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Saeid Eslamian

Conjunctive Use of Groundwater and Surface Water in a Semiarid Hard-Rock Terrain

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Conjunctive Use of Groundwater and Surface Water in a Semiarid Hard-Rock Terrain

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Handbook of Engineering Hydrology: Fundamentals and Applications

3.1 Introduction

Groundwater is a natural resource, and its development could be defined as a concerted activity toward its sustainable use for human benefit. The concept of sustainable use is related to various factors like the volume of water storage in the aquifer, annual recharge or replenishment, volume of annual pumpage for the proposed use, benefit/cost ratio of the proposed use, and environmental impacts of the proposed use.

Hard-rock aquifers in this chapter include the noncarbonate, fractured rocks like the crystalline basement complex and metamorphic rocks, which cover an area of about 800,000 km² in central and southern India. Basalts of western India also known as the Deccan traps of late Cretaceous to early Eocene period are also included as a special case (Figure 3.1a). Deccan traps comprise hundreds of...
FIGURE 3.1 (a) Geological map of India showing basement complex and basalts of peninsular region (scale: 1 cm = 200 km). Basement complex (granite, gneiss, and other metamorphic rocks) is shown in dark gray. Basaltic area is shown in medium gray. Black lines show state boundaries. The state of Maharashtra on the western coast is almost covered by basalt or Deccan trap (medium gray). Peninsular India is mostly covered by basalt and basement complex. (b) Nearly horizontal lava flows comprising the Deccan traps or basalts of western India. Location: Western Ghats hills between Pune and Mumbai, Maharashtra State.
nearly horizontal, basaltic lava flows in a thick pile and cover around 500,000 km$^2$ of western India (Figure 3.1b). The area covered by Deccan traps is the largest lava flow terrain in the world.

This pile was not tectonically disturbed after consolidation, and a hand specimen does not show any primary porosity due to the nonfothy nature of the lava [1]. Hydrogeologically, the Deccan traps have low porosity and are therefore akin to fractured hard-rock aquifers.

The most salient features of the hard-rock aquifers are as follows:

1. The depth of groundwater occurrence, in useful quantities, is usually limited to 100 m or so.
2. A topographical basin or a subbasin generally coincides with groundwater basin. Thus, the flow of groundwater across a prominent surface water divide is very rarely observed. In a basin, the groundwater resources tend to concentrate toward the central portion, closer to the main stream and its tributaries.
3. The aquifer parameters like storativity ($S$) and transmissivity ($T$) often show erratic variations within small distances. The annual fluctuation in the value of $T$ is considerable due to the change in saturated thickness of the aquifer from wet season to dry season. When different formulae are applied to pump-test data from one well, a wide range of values of $S$ and $T$ is obtained. The applicability of mathematical modeling is limited to only a few simpler cases within a watershed. But such cases do not represent conditions over the whole watershed.
4. The phreatic aquifer comprising the saturated portion of the mantle of weathered rock or alluvium or laterite, overlying the hard fractured rock, often makes a significant contribution to the yield obtained from a dug well or bore well.
5. Only a modest quantity of groundwater, in the range of 1–100 m$^3$ or so per day, is available at one spot. Drawdown in a pumping dug well or bore well is often almost equal to the total saturated thickness of the aquifer.

Groundwater development in hard-rock aquifer areas in India and many other countries has traditionally played a secondary role compared to that in the areas having high-yielding unconsolidated or semiconsolidated sediments and carbonate rocks. This has been due to the relatively poor groundwater resources in hard rocks, low specific capacity of wells, erratic variations and discontinuities in the aquifer properties, and the difficulties in exploration and quantitative assessment of the resource.

It should, however, be realized that millions of farmers in developing countries have their small farms in fractured basement or basaltic terrain. Whatever small supply available from these poor aquifers is the only hope for these farmers for upgrading their standard of living by growing irrigated crops or by protecting their rainfed crops from the vagaries of monsoon rainfall. It is also their only source for drinking water for the family and cattle. In many developing countries, like in India, hard-rock hydrogeologists have, therefore, an important role to play in promoting conjunctive use of surface water and groundwater.

