PCE16136

WATER RESOURCES SYSTEMS PLANNING & MANAGEMENT

LECTURE NOTES

Module-III

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Semester – 2th Sem

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Course Content

Module III

Water Quantity Management: Surface Water Storage Requirements, Storage Capacity and Yield, Reservoir Design, Water Allocations for Water Supply, Irrigation, Hydropower and Flood

Control, Reservoir Operations, Planning of an Irrigation System, Irrigation Scheduling, Groundwater management, Conjunctive Use of Surface and Subsurface Water Resources.

Lecture note 1

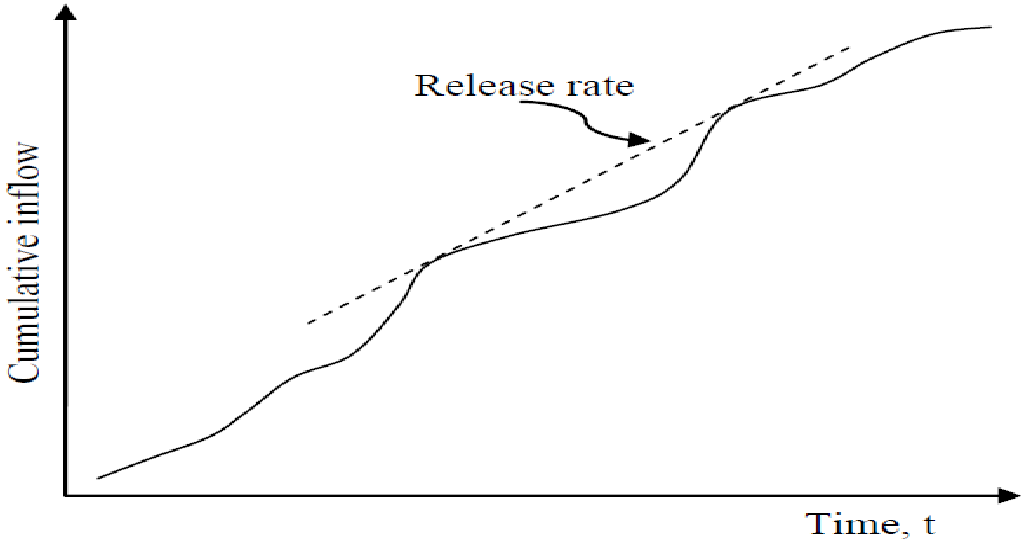
Water Quantity Management

1.1 Reservoir Sizing

- Annual demand for water at a particular site may be less than the total inflow, but the time distribution of demand may not match the time distribution of inflows resulting in surplus in some periods and deficit in some other periods.
- A reservoir is a storage structure that stores water in periods of excess flow (over demand) in order to enable a regulation of the storage to best meet the specified demands.
- The problem of reservoir sizing involves determination of the required storage capacity of the reservoir when inflows and demands in a sequence of periods are given.

1.2 Mass diagram method

- It was developed by W. Rippl (1883). A mass curve is a plot of the cumulative flow volumes as a function of time.
- Mass curve analysis is done using a graphical method called Ripple's method.
- It involves finding the maximum positive cumulative difference between a sequence of pre-specified (desired) reservoir releases Rt and known inflows Qt (as shown in figure).
- One can visualize this as starting with a full reservoir, and going through a sequence of simulations in which the inflows and releases are added and subtracted from that initial storage volume value.
- Doing this over two cycles of the record of inflows will identify the maximum deficit volume associated with those inflows and releases.
- This is the required reservoir storage.



(Typical mass curve)

1.3 Sequent Peak Algorithm

This algorithm computes the cumulative sum of differences between the inflows and reservoir releases for all periods t over the time interval [0, T]. Let Kt be the maximum total storage requirement needed for periods 1 through period t and Rt be the required release in period t, and Qt be the inflow in that period. Setting K_0 equal to 0, the procedure involves calculating Kt using equation below for upto twice the total length of record. Algebraically,

$$K_t = \begin{cases} R_t - Q_t + K_{t-1} & \text{if positive} \\ 0 & \text{otherwise} \end{cases}$$

The maximum of all Kt is the required storage capacity for the specified releases, Rt and inflows, Qt.

