is gained from a drilling program, including classification and analysis of well logs, and geophysical surveys (see Chapter 12). As part of the drilling program, pumping tests of wells are conducted to evaluate storage coefficients and transmissivities of aquifers, while samples of groundwater are collected and analyzed for quality. From interpretation of subsurface geologic data, principal aquifers and their extent are mapped together with regions of confined and unconfined groundwater. Location of faults, dikes, and other structures that may significantly affect groundwater is also a part of the geologic program.

Hydrologic Data. The principle purpose of hydrologic data collection is to evaluate the equation of hydrologic equilibrium. The following outline summarizes types of basic data required and methods of their analysis.

Surface Inflow and Outflow; Imported and Exported Water. These quantities are measurable by standard hydrographic and hydraulic procedures. Where complete data on surface flows to and from the basin are not available, supplemental stream gaging stations should be installed.

Precipitation. Records of precipitation in the area should be assembled. Gages should be well distributed over the basin to provide a good estimate of the annual precipitation from the isohyetal or Thiessen methods.* If gages are not so located, supplemental stations should be established.

Consumptive Use. All water, surface and subsurface, released into the atmosphere by processes of evaporation and transpiration is consumptive use, or evapotranspiration. To compute this discharge from a given basin, it is first necessary to make a land use, or cultural, survey to yield the amount of each type of water-consuming area. Aerial photographs are helpful for this task. Unit values of consumptive use must then be determined. For crops and native vegetation, methods based on available heat (such as the

*See, for example: R. K. Linsley, et al., *Hydrology for Engineers,* 2nd ed., McGraw-Hill, New York, 482 pp., 1975.

Thornthwaite or Blaney-Criddle method) are generally satisfactory. For water surfaces local evaporation records should be employed. Urban and industrial areas require careful estimates from samples of representative areas using metered deliveries and sewage outflows. Multiplying the unit value of consumptive use by the corresponding acreage gives the water consumption for each area; the sum of these products yields the total consumptive use over the basin.

Changes in Surface Storage. These can be computed directly from changes in water levels of surface reservoirs and lakes.

Changes in Soil Moisture. The moisture content of the soil can be measured by devices embedded in the soil or by a neutron probe (see Chapter 2). In practice, however, the variability of soil moisture both in time and place makes it difficult to obtain an accurate basin-wide measurement. The problem can be minimized by selecting periods of storage change in which the amount of water in unsaturated storage at the beginning and end of the period is nearly equal. In irrigated areas period limits should correspond to the beginning or ending of the irrigation season.

Changes in Groundwater Storage. From geologic data on aquifers and measurement of groundwater levels, changes in groundwater storage can be determined. Antecedent information on groundwater levels, pumping records, pumping tests, and artificial recharge should be collected. Specific yields of unconfined aquifers are determined by laboratory tests of samples and/or by classifications of well logs; storage coefficients are best determined from pumping tests of wells.

Select a grid of measuring wells distributed over the basin. Supplement with test holes where required. Water levels in these wells should be measured under conditions as nearly static as possible, preferably after the season of heavy draft and again after the season of recharge. A few control wells should be equipped with automatic water-level recorders or have their water levels measured monthly to facilitate detailed study of groundwater fluctuations. A basin map showing lines of equal change in groundwater level is then prepared. The product of change in water level times storage coefficient times area gives the change of groundwater storage for each aquifer within the basin.

Subsurface Inflow and Outflow. These items of the equation are the most difficult to evaluate because they cannot be directly measured. Often one of them, or the difference, is fixed by being the only unknown in the equation. From geologic investigation it may be found that either subsurface inflow or outflow is lacking, or both. Many times after study, subsurface inflow may be estimated to equal that of subsurface outflow so that the items cancel.

Difficulties arise in situations where underground flows from one basin to another occur. The direction of flow can be established from water table or piezometric gradients. Knowing groundwater slopes and transmissivities, subsurface flows can be computed from Darcy's law. Where surface streams and subsurface drainage systems control groundwater levels, better estimates of subsurface flow are usually possible because more data are available.

Alternative Basin Yields

The maximum quantity of water that is actually available from a groundwater basin on a perennial basis is limited by the possible deleterious side effects that can be caused by pumping and by the operation of the basin. As a result, several concepts of basin yield are generally recognized.[2] These are briefly defined in the following subsections together with comments as to their consequences.

Mining Yield. If groundwater is withdrawn at a rate exceeding the recharge, a *mining yield* exists.[17] As a consequence, this yield must be limited in time until the aquifer storage is depleted. Many groundwater basins today are being mined; if mining continues, the local economy served by this pumping may change, evolving into other forms that use less water or involve importations of water into the basin. The Salt River Valley of southern Arizona and the High Plains of western Texas are classic examples of such situations.

Various valid arguments, economic and other, have been advanced to justify mining of groundwater. One is that water in storage is of no value unless it is used.[46] In arid areas, such as the Sahara Desert, where groundwater represents the only available water resource, almost any development of groundwater constitutes a mining yield. But the needs are there and the benefits are great so that such exploitation will continue. With proper management plus water conservation, such groundwater resources can be made to last from several decades to a few centuries.

Perennial Yield. The *perennial yield* of a groundwater basin defines the rate at which water can be withdrawn perennially under specified operating conditions without producing an undesired result.* An undesired result is an adverse situation such as (1) progressive reduction of the water resource, (2) development of uneconomic pumping conditions, (3) degradation of groundwater quality,

*In the past the term *safe yield*, implying a fixed quantity of extractable water basically limited to the average annual basin recharge, has been widely used. The term has now fallen into disfavor because a never-changing quantity of available water depending solely on natural water sources and a specified configuration of wells is essentially meaningless from a hydrologic standpoint.

(4) interference with prior water rights, or (5) land subsidence caused by lowered groundwater levels.[29,30,54] Evaluation of perennial yield is discussed in a subsequent section. Any draft in excess of perennial yield is referred to as *overdraft*. Existence of overdraft implies that continuation of present water management practices will result in significant negative impacts on environmental, social, or economic conditions.

A schematic diagram of a groundwater basin developed to less than perennial yield is shown in Fig. 9.4*a*. Here a portion of the natural recharge is lost by subsurface outflow from the basin. But Fig. 9.4*b* suggests a minimum perennial yield situation in which extractions balance recharge so that no groundwater is lost.

Deferred Perennial Yield. The concept of a deferred perennial yield consists of two different pumping rates. The initial rate is larger and exceeds the perennial yield, thereby reducing the groundwater level. This planned overdraft furnishes water from storage at low cost and without creating any undesirable effects. In fact, reducing storage eliminates wasteful subsurface outflow of groundwater and losses to the atmosphere by evapotranspiration from high water table areas. After the groundwater level has been lowered to a predetermined depth, a second rate, comparable to that of perennial yield, is established so that a balance of water entering and leaving the basin is maintained thereafter. With a larger available storage volume, more water can be recharged and a larger perennial yield can be obtained. Figure 9.4*c* indicates this situation schematically.