### 3.2 Occurrence of Groundwater

Groundwater under phreatic condition occurs in the soft mantle of weathered rock, alluvium, and laterite overlying the hard rock. Under this soft mantle, groundwater is mostly in semi-confined state in the fissures, fractures, cracks, and joints [2]. In basaltic terrain, the lava flow junctions and red boles sandwiched between two layers of lava flows also provide additional porosity (Figure 3.2).

The ratio of the volume of water stored under semiconfined condition within the body of the hard rock to the volume of water in the overlying phreatic aquifer depends on local conditions in the mini-watershed. Dug-cum-bored wells tap water from the phreatic aquifer and also from the network of fissures, joints, and fractures in the underlying hard rock (Figure 3.3a and b).

The recharge to groundwater takes place during the rainy season through direct infiltration into the soft mantle overlying the hard rock and also into the exposed portions of the network of fissures and
fractures. In India and other Asian countries in monsoon climate, the ratio of recharge to rainfall in hard-rock terrain is assumed between 3% and 15% [6]. This ratio depends upon the amount and nature of precipitation, the nature and thickness of topsoil and weathered zone, type of vegetation, evaporation from the surface of wet soil, profile of underlying hard rock, the topographical features of the subbasin, and the status of soil and water conservation activities adopted by villagers. Groundwater flow rarely occurs across the topographical water divides, and each basin or subbasin can be treated as a separate hydrogeological unit for planning the development of groundwater resources. After the rainy season, the fully recharged hard-rock aquifer gradually loses its storage mainly due to pumpage and effluent drainage by streams and rivers. The dry season flow of the streams is thus supported by groundwater outflow. The flow of groundwater is from the peripheral portions of a subbasin to the central-valley

FIGURE 3.2 Red bole (intertrappean bed) sandwiched between hard, fractured basalt flows.

FIGURE 3.3 (a) and (b) Dug-cum-bored wells. GL, Ground level; HB, horizontal bore; HR, hard rock; SF, sheet fracture or joint; VB, vertical bore; VF, vertical fracture; WR, weathered rock; WT, water table.
portion, thereby causing dewatering of the portions closer to topographical water divides. In many cases, the dug wells and bore wells yielding perennial supply of groundwater can only be located in the central-valley portion.

The annual recharge during monsoons being a sizable part of the total storage of the aquifer, the whole system in a subbasin or mini-basin, is very sensitive to the availability of this recharge. A couple of drought years in succession could pose a serious problem. The low permeability of hard-rock aquifer is a redeeming feature under such conditions because it makes small quantities of water available, at least for drinking purpose, in the dug wells or bore wells in the central portion of a subbasin. If the hard rocks had very high permeability, the groundwater body would have quickly moved toward the main river basin, thereby leaving the tributary subbasins high and dry. The low permeability in the range of 0.05–1.0 m/day thus helps in retarding the outflow and regulating the availability of water in individual farm wells. More farmers are thus able to dig or drill their wells and irrigate small plots of land without causing harmful mutual interference.

### 3.3 Groundwater Development

In the highly populated but economically backward areas in hard-rock terrain, governments in many developing countries have taken up schemes to encourage small farmers to dig or drill wells for small-scale irrigation. This is especially true for the semiarid regions where surface water resources are meager and seasonal. For example, in peninsular India, hard rocks such as granite, gneiss, schist, quartzite (800,000 km²), and basalts (Deccan traps—500,000 km²) occupy about 1.30 million square kilometers area out of which about 40% is in semiarid zone, receiving less than 750 mm rainfall per year. Over 4.50 million dug wells and bore wells are being used in the semiarid region for irrigating small farm plots and for providing domestic water supply.

The development of groundwater resources for irrigational and domestic use is thus a key factor in the economic thrift of vast stretches of semiarid, hard-rock areas. The basic need of millions of farmers in such areas is to obtain an assured supply for protective irrigation of at least one rainfed crop per year and to have a protected, perennial drinking water supply within a reasonable walking distance. The hard-rock hydrogeologists in many developing countries have to meet this challenge to impart social and economic stability to the rural population, which otherwise would migrate to the neighboring cities. Rapid and uncontrolled urbanization caused by exodus of rural population toward the cities is creating excessive stress and degradation in urban infrastructure. This is a common problem for many developing countries and could only be solved by providing assurance of at least one crop and increasing the opportunity for employment on farms for landless people.