1.4 Formulation of reservoir sizing using LP

Linear Programming can be used to obtain reservoir capacity more elegantly by considering variable demands and evaporation rates. The optimization problem is

Minimize K_a

Where K_a is the active storage capacity

Subject to

(i) Hydraulic constraints as defined by the reservoir continuity equation

$$S_{t+1} = S_t + I_t - EV_t - R_t - O_t \quad \text{for all } t$$

(ii) Reservoir capacity

$$S_t \leq K_a \qquad \text{for all } t$$

$$S_{T+1} = S_t \qquad \text{where T is the last period.}$$

(iii) Target demands

$$R_t \geq D_t \qquad \text{for all t.}$$

1.5 Storage Yield

A complementary problem to reservoir capacity estimation can be done by maximizing the yield. Firm yield is the constant (or largest) quantity of flow that can be released at all times. It is the flow magnitude that is equalled or exceeded 100% of time for a historical sequence of flows. Linear Programming can be used to maximize the yield, R (per period) from a reservoir of given capacity, K. The optimization problem can be stated as:

$$\text{Maximize } R$$

Subject to

(i) Storage continuity equation

$$S_{t+1} = S_t + I_t - EV_t - R_t - O_t \qquad \text{for all } t$$

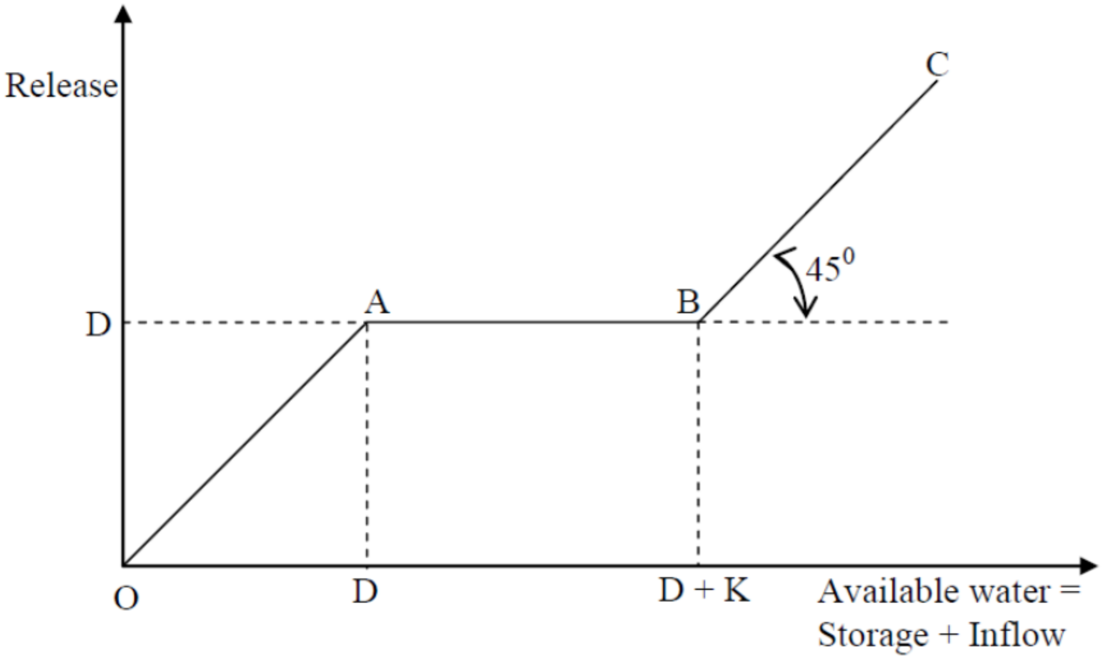
(ii) Reservoir capacity

$$S_t \leq K_a \qquad \text{for all } t$$

$$S_{T+1} = S_t \qquad \text{where T is the last period.}$$

1.6 Reservoir Operation

Reservoir operation policies are developed to enable the operator to take appropriate decision. The reservoir operation policy indicates the amount of water to be released based on the state of the reservoir, demands and the likely inflow to the reservoir. The release from a single purpose reservoir can be done with the objective of maximizing the benefits. For multi-purpose reservoirs, there is a need to optimally allocate the releases among purposes. The simplest of the operation policies is the standard operation policy (SOP). According to SOP, if the water available (storage, S_t+ inflow, I_t) at a particular period is less than the demand D_t, then all the available water is released. If the available water is more than the demand but less than demand + storage capacity K, then release is equal to the demand. If after releasing the demands, there is no space for extra water, then the excess water is also released. This is shown graphically in figure below.



(Standard operating policy)

Along OA: Release = water available; reservoir will be empty after release.

Along AB: Release = demand; excess water is stored in the reservoir (filling phase).