Maximum Perennial Yield. The *maximum perennial yield*, as the name suggests, means the maximum quantity of groundwater perennially available if all possible methods and sources are developed for recharging the basin. In effect, this quantity depends on the amount of water economically, legally, and politically available to the organization or agency managing the basin. Clearly, the more water that can be recharged both naturally and artificially to a basin, the greater the yield.

To achieve the maximum perennial yield the aquifer should be managed as a unit. Thus, efficient and economic production of water requires that all pumping, importations, and distributions of water be done for the benefit of the largest manageable system. Where surface water is available in addition to groundwater, these two sources are operated conjunctively. Such a conjunctive use scheme provides a larger and more economic yield of water than can be obtained

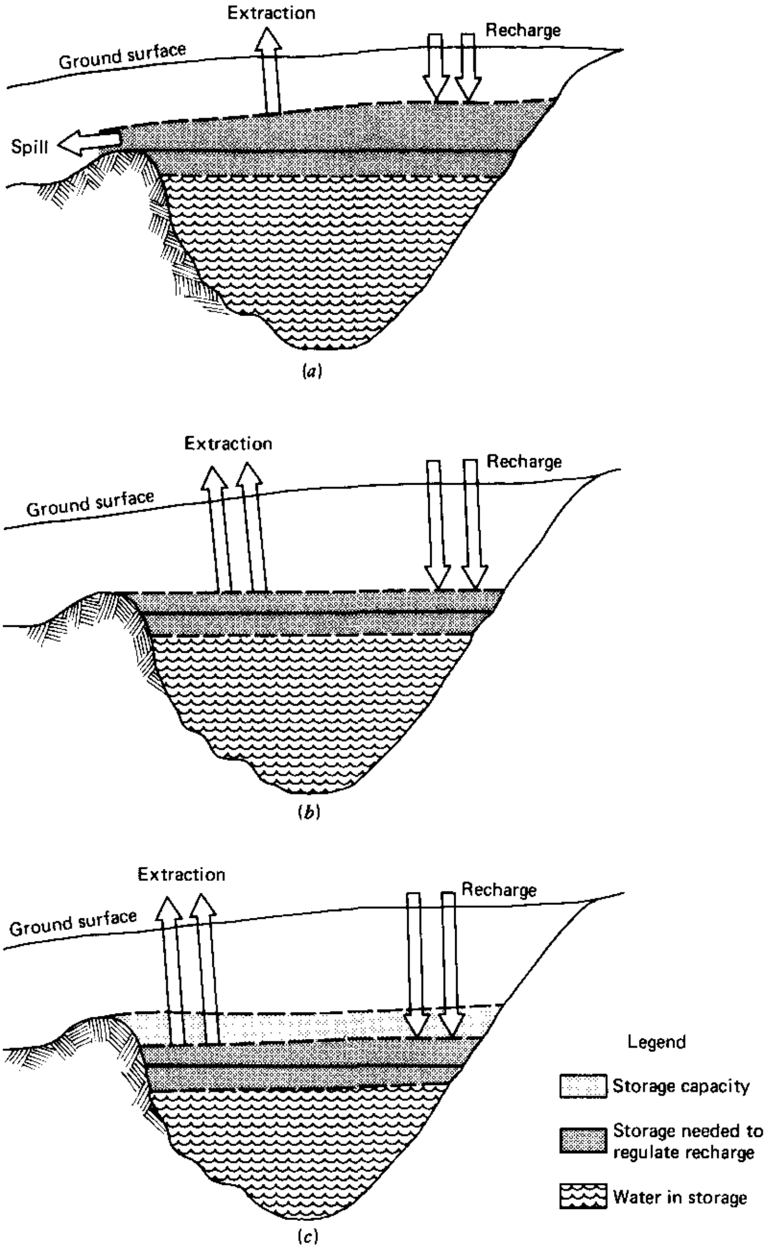

Fig. 9.4 Schematic diagram showing storage relations in a groundwater basin for three stages of development. (*a*) Less than perennial yield. (*b*) Minimum perennial yield. (*c*) Increased perennial yield (after Peters[39]).

from the two sources operated independently. The limit to such an operation is governed by the ability to import and distribute water and also by the storage available for surface water and groundwater.

Evaluation of Perennial Yield

Consideration of the above definitions of perennial yield reveals that there can be more than one "undesired result" from pumping a groundwater basin, that perennial yield may be limited to an amount less than the net amount of water supplied to the basin, and that perennial yield can vary with different patterns of recharge, development, and use of water in a basin.

If groundwater is regarded as a renewable natural resource, then only a certain quantity of water may be withdrawn annually from a groundwater basin. The maximum quantity of water that can be extracted from an underground reservoir, and still maintain that supply unimpaired, depends on the perennial yield. Overdraft areas constitute the largest potential groundwater problem in the United States.[49] Until overdrafts are reduced to perennial yields in these basins, permanent damage or depletion of groundwater supplies must be anticipated.

Factors Governing Perennial Yield. Determination of the perennial yield of a groundwater basin requires analysis of the undesired results that may accrue if the extraction rate is exceeded. The recharge* criterion (progressive reduction of the water resource) is the most important because exceeding this factor is normally responsible for introducing other undesired results. Water supplied to a basin may be limited either by the storage volume of the underground basin or by the rate of water movement through the basin from the recharge area to the withdrawal area. The quantity concept is usually applicable to unconfined aquifers where supply and disposal areas are near, whereas the rate concept applies more to confined aquifers where supply and disposal areas are widely separated.

Economic considerations can govern perennial yield in basins where the cost of pumping groundwater becomes excessive. Excessive costs may be associated with lowered groundwater levels, necessitating deepening wells, lowering pump bowls, and installing larger pumps. Where pumpage is largely for irrigation, power costs, crop prices, or government farm subsidies may establish an eco-

*Recharge here refers to water reaching the saturated zone of an aquifer, where it is available for extraction.

nomic limit for pumping groundwater; alternatively, other uses that can support higher pumping costs may evolve.

Water quality can govern perennial yield if draft on a basin produces groundwater of inferior quality. Possibilities include: (1) pumping in a coastal aquifer could induce seawater intrusion into the basin (see Chapter 14); (2) lowered groundwater levels could lead to pumping of underlying connate brines; (3) polluted water from nearby areas might be drawn into a pumped aquifer. A quality limitation on perennial yield depends on the minimum acceptable standard of water quality, which in turn depends on the use made of the pumped water. Therefore, by lowering the quality requirement, the perennial yield can be increased.

Legal considerations affect perennial yield if pumpage interferes with prior water rights.[32] Finally, if pumpage is responsible for land subsidence, a limitation on perennial yield can result.