Groundwater development in a subbasin results in increased pumpage and lowering of the water table due to the new wells, resulting in the reduction of the effluent drainage from the subbasin. Such development in several subbasins draining into the main river of the region reduces the surface flow and the underflow of the river, thereby affecting the function of the surface water schemes depending on the river flow. In order to minimize such interference, it is advisable to augment groundwater recharge by adopting artificial recharge techniques during rainy season and also during dry season. The measures for artificial recharge during monsoon rains include contour trenching on hillslopes, contour bunding of farms, gully plugging, farm ponds, underground stream bunds, and forestation of barren lands with suitable varieties of grass, bushes, and trees. Artificial recharge in dry season is achieved through the construction of PTs.

However, the increase in pumpage takes place through the initiative of individual farmers to improve their living standard through the irrigation of high-value crops, while recharge augmentation is traditionally considered as government’s responsibility and always lags far behind the increase in pumpage. In many parts of the world, particularly in developing countries, groundwater is thus being massively over-abstracted. This is resulting in falling water levels and declining well yields, land subsidence, intrusion of saltwater into freshwater supplies, and ecological damages, such as drying out wetlands.
Groundwater governance through regulations has been attempted without much success, because the farmers have a strong sense of ownership of groundwater occurring in their farms. Integrated Water Resources Management (IWRM) is being promoted as a policy or a principle at national and international levels, but in practice at field level, it cannot be attained without the cooperation of rural community. NGOs sometimes play an important role in educating the villagers and ensure their cooperation.

3.4 Conjunctive Use through Dry Season
Recharge from Percolation Tank

During the rainy season from June to September, the recharge from rainfall causes the recuperation of water table in a subbasin from its minimum level in early June to its maximum level in late September. This is represented by the equation

\[ P = R + ET + r \]  \hspace{1cm} (3.1)

where
- \( P \) is the precipitation
- \( R \) is surface runoff
- \( ET \) is evapotranspiration during the rainy season
- \( r \) is the net recharge, represented by the difference between the minimum storage and maximum storage in the aquifer

However, after the aquifer gets fully saturated, the additional infiltration during the monsoons is rejected and appears as delayed runoff.

During the dry season, the depletion of the aquifer storage in a subbasin, from its maximum value to minimum value, is represented by the following equation:

\[ S = s + P + F + R \]  \hspace{1cm} (3.2)

where
- \( S \) is the aquifer storage at the end of rainy season, that is, maximum storage
- \( s \) is the aquifer storage at the end of summer season, that is, minimum storage
- \( P \) is the pumpage, mainly for irrigation, during the dry season from dug wells and bore wells
- \( F \) is the dry season effluent streamflow and underflow supported by groundwater
- \( R \) is the recharge, if any, available during the dry season, including the return flow from irrigated crops

The left-hand side of the aforementioned equation has an upper limit, as mentioned earlier. On the right-hand side, the minimum storage cannot be depleted beyond a certain limit, due to the requirement for drinking water for people and cattle. Dry season streamflow and underflow supported by groundwater have to be protected, as explained earlier, so that the projects depending upon the surface flow of the main river are not adversely affected. Any increase in the pumpage for irrigation during dry season due to new wells must therefore be balanced by increasing the dry season recharge.

The best way to provide dry season recharge is to create small storages at various places in the basin by bunding gullies and streams for storing runoff during the rainy season (Figure 3.4) and allowing it to percolate gradually during the first few months of the dry season. Such storages created behind earthen bunds put across small streams are popularly known as PTs.