At A: Reservoir is empty after release.

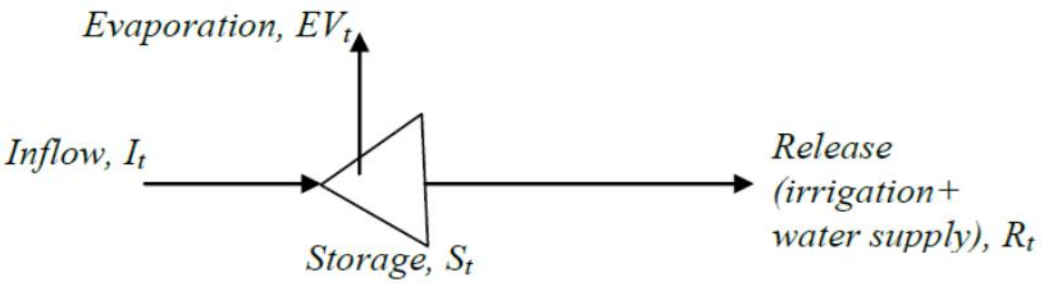
At B: Reservoir is full after release.

Along BC: Release = demand + excess of availability over the capacity (spill)

The releases according to the SOP need not be optimum. The optimization of reservoir operation is done often by linear programming (LP) and dynamic programming (DP).

1.7 Derivation of optimal operating policy using LP

Consider a reservoir of capacity K. The optimization problem is to determine the releases Rt that optimize an objective function satisfying all the constraints. The objective function can be a function of storage volume or release. The typical constraints in a reservoir optimization model include conservation of mass and other hydrological and hydraulic constraints, minimum and maximum storage and release, hydropower and water requirements as well as hydropower generation limitations.



(Single reservoir operation)

Consider the objective of meeting the demands to the extent possible i.e., maximizing the releases. The optimization model can be formulated as:

$$\text{Maximize } \sum_t R_t$$

Subject to

(i) Hydraulic constraints as defined by the reservoir continuity equation

$$S_{t+1} = S_t + I_t - EV_t - R_t - O_t \quad \text{for all } t$$

Where Ot is the outflow. The constraints for outflow are

$$O_t = 0 \qquad \text{if} \quad S_t + I_t - EV_t - R_t \le K$$

$$= K - [S_t + I_t - EV_t - R_t] \qquad \text{if} \quad S_t + I_t - EV_t - R_t > K$$

(ii) Reservoir capacity

$$S_t \le K - K_d \qquad \text{for all t, where } K_d \text{ is the dead storage}$$

or simply $S_t \le K$

$$S_t \ge 0 \qquad \text{for all t.}$$

(iii) Target demand

$$R_t \le D_t \qquad \text{for all t.}$$

$$R_t \ge 0 \qquad \text{for all t.}$$

Large LP problems can be solved very efficiently using LINGO - Language for Interactive General Optimization, LINDO Systems Inc, USA.

1.8 Ground water management

Ground water is the common pool resource used by millions of farmers in the country and remains the predominant drinking water source for rural water supply. It also supports industrial usages. The scarcity of water resources and ever increasing demand of these vital resources require identification, quantification and management of ground water in a way that prevents overexploitation and consequent economic and environmental damage, while satisfying demand for water supply of competing sectors. Participatory ground water management is envisaged to make a significant step in ground water management at grass root level to enable the community and stake holders to monitor and manage the ground water as common pool resources themselves.

It is imperative to have the aquifer mapping activity with a road map for groundwater management plan to ensure its transition into a participatory groundwater management programme for effective implementation of the Aquifer Management Plans (AMPs). This would require a coordinated effort involving government departments, research institutes, PRIs, civil society organizations and the stakeholders at the village level who would guide collective sharing and use of groundwater based on a careful understanding of the storage and transmission characteristics of different aquifer units. A National level identified consortium of NGOs is desirable for developing benchmark for this activity and facilitating its implementation.