Calculation of Perennial Yield. In general, the basin recharge criterion will govern perennial yield because, as mentioned earlier, one or more of the other undesired results will often be induced by pumpage exceeding this rate. Quantitative determination of perennial yield where recharge is the limiting factor can be made under specified conditions if adequate knowledge of the hydrology of the basin is available. Methods are based on the equation of hydrologic equilibrium or approximations thereto.[31] Basically, this implies that perennial yield is defined in terms of a rate at which groundwater can be withdrawn from a basin over a representative time period without producing a significant change in groundwater storage.

Variability of Perennial Yield. It is important to recognize that perennial yield of a groundwater basin tends to vary with time. Any quantitative determination is based on specified conditions, either existing or assumed, and any changes in these conditions will modify the perennial yield. This fact applies to the degree and pattern of groundwater development within a basin as well as to the other factors that govern safe yield.

Investigations of the availability of groundwater within a basin are typically not initiated until basin development has produced an overdraft. Yet this is almost necessary in order to obtain a reasonable estimate for perennial yield. In a virgin basin, where a balance exists between natural inflow and outflow and there is no pumping, the absence of hydrogeologic data may not justify the cost of a management investigation. Similarly, estimating future perennial yield of a basin under greater development than at present requires careful evaluation of all items in the equation of hydrologic equilibrium.

Perennial yield may vary with the level of groundwater within a basin. Thus, if levels are lowered, subsurface inflow will be increased and subsurface outflow will be decreased, recharge from losing streams will be increased and discharge from gaining streams will be decreased, and uneconomic evapotranspiration losses will be reduced. Conversely, a rise in water levels will have the opposite effects. Therefore, where recharge is sufficient, the greater the utilization of underground water, the larger the perennial yield. The maximum perennial yield will be controlled by economic or legal constraints.

An unconfined basin fed by an adequate recharge source can increase its perennial yield, not only by increasing pumpage but also by rearrangement of the pumping pattern. If the concentration of wells is shifted to near the recharge source, greater inflow can be induced. The rearrangement has the additional advantage that a greater supply may be obtained without necessarily increasing pumping lifts. For example, in the cross section shown in Fig. 9.5*a*, it is assumed that the stream is the principal recharge source. By moving the well field nearer to the stream as in Fig. 9.5*b*, the water

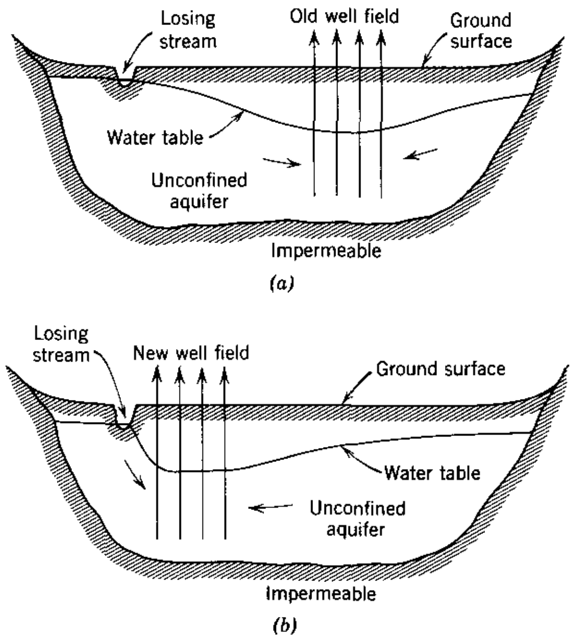

Fig. 9.5 Example of increased groundwater yield for same pumping depths obtained by shifting wells nearer to a recharge source.

table slope is increased and a greater yield for equal pumping depths results.

For a confined aquifer with its recharge area located some distance from the pumping area, the rate of flow through the aquifer will govern the perennial yield. In large confined aquifers, pumpage of water from storage can be carried on for many years without establishing an equilibrium with basin recharge. Although the slope of the piezometric surface will increase, the permeability of the aquifer is seldom sufficient to maintain a compensating flow into the basin.[49]

Besides operational changes perennial yield can also vary due to gradual and subtle modifications occurring within a basin. Changes in vegetation and even in crops, particularly where root depth is affected, may influence surface infiltration and subsequent percolation to the water table. Urbanization of an area, accompanied by greater surface runoff and installation of sewer systems, can be expected to reduce recharge. Changes in the purpose of pumping groundwater, such as from irrigation to municipal or industrial use, may—from an economic viewpoint—permit greater pumping lifts; consequently, perennial yield can be increased. Other economic factors include, among others, changes in value of irrigated crops, increased efficiency of new wells and pumps, treatment to meet revised water quality standards, and power costs.

Salt Balance

Maintenance of a usable groundwater basin requires that the salinity of the groundwater not increase with time to a point where it destroys the value of the resource. A dynamic balance of total salts entering and leaving a basin is desired, so that on a long-term basin

$$\sum_n (CQ)_i = 0 \tag{9.2}$$

where $(CQ)_i$ is the salt concentration times the discharge of one of n flow components to or from the basin. In practice this condition seldom exists because most uses of water add dissolved solids to water, which is subsequently recharged to groundwater.

Salt may be added to groundwater by solution of aquifer materials, from rainfall and surface and subsurface inflows, and in special circumstances from connate brines and seawater. Evapotranspiration removes water, leaving higher salt concentrations behind. Domestic and industrial uses of water add salts, as do fertilizers, soil conditioners, pesticides, and other chemicals in agricultural areas. Salts leave a groundwater basin by natural outflow, drainage, and pumped extractions.[11]

The salt problem becomes most important for irrigated land in arid and semiarid regions.[23,37] If a high water table persists with inadequate drainage, evapotranspiration of irrigation water and groundwater gradually increases the salt content of the soil, leading to destruction of the land for agricultural purposes. The solution depends on local conditions, but, in general, the requirements are that the water table be lowered, that soil salinity be reduced by leaching, and that a drainage system to transport saline water out of the basin be constructed.

It should be recognized that excellent groundwater can be found in a basin with an adverse salt balance, and vice versa. Groundwater is rarely uniformly mixed. Typically, good- and poor-quality groundwaters are segregated both horizontally and vertically within a basin. Thus, an unfavorable salt balance poses a serious long-term threat but seldom concerns the current usability of groundwater.

An illustration of salt balance for a semiarid region in the Central Valley of California is shown in Table 9.2. Under 1970 conditions it can be seen that input of salt exceeds output by 1629 tons. During the decade 1970–1980 an increased volume of imported water entered the basin, newly irrigated lands were leached, and a drainage system was started. The effect of these changes by 1980 is a projected

TABLE 9.2 Calculated and Projected Salt Balances for the Tulare Lake Basin, California (after Schmidt[47]) (values in 1000 tons)

Item	1970	1980
Input		
Precipitation	23	25
Streamflow	357	357
Imported water	326	846
Soil amendments	476	543
Fertilizers	176	190
Animal waste	51	55
Leaching new lands	0	771
Municipal wastewater	38	44
Urban runoff	7	8
Industrial waste	28	30
Oil field waste	182	5
Subtotal	1664	2874
Output		
Streamflow and groundwater	35	102
Subsurface drainage export	0	545
Subtotal	35	647
Net accretion	1629	2227

net input of 2227 tons of salt, representing an increase of 73 percent in salt accumulation. Assuming this salt is mixed within the principal aquifers, the salinity of the groundwater will increase 1 to 4 mg/l per year in the eastern zone of higher precipitation and 10 to 30 mg/l per year in the arid western zone.