In semi-arid regions, an ideal PT with a catchment area of 10–50 km² or so holds maximum quantity by the end of September and allows it to percolate for the next 4–5 months of winter season. The excess of runoff water received in monsoon flows over the masonry waste weir constructed at one end of the earthen bund. By February or March, the tank is dry, so that the shallow water body is not exposed to
high rates of evaporation in summer months (Figure 3.6). Groundwater movement being very slow, whatever quantity percolates between October and March, is available in the wells on the downstream side of the tank even in summer months till June or the beginning of next monsoon season. The irrigation of small plots by farmers creates greenery in otherwise barren landscape of the watershed. Studies carried out in granite–gneiss terrain have indicated that about 30% of the stored water in the tank percolates as recharge to groundwater in the dry season. The efficiency is thus 30%. In basaltic terrain, if the tank is located at suitable site and the cutoff trench in the foundation of tank bund does not reach up to the hard rock, higher efficiencies up to 70% could be obtained [5]. However, more research is required for the estimation of the impact of PTs in recharge augmentation. In the state of Maharashtra in western India, over 10,000 PTs have been constructed so far [3] (Figure 3.5). They are beneficial to the farmers and are very popular with them.

The initial efficiency of a PT reduces due to silting of its bottom by receiving muddy runoff from the watershed. If the watershed is well forested and has a cover of grass, bushes, and crops, the silting is
minimal. But in an average of 5–6 monsoon seasons, the tank bed accumulates about 0.20–1.00 m of silt. Silt reduces the storage capacity of the tank and also impedes the rate of vertical flow of recharge because of its low permeability. The efficiency gets reduced due to silting and desilting of tank bed when it dries in summer becomes necessary [4] (Figure 3.6).

Another type of recharge available during the dry season is the return flow or the percolation below the root zone of crops from irrigated farms. This return flow to groundwater is usually estimated at about 25%–30% of the volume of groundwater pumped in dry season and applied for irrigation. However, due to increasing popularity of more efficient irrigation methods like sprinkler or drip systems, this type of recharge has a declining trend.

3.5 Problems at Field Level

Although the construction of PTs and of soil and water conservation structures in a watershed promotes conjunctive use of surface water and groundwater, such recharge augmentation in dry season at several PTs in a river basin could create problems at field level. Suppose a major surface water supply project has been competed by building a big dam on a river and the large reservoir created behind the dam is supplying water to major cities and industrial areas. While designing such a major dam, certain calculations are made as to the “water crop” or “water harvest” coming into the reservoir for a given amount of rainfall in the large catchment area. If several PTs are constructed on small streams within this large catchment area of the river and water in these tanks makes a significant contribution to groundwater recharge in dry season, the “water harvest” at the big dam would get reduced, thereby causing water scarcity in cities and industrial areas. In semiarid regions, significant percentage of water accumulated at tiny field bunds constructed for soil conservation may be lost to evaporation and may not contribute to surface runoff or to groundwater recharge. The water supply department looking after the water supply to cities and industries from the reservoir at the dam is interested in getting more “water harvest” and would therefore object to the construction of too many PTs and field bunds. On the other hand, the
farmers in the catchment area at higher level than the reservoir like to assert their right on the runoff that flows from their farms to the reservoir, by impounding the runoff at tiny farm bunds and PTs.

In such a conflict of interests, the NGOs usually take the side of dryland farmers in the catchment area and support their right to harvest the rainfall in farm ponds, field bunds, and PTs, so as to promote recharge to groundwater. Promoting such recharge is the only way for these poor farmers to get some assured crop by using groundwater for small-scale irrigation and to obtain safe quality drinking water. Moreover, the NGOs argue that the surface water collected in the large reservoir at the dam is never used efficiently. The farmers in the lower valley getting water for irrigation from canals coming from the large reservoir always over-irrigate their farms causing waterlogging in the command area of the canals. Such a gross wastage of water should be avoided first before complaining about the reduction in “water harvest” due to field bunds and PTs in the catchment area.

One more point in favor of the construction of field bunds and PTs to promote groundwater recharge in catchment area is that they reduce the silt load coming from the catchment into the reservoir of the big dam, thereby prolonging the useful life of the dam project.

It may, however, be noted that there is also a change of domain here. Surface water management is mostly in government sector, that is, public domain. Groundwater is traditionally owned by farmers and is in the private domain. Questions could be asked as to the productivity, that is, the contribution to the GDP from 1 m³ of groundwater recharged from surface water for agricultural use by farmers, vis-a-vis its productivity if that cubic meter of water was used in surface water supply to city or industry. Although the contribution to GDP per cubic meter of water from urban sector is much more than that from the agricultural sector, the farmers’ population has to survive and produce food. So, contribution to GDP cannot be the sole criterion. In other words, a balanced approach is needed at field level in order to maintain amicable relations between the competing stakeholders. Industrial and urban wastewater has to be recycled and reused, while irrigation has to be made more efficient so as to generate more output per cubic meter of water. IWRM through the conjunctive use of surface water and groundwater is thus a complicated matter at field level.