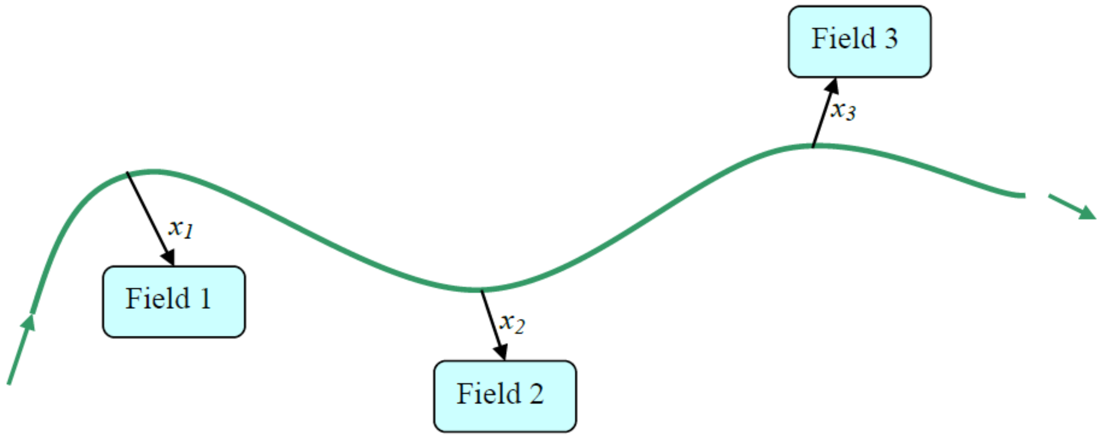
The implementation of AMPs is proposed through collaborative approach amongst government departments, research institutes, PRIs, civil society organizations and the local community. The stakeholders would include farmers, landless farm workers with appropriate SC, ST and Women's representatives. Consensus based decision making is the goal of local water users association (WUA). Social audit by members not involved in the implementation process is inbuilt within the participatory ground water management. Gram Sabha is proposed to be the final arbiter in case of disputes and for establishing some basic regulatory norms under PRI system. A national level independent agency shall be entrusted for evaluation of the project. The programme envisaged activities towards building capacity, skills and knowledge to ground water users. Programme will be executed by engaging suitable youth, women etc as grass root ground water workers after providing necessary trainings to them to function as facilitators, trainers and data managers at the village level. Two major issues to be addressed by the proposed programme are:–

- Management of Groundwater
- Monitoring leading to sustainability of Groundwater

Even though Aquifer mapping is a fairly complex exercise involving profound knowledge of Hydrogeology and other disciplines, the role of grass root workers (para-hydrogeologists) cannot be understated. They shall be responsible for collection of primary Hydrogeological data, periodic monitoring of identified key wells, and sensitization of the villagers regarding ground water trends, extensive usage and its ramification. The Central and State organizations shall be assisted by the designated NGOs to identify and facilitate training of grass root workers for the implementation of AMPs. The program will catalyse and scale up the PGWM process to facilitate the field level outreach of ground water development measures.

1.9 Water allocation problem

Consider a canal supplying water to three fields in which three different crops are being cultivated as shown in figure 1. The maximum capacity of the canal is given as Q units of water. The three fields can be denoted as i=1,2,3 and the amount of water allocated to each field as x_i.



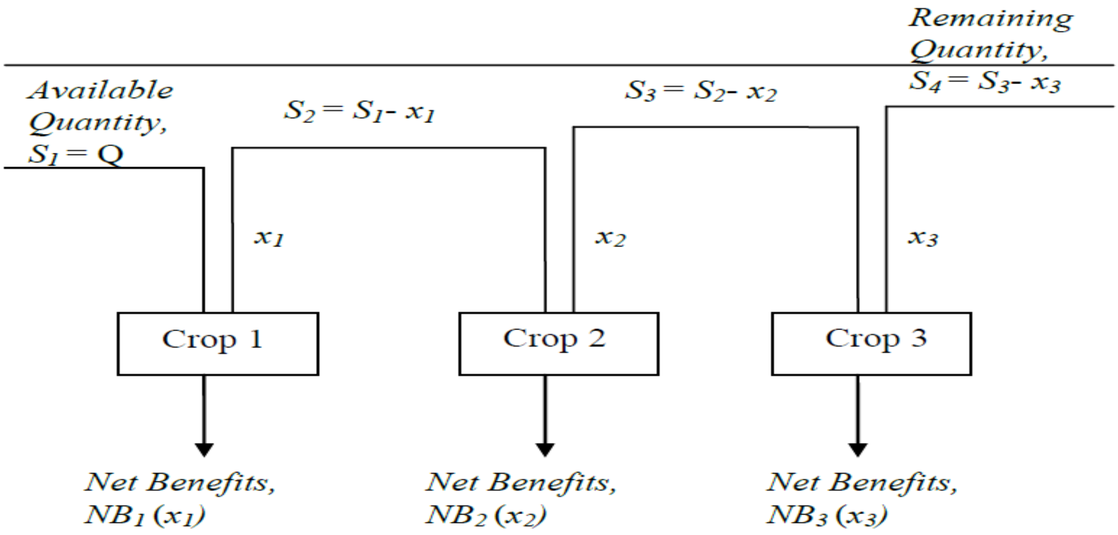
(Water allocation process)