Basin Management by Conjunctive Use

In basins approaching full development of water resources, optimal benefical use can be obtained by *conjunctive use,* which involves the coordinated and planned operation of both surface water and groundwater resources to meet water requirements in a manner whereby water is conserved.* The basic difference between the usual surface water development with its associated groundwater development and a conjunctive operation of surface water and groundwater resources is that the separate firm yields of the former can be replaced by the larger and more economic joint yields of the latter.

The concept of conjunctive use of surface water and groundwater is predicated on surface reservoirs impounding streamflow, which is then transferred at an optimum rate to groundwater storage. Surface storage in reservoirs behind dams supplies most annual water requirements, while the groundwater storage can be retained primarily for cyclic storage to cover years of subnormal precipitation. Thus, groundwater levels would fluctuate, being lowered during a cycle of dry years and being raised during an ensuing wet period. Figure 9.6 depicts how groundwater levels might vary under such a system of conjunctive use.

During periods of above-normal precipitation, surface water is utilized to the maximum extent possible and also artificially recharged into the ground to augment groundwater storage and raise groundwater levels (see Chapter 13). Conversely, during drought periods limited surface water resources are supplemented by pumping groundwater, thereby lowering groundwater levels. The feasibility of the conjunctive-use approach depends on operating a groundwater basin over a range of water levels; that is, there must be space to store recharged water, and, in addition, there must be water in storage for pumping when needed.

Management by conjunctive use requires physical facilities for water distribution, for artificial recharge, and for pumping. The procedure does require careful planning to optimize use of avail-

*Coordinated use of surface water and groundwater does not preclude importing water, as required, to meet growing needs. In fact, to store and distribute additional water economically may require more intensive use of groundwater storage space.

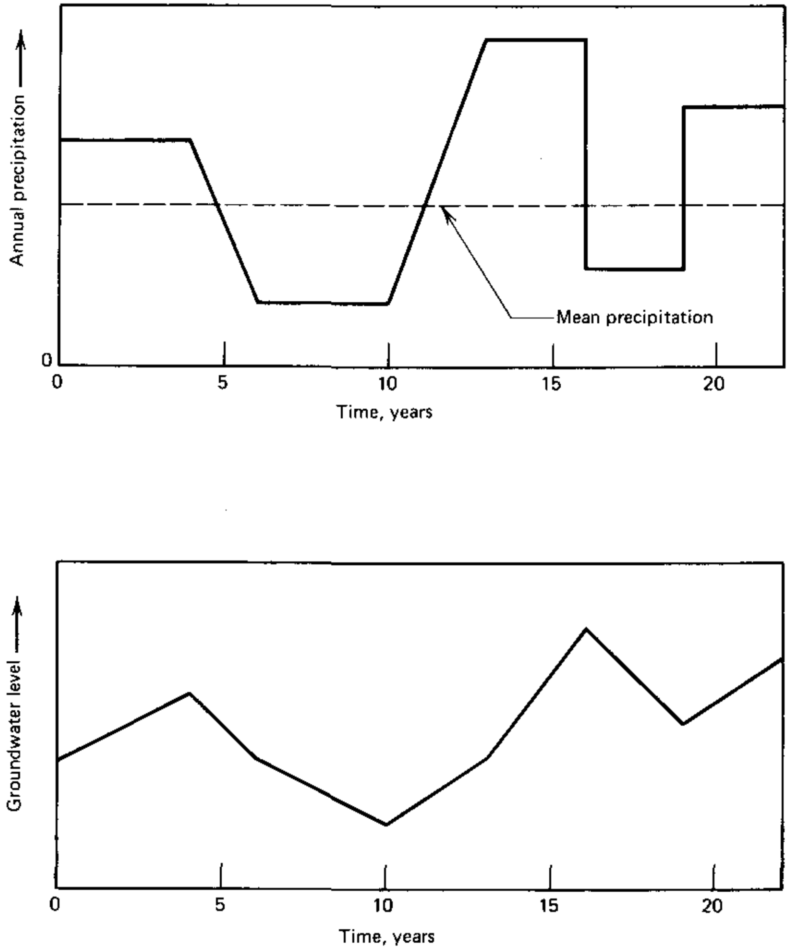

Fig. 9.6 Illustrative example of variation in groundwater levels in relation to annual precipitation under conjunctive use management.

able surface-water and groundwater resources. Such operations can be complex and highly technical; they require competent personnel, detailed knowledge of the hydrogeology of the basin, records of pumping and recharge rates, and continually updated information on groundwater levels and quality. A schematic diagram of a systematic approach for a conjunctive use analysis is illustrated in Fig. 9.7.

A conjunctive use management study requires data on surface water resources, groundwater resources, and geologic conditions;

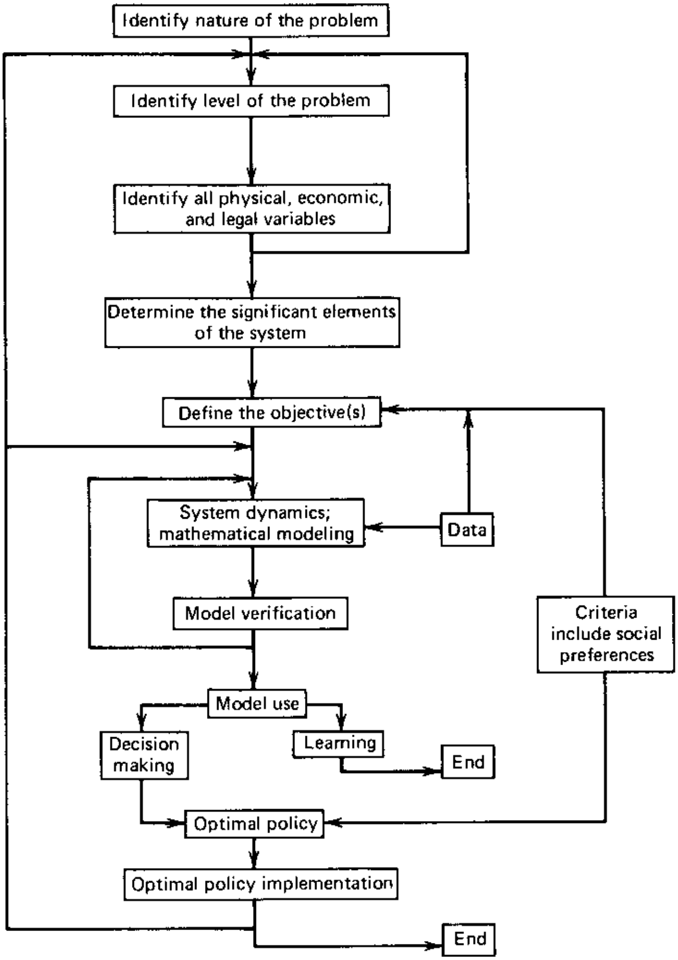

Fig. 9.7 Schematic diagram of a systematic approach for studying conjunctive use problems (after Maknoon and Burges[27]; reprinted from *Journal American Water Works Association*, Vol. 70, by permission of the Association; copyright © 1978 by American Water Works Association, 6666 West Quincy Avenue, Denver, Col. 80235).

data on water distribution systems, water use, and wastewater disposal are also necessary.[24,41] Figure 9.8 shows a simplified flowchart of the various phases and steps involved for a basin management study in California. This suggests the diversity of data and effort required in order to determine an optimal basin management plan.