Equally complicated is the management or pumpage control of groundwater even in overexploited watersheds, because groundwater is traditionally the landowner’s property. A farmer has therefore a right to dig or drill anywhere in his land and to pump as much water as possible, even if such pumping results in diminishing the yields of surrounding wells owned by others. There are no legal battles over this. Suppose a farmer has 1 ha of farm in a watershed of 500 ha and luckily has a very good well in his farm. Then, he pumps water for day and night and irrigates the whole farm with water-intensive crops like banana or sugarcane. Here, his equitable share in the groundwater of the watershed is only 0.2%. Because he is lucky to have a very good well in the farm, how much should he increase his share in groundwater resources of the watershed? Ten to fifty times? Such questions are difficult to answer. Moreover, through the intervention and social pressure from the village council, if the farmer reduces his pumping say by 50%, in hard-rock aquifers, it is difficult to assess where the unpumped 50% would flow. So a better alternative is to pump the high-yielding wells to full extent and give 50% to the well owner and 50% to neighboring farmers. The same high-yielding wells should be used for recharging during the rainy season thereby promoting the conjunctive use. Such activities would not be possible through any legislation. Only the village councils and active NGOs could follow this difficult path, leading to a kind of social revolution in which community’s right on private groundwater body would be established and the recharge activity would be partly brought into the private domain.

### 3.6 Summary and Conclusions

A watershed is the meeting point of climatology and hydrology. It is therefore necessary to manage our watersheds so as to absorb the climatic shocks likely to come from the erratic climatic patterns expected in the near future. This can be done only through practicing soil and water conservation techniques
for artificial recharge during rainy season and through construction of small PTs for artificial recharge during the dry season.

Basin or subbasin management begins with soil and water conservation activities taken up with people’s active participation in several subbasins within a large basin. This improves the shape of hydrograph of the stream or river in the basin, from a “small time-based and sharp-peaked hydrograph” to a “broad time-based and low-peak hydrograph.” Such a change also increases groundwater recharge.

Small water storages or tanks created in the subbasins by bunding streams and gullies store runoff water during the monsoon season and cause recharge to groundwater during the next few months of dry season. The residence time of water in the basins is thus increased from a few months to a few years, and the percolated water is available in the wells even during the summer season of a drought year.

After a few years of operation, silting of the tank bed reduces the volume of water stored and also the rate of vertical infiltration. Regular desilting of tanks by local people is, therefore, advisable.

A national policy for afforestation of degraded basins with proper species of grass, bushes, and trees should be formulated. Afforestation with eucalyptus trees should not be encouraged in low-rainfall areas as this effectively reduces groundwater recharge. The main aim of forestation of a degraded watershed with local spices of hardy trees, grasses, etc., should be to conserve soil, reduce velocity of runoff water, promote recharge to groundwater, and increase the biomass output of the watershed.

The involvement of NGOs should be encouraged in forestation schemes and soil and water conservation programs so as to ensure active participation of rural community in recharge augmentation. NGOs also motivate the farmers to maintain the soil and water conservation structures put in by government departments so as to ensure long-term augmentation of recharge to groundwater. Along with such management on supply side, demand management is also equally important. NGOs play a significant role in promoting the use of efficient irrigation methods and selection of crops with low water requirement.

The conjunctive use of surface water and groundwater is ideal in theory, but in practice, several problems arise at field level during implementation. NGOs play an important role in bringing competing stakeholder on one platform and reach an amicable solution. The problem in many developing countries is that although the Governments own most of the major sources of surface water they are not able to manage surface water provided for irrigation through canals. Several thousands of hectares get water logged every year. Governments also cannot effectively mange ground water because the it is owned by the farmers. NGOs therefore play a role in educating the farmers.

Although the discussion in the chapter refers to hard-rock terrain in India, it would be equally applicable to many other developing countries, having a similar hydrogeological and climatic setup.

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