The net benefits from producing the crops in each field are given by the functions below.

$$NB_1(x_1) = 5x_1 - 0.5{x_1}^2$$
$$NB_2(x_2) = 8x_2 - 1.5{x_2}^2$$
$$NB_3(x_3) = 7x_3 - {x_3}^2$$

The problem is to determine the optimal allocations xi to each field that maximizes the total net benefits from all the three crops. This type of problem is readily solvable using dynamic programming.

The first step in the dynamic programming is to structure this problem as a sequential allocation process or a multistage decision making procedure. The allocation to each crop is considered as a decision stage in a sequence of decisions. If the amount of water allocated from the total available water *Q*, to crop *i* is *xi*, then the net benefit from this allocation is *NBi(xi)*. Let the state variable *Si* define the amount of water available to the remaining *(3-i)* crops. The state transformation equation can be written as $S_{i+1} = S_i + x_i$ defines the state in the next stage. Figure below shows the allocation problem as a sequential process.



(Fig – Sequential process of allocation)

- The objective function for this allocation problem is defined to maximize the net benefits,

i.e., $\max \sum_{i=1}^{3} NB_i(x_i)$. The constraints can be written as

$$x_1 + x_2 + x_3 \le Q$$
$$0 \le x_i \le Q \qquad for\ \ i = 1,2,3$$

Let $f_1 Q$ Q be the maximum net benefits that can be obtained from allocating water to crops 1, 2 and 3. Thus,

$$f_1(Q) = \max_{\substack{x_1+x_2+x_3 \le Q \\ x_1, x_2, x_3 \ge 0}} \left[\sum_{i=1}^{3} NB_i(x_i) \right]$$

Transforming this into three problems each having only one decision variable,

$$f_1(Q) = \max_{\substack{x_1 \\ 0 \le x_1 \le Q}} \left[NB_1(x_1) + \max_{\substack{x_2 \\ 0 \le x_2 \le Q - x_1 = S_2}} \left\{ NB_2(x_2) + \max_{\substack{x_3 \\ 0 \le x_3 \le S_2 - x_2 = S_3}} NB_3(x_3) \right\} \right]$$

Lecture note 2

2.1 Conjunctive use of ground and surface water

Conjunctive use of groundwater and surface water in an irrigation setting is the process of using water from the two different sources for consumptive purposes. Conjunctive use can refer to the practice at the farm level of sourcing water from both a well and from an irrigation delivery canal, or can refer to a strategic approach at the irrigation command level where surface water and groundwater inputs are centrally managed as an input to irrigation systems. Accordingly, conjunctive use can be characterised as being planned (where it is practiced as a direct result of management intention – generally a top down approach) compared with spontaneous use (where it occurs at a grass roots level – generally a bottom up approach). The significant difference between unplanned and planned conjunctive use, and the approach governance must take to maximise the potential benefits from such use, is explored within this paper. Where both surface and groundwater sources are directly available to the end user, spontaneous conjunctive use usually proliferates, with individuals opportunistically able to make decisions about water sources at the farm scale.

The planned conjunctive use of groundwater and surface water has the potential to offer benefits in terms of economic and social outcomes through significantly increased water use efficiency. It supports greater food and fibre yield per unit of water use, an important consideration within the international policy arena given the critical concerns for food security that prevail in many parts of the world. At the resource level, groundwater pumping for irrigation used in conjunction with surface water provides benefits that increase the water supply or mitigate undesirable fluctuations in the supply (Tsur, 1990) and control shallow water table levels and consequent soil salinity.