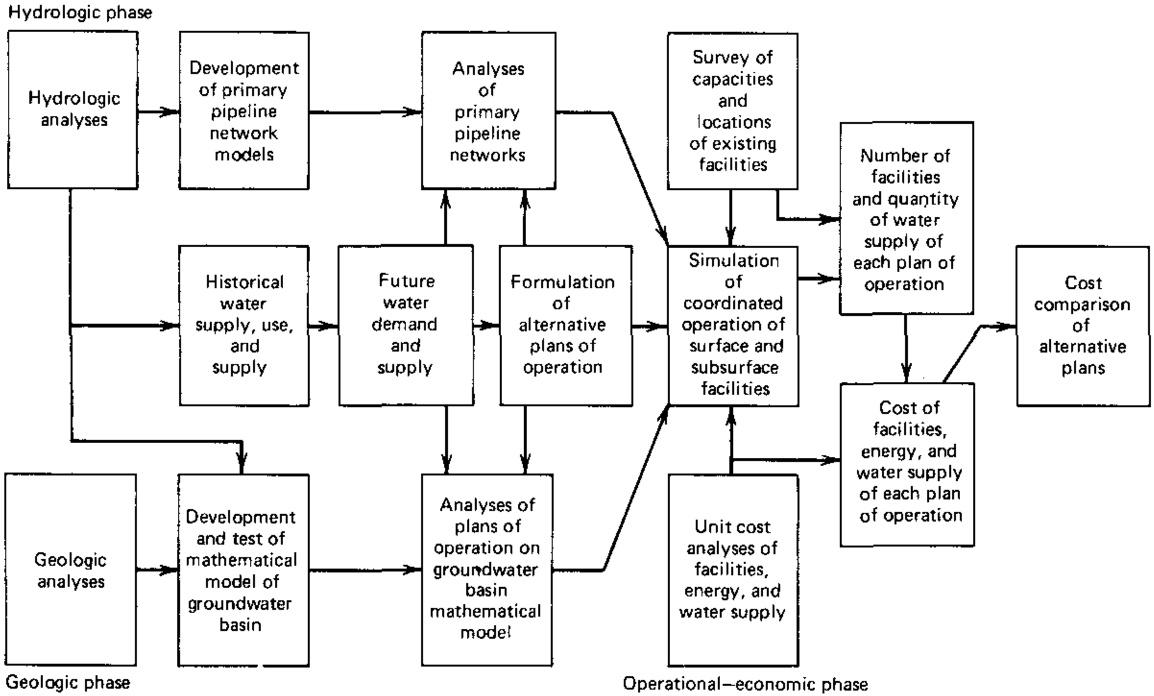

Fig. 9.8 Flow diagram of a management study for the San Gabriel Valley, California, groundwater basin (after Amer. Soc. Civil Engrs.[2]).

It should be noted from Figs. 9.7 and 9.8 that mathematical models are usually incorporated in such studies (see Chapter 10). A basin model simulates the responses of a basin to variations in variables such as natural and artificial recharge and pumping so that the best operating procedures for basin management can be practiced. In effect, this will optimize the water supply obtained from the basin.[16,22,44]

Because every water development project is unique, it is impossible to present economic considerations generally for conjunctive operations and have them apply specifically to any given situation. Nevertheless, the advantages and disadvantages, mostly economic, are summarized in Table 9.3. The tabulation compares a conjunctive-use operation relative to development of surface-water resources only, assuming irrigation to be the principal water use in a semiarid region.

Total usable water supply can be increased by coordinated operation of surface and underground water resources. With an optimum coordinated operation the unit cost of water supply storage and distribution can be minimized. The basic principles of groundwater

TABLE 9.3 Conjunctive Use of Surface Water and Groundwater Resources (after Clendenen[13])

Advantages	Disadvantages
1. Greater water conservation	1. Less hydroelectric power
2. Smaller surface storage	2. Greater power consumption
3. Smaller surface distribution system	3. Decreased pumping efficiency
4. Smaller drainage system	4. Greater water salination
5. Reduced canal lining	5. More complex project operation
6. Greater flood control	6. More difficult cost allocation
7. Ready integration with existing development	7. Artificial recharge is required
8. Stage development facilitated	8. Danger of land subsidence
9. Smaller evapotranspiration losses	
10. Greater control over outflow	
11. Improvement of power load and pumping plant use factors	
12. Less danger from dam failure	
13. Reduction in weed seed distribution	
14. Better timing of water distribution	

basin operation that will produce an optimum water resources management scheme include, as reported by Fowler:[19]

1. The surface and underground storage capacities must be integrated to obtain the most economical utilization of the local storage resources and the optimum amount of water conservation.
2. The surface distribution system must be integrated with the groundwater basin transmission characteristics to provide the minimum cost distribution system.
3. An operating agency must be available with adequate power to manage surface-water resources, groundwater recharge sites, surface-water distribution facilities, and groundwater extractions.

The procedure for developing a sound conjunctive-use operation within a basin requires estimation of the various elements of water supply and distribution. The optimum use of surface-water and groundwater resources is determined for assumed conditions, usually those during the most critical drought period of record. Examples of coordinated basin management include studies for basins in California,[5,33,38,53] Colorado,[6,34,48] Idaho,[42] Maryland,[21] New York,[20] England,[18] and India.[45]

Examples of Groundwater Management

Los Angeles Coastal Plain, California. This 1240 km^2 basin supplies approximately one-half of the water supply for the Los Angeles metropolitan area. In the recent past the basin has been critically overdrawn, resulting in declining groundwater levels and seawater intrusion. Detailed management studies[10,12] were undertaken to formulate the most economic plan for operating the groundwater basin in coordination with surface-water storage and transmission facilities to: (1) meet the growing and fluctuating water demands of the area, (2) conserve the maximum amount of locally available water, and (3) minimize the undesirable effects of overdraft. A schematic representation of the coordinated use of surface-water and groundwater resources in shown in Fig. 9.9.