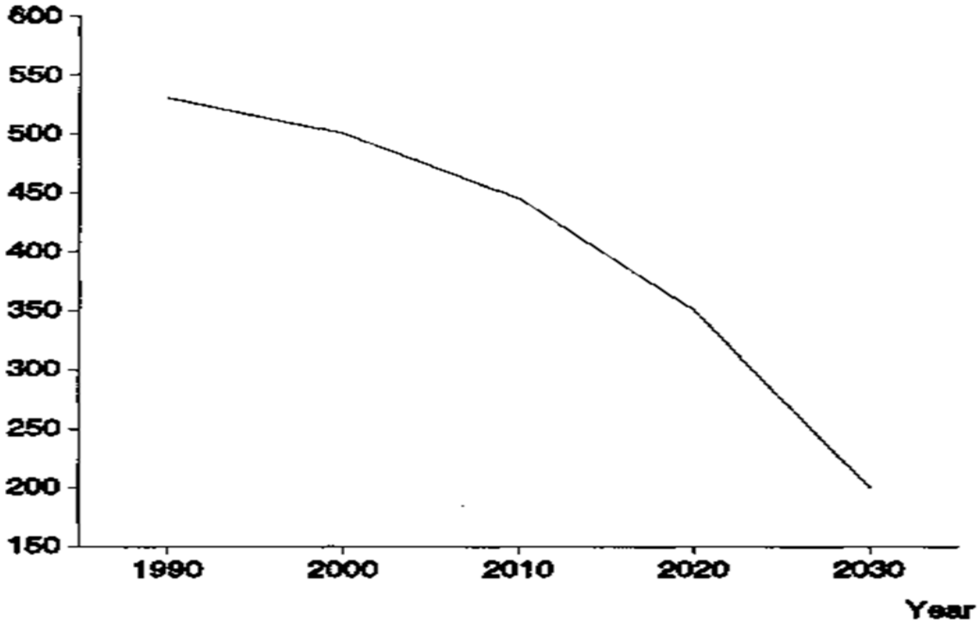
In most climates of the world, precipitation, either rain or snow, and consequently peak runoff corresponding to a significant part of the total discharge of the rivers, occur during a particular season of the year which usually coincides with the smallest water demand. The water development problem therefore consists of transferring water from the high supply season to the high demand season. The most obvious and the most common solution to that problem consists of storing surface water behind dams, but storage of water in the ground may be a valuable alternative to surface storage systems, although not always systematically considered when planning water development. Yet surface reservoirs have many drawbacks, especially:

- **Evaporation**: large open water areas are exposed, during several months and even years, to high evaporation rates leading to water losses sometimes exceeding 20 percent of the average annual runoff. Losses may be even higher when the width of the impounded valley is considerable, and induces a larger open water area.

- **Sedimentation**: soil erosion in the catchment results in siltation in the surface reservoirs and in the equivalent reduction of the storage capacity. The soil vulnerability to erosion, and therefore the importance of the siltation problems in surface reservoirs, grows as the vegetation cover shrinks, so the more arid the climate, the less the vegetation cover, the higher the probability of sediment accumulation in the surface reservoirs. Draining part of the mud from the reservoirs is occasionally possible through specially designed pipes placed at the bottom of the dam, but each operation is water consuming (to flush the mud) and may be detrimental to downstream environment.

- **Environmental impact:** of surface reservoirs may often be highly undesirable for human health, flooding of inhabited, or good agricultural land.
- **Distribution of water:** from the reservoir may be expensive and requires the construction of costly canals because of the distance between dam and utilization areas

MOROCCO - MOHAMED V RESERVOIR: Reduction of storage capacity



In contrast, groundwater is not exposed to evaporation; does not suffer from reduction of storage capacity because of siltation; is seldom harmful to environment and offers a natural water distribution up to the users.

2.2 Why is surface water storage always preferred to groundwater development?

When looking at these advantages and disadvantages, groundwater seems to be a better alternative that should be preferred, but this not the case; large and concentrated water demand such as that from large irrigation schemes is usually supplied from surface water storage, and there are various reasons for that choice:

- groundwater aquifers seldom offer large storage capacity able to absorb large volumes of flood in a short period of time, and are unable to return them as significant discharge per unit production system of well or borehole,

- surface water storage, because of the large investments involved, is often preferred because it offers a much higher political visibility and because high construction costs give an opportunity for private profit and corruption, opening the way for improper influence on decision making.

2.3 A reasonable solution

Conjunctive use of surface and groundwater consists of harmoniously combining the use of both sources of water in order to minimize the undesirable physical, environmental and economical effects of each solution and to optimize the water demand/supply balance. Usually conjunctive use of surface and groundwater is considered within a river basin management programme - i.e. both the river and the aquifer belong to the same basin.

Assuming that the mixed solution is part of the national policy, several problems need to be carefully studied before selecting the different options and elaborating a programme of conjunctive use of surface and groundwater:

- Underground storage availability to be determined,

- Production capacity of the aquifer(s) in term of potential discharge,

- Natural recharge of the aquifer(s)

- Induced natural recharge of the aquifer(s)

- Potential for artificial recharge of the aquifer(s)

- Comparative economic and environmental benefits derived from the various possible options.