Because of the vast increases in imported water to the Los Angeles area,* the study concentrated, first, on evaluating the dynamic response of the basin to recharging and pumping so that maximum use of the underground reservoir could be made, and, second, on determining the most economic plan for operating the basin—taking into

*It should be noted that the Los Angeles coastal plain is served by a network of water sources, including local surface water and groundwater, reclaimed wastewater, and imported water from the Owens, Colorado, and Feather rivers.

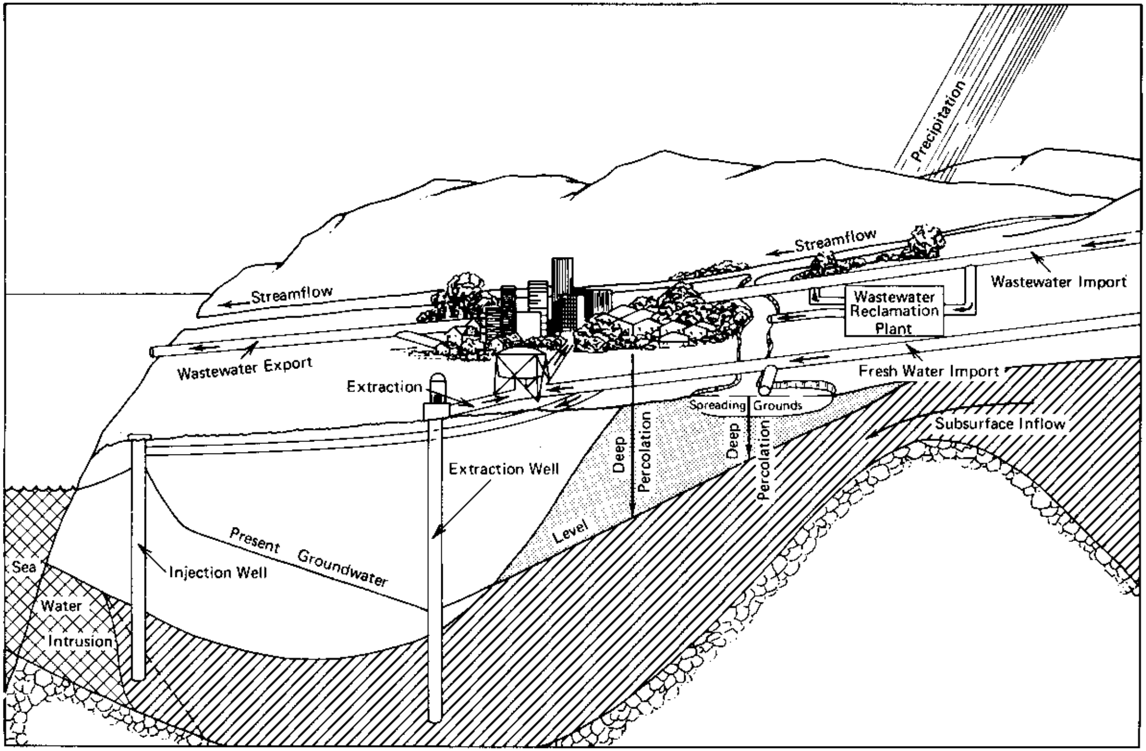

Fig. 9.9 Pictorial representation of conjunctive use of surface water and groundwater resources, Los Angeles Coastal Plain, California (after Calif. Dept. Water Resources[10]).

account patterns and rates of water extraction, rates of artificial recharge, and methods for controlling seawater intrusion.

High Plains, Texas and New Mexico. The High Plains straddling the Texas–New Mexico border define the boundaries of the Ogallala Formation, an aquifer containing approximately 250×10^9 m^3 of water in 1958. A phenomenal increase in pumping of groundwater for irrigation began in the 1940s resulting in an increase of 362 percent of irrigated acreage in the 1948–1958 decade together with an increase in wells from 8,356 to 45,522 during the same period. Already by 1958 some 50×10^9 m^3 of water had been extracted and the pumping rate amounted to 9×10^9 m^3/yr, which was more than 100 times the recharge rate. Effects on wells are apparent in Fig. 9.10 in terms of changes in yields and pumping lifts. Although rapid mining of groundwater is underway, restricting pumpage to the rate of recharge would also essentially stop all extraction and permit a large volume of water to remain unused.

Recognizing the economic and political constraints on obtaining imported water, the only feasible solution involves managed mining of the groundwater.[7,24,43] Because the aquifer has a low transmis-

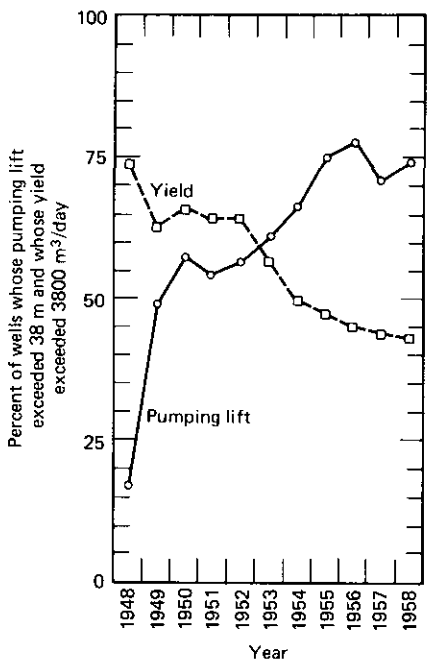

Fig. 9.10 Graph showing decreased well yield and increased pumping lift for wells in the High Plains of Texas and New Mexico as mining of groundwater occurred during the 1948–1958 decade (after Nace[36]).

sivity, depressions in the water table reflect centers of concentrated pumping. By conservative pumping from adequately spaced wells, optimum development based on long-term economic considerations can be achieved.* An example of such management has been established in the New Mexico portion of the High Plains.[15] Here groundwater extraction is limited, on a township basis, to what will provide a firm minimum supply for a period of 40 years. With time it is anticipated that improved conservation measures, changed water uses, and possible imported supplemental water will enable needs to be met further into the future. Stable development over a long term permits amortization of capital expenditures and enhances opportunities for measures to secure a more permanent water supply.

Indus River Valley, Pakistan. With the advent of canal irrigation before 1900, the Indus Plain of Pakistan developed gradually into the largest single irrigated region on the earth.† Leakage from the canal network, however, brought the water table close to ground surface over large areas (see Fig. 6.16) so that about 2.6×10^6 ha have reduced fertility caused by salinity and waterlogging. With inadequate drainage, minimal application of irrigation water, and a high evaporation rate, salts continue to accumulate and expand the problem areas. Considering Pakistan's dependence on agriculture and its continued population growth, the problem is really twofold: to eliminate salinity and waterlogging and to increase agricultural production.[40]

The solution that has been undertaken[28,35] involves drilling a large network of deep (60–100 m) high-capacity wells spaced about 1.6 km apart. Water pumped from the wells is released into existing local canals for irrigation use. In effect, the wells serve three complementary purposes by (1) lowering the water table, (2) providing supplemental irrigation water for agricultural production, and (3) furnishing water for leaching of saline soils.** Figure 9.11 illustrates the

*Also, as a result of strong local cooperation, a program for conserving all available water is effectively underway. This involves recharging ponded surface runoff and irrigation tailwater into wells.

†The irrigated area amounts to some 9×10^6 ha, comparable to the total irrigated acreage in the entire United States. The Indus River, which supplies the water, has an average discharge twice that of the Nile and more than ten times that of the Colorado River.

**It should be noted that the wells disperse the salinity of the upper soil layer throughout the body of the groundwater but do not remove the salt. The salinity of the groundwater will slowly increase; when necessary in the future, a fraction of the groundwater can be pumped to waste to achieve a salt balance.

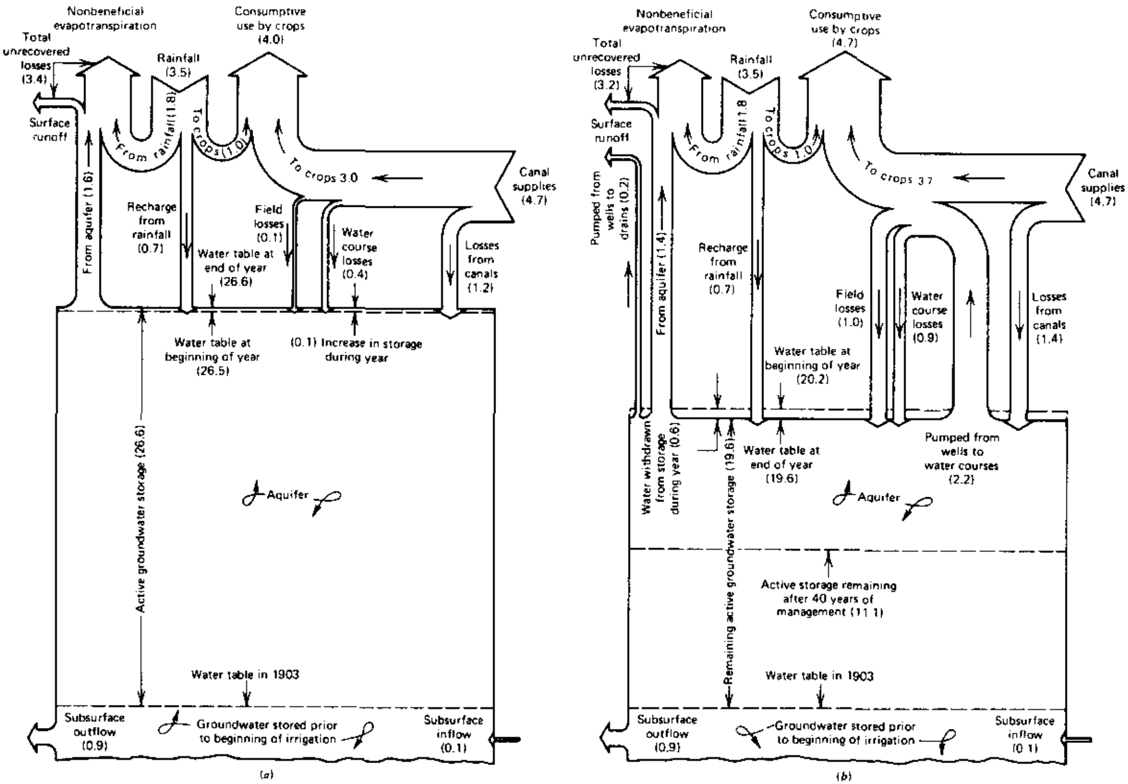

Fig. 9.11 Schematic water balances for Chaj Doab, a portion of the Indus River Plain, Pakistan. (*a*) Premanagement conditions. (*b*) Ten years after start of management program. All values are in 10^9 m^3/yr (after Tipton and Kalmbach, Inc., *Feasibility Rept. on Salinity Control and Reclamation, Project No. 2, West Pakistan,* Denver, CO, 1960).

hydrologic balances before and after the wells were in operation. By this system of basin management, together with improvements in agricultural techniques, agricultural productivity is being increased several fold.

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steady two-dimensional flow in a homogeneous and isotropic confined aquifer, is given by (from Eq. 10.17)

$$h_2 + h_3 + h_4 + h_5 - 4h_1 = 0 \tag{10.19}$$

Digital Computer Models

With the widespread availability of digital computers has come the development of mathematical models of aquifers.[58] Applications are expanding, programming techniques are steadily improving, and computer capabilities are growing so that it is safe to say that almost any type of groundwater situation can be studied by means of a digital computer model.[41,45,57] Finite-difference methods, similar to those for electric analog simulation, are well developed; more recently, finite-element methods have emerged as promising alternative techniques. Finally, hybrid computer models combine a resistance network with a digital computer.

Finite-Difference Methods. The finite-difference method is a computational procedure based on dividing an aquifer into a grid and analyzing the flows associated within a single zone of the aquifer. The flow equation is based on the equation of continuity

$$\text{inflow} - \text{outflow} = \text{change of storage} \tag{10.21}$$

which for a small portion of an aquifer can be restated as

$$\text{sum of subsurface flows} + \text{net flow to or from surface} = \text{change in storage} \tag{10.22}$$

This relation plus Darcy's law for the equation of motion yields the equation[79]

$$\frac{\partial}{\partial x}\left(T\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(T\frac{\partial h}{\partial y}\right) - Q = S\frac{\partial h}{\partial t} \tag{10.23}$$

where T and S are the aquifer transmissivity and storage coefficient, respectively, Q is the net external inflow, h is head, and t is time.

In finite-difference form Eq. 10.23 can be expressed as

$$\sum_i \frac{W_{iB}T_{iB}}{L_{iB}}(h_i^{j+1} - h_B^{j+1}) - A_B Q_B^{j+1} = \frac{A_B S_B}{\Delta t}(h_B^{j+1} - h_B^j) \tag{10.24}$$

where W, T, and L are the zonal boundary width, transmissivity, and flow path length, respectively (see Fig. 10.11); A is the area of a single zone; the superscript j denotes points along the time coordinate with Δt being one time step; the subscripts i and B refer to a contiguous zone and the zone in question, respectively (see Fig. 10.11).

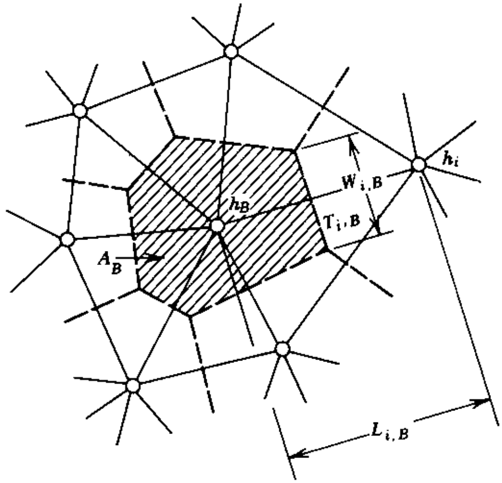

Fig. 10.11 Geometry of an aquifer zone for a finite-difference solution to flow within an aquifer. Zones may have any polygonal form; however, squares are often adopted for convenience of computation (after Tyson and Weber[79]).