2.4 Underground Storage Availability and Production Capacity of the Aquifer

In order to use the underground reservoir to store a significant volume of water - possibly of the same order of magnitude as the annual runoff - with the intent to use it at a later stage, it is necessary to ascertain the potential storage capacity of the groundwater reservoir as well as its suitability for being recharged by the surface water and for easily returning the stored water when needed. The groundwater reservoir should present sufficient free space between the ground surface and the water table to accommodate and retain the water to be recharged, for the period during which water is not needed. This condition requires accurate hydrogeological investigations including geological mapping, geophysics and reconnaissance drilling, in order to determine the configuration and the storage capacity of the underground reservoir.

The suitability of an aquifer for recharging may be estimated from the following parameters:

- Surface material has to be highly permeable so as to allow water to percolate easily;

- The unsaturated zone should present a high vertical permeability, and vertical flow of water should not be restrained by less permeable clayey layers;

- Depth to water level should not be less than 5 to 10 m;

- Aquifer transmissivity should be high enough to allow water to move rapidly from the mound created under the recharge basin but should not be too high (as in karstic channels) so that water cannot be recovered.

An adequate transmissivity for recharge is also a good indicator of the aquifer capacity to produce high well discharge and therefore easily to return the water stored.

2.5 Natural And Induced Recharge of the Aquifer

Should a significant natural recharge of the aquifer occur from the surface runoff and the deep percolation of rainfall, and should the average annual amount of recharge be of the same order of magnitude as the water demand, there would not be the need for any additional human intervention. On the contrary, any tentative modification of the natural course of surface water may significantly alter the groundwater renewable resources. There are many examples of double counting of water resources as if surface and groundwater were independent. Because of this wrong approach, dams have been built with the intent to store the surface water and to create an additional resource. The resulting situation has often been catastrophic with rapid depletion of the aquifer not recharged any more, destruction of the ecosystem based on the groundwater and extreme difficulty to go back to initial conditions.

Induced natural recharge occurs when intensive exploitation of groundwater close to a river results in an important depression of the groundwater level and in a water inflow from the river. This phenomenon is well known in temperate climate where rivers flow all year long; but it may also occur in semi-arid climates where a depression of the piezometric level of an aquifer underlying a temporary river creates the empty space in the aquifer which facilitates its recharge during floods.

2.6 Artificial Recharge

Artificial recharge of aquifers can be achieved using three different methods, namely **surface spreading, watershed management** (water harvesting) and **recharge wells.**

2.6.1 Surface Spreading

Artificial recharge by the spreading method consists of increasing the surface area of infiltration by releasing water from the source to the surface of a basin, pond, pit or channel. This is certainly the most efficient and most cost-effective method for aquifer recharge. However, only phreatic (unconfined) aquifers can be recharged by the spreading method, which also requires large surface areas to accommodate the recharge scheme, allowing water to evaporate if percolation in the ground is slow.

Surface spreading usually needs two structures: the diversion structure and the infiltration scheme.

Diversion structures are the same as those used for spate irrigation. The traditional methods, based on centuries of experience, are well adapted to the conditions of arid land wadis. They consist of the construction of earthen bunds (*ogmas*) and deflectors across the wadi to divert the flow into the fields. But large spates usually destroy the *ogmas* and reduce irrigation of the fields. Furthermore, the very high sediment content of spate water tends to fill the diversion canals, which have to be cleaned regularly. So, although the ogmas are relatively inexpensive to rebuild, the overall cost of seasonal maintenance and repair of the scheme is high.

Several techniques have been tested with the objective of achieving a better control and regulation of spate and reducing sediment transport in the canals. Due to the hydrological characteristics of wadis, it soon became evident that it is not economic to provide diversion weirs which will control the probable maximum flood. Thus, the tendency nowadays is to build diversion structures with a canal head regulator, sediment excluder and a spillway on one flank and a fusible dyke across the wadi. Unfortunately, present design and feasibility studies are often hampered by lack of adequate data on spate runoff. These techniques were developed with the intention of improving the spate irrigation systems, but the results can apply to the diversion structures (diversion weirs) needed for artificial recharge by surface spreading.