The quantity Q represents the algebraic sum of extraction flows (pumpage) and replenishment flows (including precipitation, excess irrigation, imported water, stream percolation, and artificial recharge).

With the zonal configurations defining values of *W*, *L*, and *A*, and estimates from hydrogeologic data for *S*, *T*, and *Q*, time variations of *h* over the aquifer can then be computed from solution of the system of simultaneous equations. For verification of the model, a period of past records of groundwater levels is selected. Adjustments of the physical constants *S*, *T*, and perhaps *Q* are made, as needed, until a satisfactory agreement is reached between the computed water-level responses and the historical data. Once the model has been calibrated, it can be applied to study the dynamic behavior of the basin for a variety of alternative future operational conditions.

One of the earliest digital computer models employing the finite-difference method was developed by the California Department of Water Resources[79] to study the dynamic behavior of the Los Angeles coastal plain groundwater basin, comprising an area of 1240 km^2. Since then several computer methods have been developed for solving the simultaneous equations.[49,56] Detailed computer programs are available in the literature.[10,27,28,29,77]

Applications of numerical modeling employing finite-difference methods cover a wide range of groundwater topics: groundwater and well flow,[15,20,59,71,76] unsaturated flow,[31] flow with surface water bodies,[85] dispersion,[64] saltwater intrusion,[50,63] land subsidence,[30] mass transport (quality models),[11,17,42,61] and management.[12,43,79,87]

Finite-Element Methods. The finite-element technique involves solving a differential equation for groundwater flow by means of variational calculus.[32,48,51,52] The equation for two-dimensional nonsteady groundwater flow in a nonhomogeneous aquifer can be expressed as

$$\frac{\partial}{\partial x}\left(K_x b \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y b \frac{\partial h}{\partial y}\right) + Q_s = S \frac{\partial h}{\partial t} \tag{10.25}$$

where K_x and K_y are hydraulic conductivities in the coordinate directions, L is head, b is aquifer thickness, and Q_s is a source or sink function. The solution to this equation is equivalent to finding a solution for h that minimizes the variational function

$$F = \iint \left[\frac{K_x}{2}\left(\frac{\partial h}{\partial x}\right)^2 + \frac{K_y}{2}\left(\frac{\partial h}{\partial y}\right)^2 + \left(S \frac{\partial h}{\partial t} - Q_s\right) h\right] dx\, dy \tag{10.26}$$

To obtain a numerical solution to Eq. 10.26, the aquifer is subdivided into "finite elements." Figure 10.12 shows an example of such an element within an aquifer. The size and shape of the finite elements are arbitrary, typically being triangular or quadrilateral. In fact, the elements can be disordered and nonuniform and should be smallest where flow is concentrated, such as near a well. The parameters K_x, K_y, S, and Q_s are kept constant for a given element, but they may vary from element to element. To minimize Eq. 10.26,

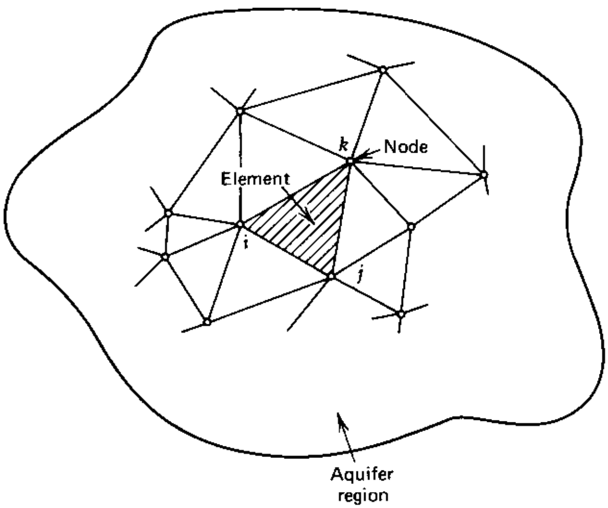

Fig. 10.12 Example of a triangular finite element within an aquifer (after Prickett[53]).

the differential $\partial F/\partial h$ is evaluated for each node and equated to zero. The resulting system of simultaneous equations can then be readily solved by a digital computer.[52]

The choice of whether a finite-element or a finite-difference method is better for aquifer modeling depends on variables such as (1) complexity of the flow system, (2) computer time required for solution, (3) problems of stability and truncation error, and (4) applicability of computer programs. The finite-element method is relatively new; the literature contains applications[23,24,82,89] as well as comparisons of the technique with the finite-difference method.

Hybrid Computer Models. A combination of a digital model and a resistance network analog, known as a hybrid computer model, has been developed to reduce the lengthy computer time sometimes required for iterative finite-difference solutions.[46,81] The digital computer provides the input data, such as sources, sinks, and aquifer properties and boundaries; these are expressed in electric form by a digital-analog converter and connected with the resistance network by means of a distributor. After the analog relaxes the system, the node voltages are fed back to the digital computer through a multiplexer and an analog-digital converter. This approach is most advantageous for solving iteration-intensive problems such as nonsteady flows in unconfined aquifers.

Modeling for Groundwater Management. The development and use of improved mathematical tools are necessary to foster more efficient groundwater management. Digital computer models serve as tools with considerable capability for aiding in decision making related to the various uses, both actual and potential, of groundwater systems.

Numerical modeling of groundwater is a relatively new field; it was not extensively pursued until the mid-1960s, when digital computers with adequate capacity became generally available.[3] Since then significant progress has been made in the development and application of such techniques to groundwater management. A recent survey,[4] however, pointed out gaps that exist between the need for and the actual use of groundwater models in management. Specifically, it was pointed out that:

1. Difficulties in the accessibility of existing models to potential users form a serious impediment; documentation including descriptions of models, listings of codes, and user's manuals would help alleviate this problem.

2. There is need for improved communications between water managers and technical personnel responsible for modeling.

3. Because of inadequacies of input data, the reliability of model output is often seriously questioned; hence, more cost-effective means of data collection are required.

4. Improvements in modeling are needed to make computer codes more understandable and easier to use.

5. Further model development is needed to handle problems in the following areas:

- Flow in media of secondary porosity.
- Flow of immiscible fluids.
- Fully integrated surface and subsurface flows.
- Pollutant transport with chemical and biological reactions.
- Socioeconomic aspects.
- Ecological aspects.
- Consideration of stochasticity.
- Parameter identification.

At present the majority of groundwater modeling is concerned with flows; however, mass-transport models for handling groundwater quality, pollution, and dispersion are increasingly in evidence. The future, in Prickett's words,[54] "looks exciting as more models will be developed, more investigators at the grass-roots level will be effectively using models, and low-priced computer equipment will become commonplace for nearly everyone's use."

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