The **infiltration scheme** may consist of basins, channels or pits depending on the local topography and on land use. The most common system consists of a number of **basins** each one having an area ranging from 0.1 to 10 ha according to space availability. Each basin must have its own water supply and drainage so that each basin can be flooded, dried and cleaned according to its best schedule. Basins should never be in series, because in such a system, they cannot be dried and cleaned individually. Often the first basins are used as pre-sedimentation facilities.

In the vicinity of urban agglomerations, **pits** may have been dug in ancient paths of wadis in order to extract construction material (gravel, sand). The depth of these pits may range from 2 to 3 m up to 30 to 40 m. Pits may also be excavated for the specific purpose of artificial recharge. Aquifer recharge simply consists of diverting water from the main channel to the pit. Even with a deep pit, it may be advisable to have a smaller settling pit between the main channel and the larger recharge pit. Both recharge and settling pits should be fenced and have a suitable inlet so that the inflowing water does not erode the walls of the pits.

Other techniques may also be identified with the surface spreading method: spate irrigation, check dams, underground dams and sand dams.

Spate irrigation is a well known traditional technique in the Near East consisting of watering terraced fields which flank the wadi, by diverting flood flows into them. Although the primary objective of spate irrigation is not aquifer recharge, this technique usually contributes significantly to increasing the infiltration of water into the underlying groundwater reservoirs. The storage of excess water into the aquifer and its subsequent retrieval alleviates some of the risks inherent to runoff based irrigation in arid zones.

Check dams are small structures built across wadis with a view to slowing down the velocity of water, allowing it to percolate into the alluvial aquifer. When the wadi usually flows into a narrow channel surrounded by plains located a few metres above the bottom of the channel, check dams may be built in the channel, raised 1 to 2 metres above the ground level of the plain and extended laterally by two wings crossing most of the valley. The flood is then forced to expand over a large area, thus facilitating the infiltration of water.

Underground dams apply in shallow depth alluvial deposits to prevent groundwater (underflow of the wadi) from flowing away immediately after it is stored in the aquifer. They consist of digging a 1 to 1.5 m wide trench across the valley, down to the bedrock (which should be impervious) and then filling the trench either with loose impervious material (clay) or by building a wall made of local bricks. Underground dams may be complemented by **sand dams** consisting of raising the dam above ground by 1 or 2 metres so that the solid transport (usually sand and gravel) of the floods can accumulate behind the surface dam and thus increase the storage capacity of the alluvium.

2.6.2 Watershed management and water harvesting

Watershed management offers an effective method to intercept dispersed runoff. Many techniques of water conservation have been developed along hill slopes with the intention of preventing soil erosion and reducing surface runoff, then increasing the infiltration in the ground, thus recharging the aquifers. Traditional terraced agriculture is certainly one of the most common water harvesting methods in arid areas and particularly in the Near East. Where the terraces are well maintained, they effectively control runoff and improve aquifer recharge but, once allowed to fall into disuse, they progressively lead to gully erosion, collapse of the retaining walls, destruction of the whole system and severe modification of the hydrological regime. Therefore, whatever the economic virtues of such terraces, it should be recognized that their abandonment on a large scale can upset the hydrological conditions within a basin for a considerable period of time.

Because of the siltation problems in the surface reservoirs resulting from soil erosion in the upper catchment, large programmes of soil and water conservation as well as forestation are being undertaken in several semiarid countries. Although the primary objective of the watershed management is to limit the soil erosion and therefore to reduce sediment accumulation in the surface reservoirs downstream, the effect of these practices may become significant on the aquifer recharge when large areas are included in the programmes. However there are few examples of quantitative analysis of the modification of the water cycle in a catchment where soil and water conservation has been practiced.

2.6.3 Recharge wells

Artificial recharge by injection consists of using a conduit access, such as a tubewell, shaft or connector well, to convey the water to the aquifer. It is the only method for artificial recharge of confined aquifers or deep-seated aquifers with poorly permeable overburden. The recharge is instantaneous and there are no transit or evaporation losses. The method is very effective in the case of highly fractured hard rocks and karstic limestones.

Recharge wells or "injection" wells are similar in construction to pumped wells, using screened sections.

The great difficulty in using recharge wells is always their rapid clogging. While a basin may clog within years and in any case may easily be reconditioned, a recharge well may clog in a few days or weeks and is always difficult to keep in good operating condition. There are many possible causes of clogging.

- First there is suspended matter present in the water; it reduces the pore space in the gravel pack and in the formation at the interface with the gravel pack. This causes clogging to be more severe in aquifers with finer grain size.

- High content of organic matter may result in bacteriological growth. This is why clogging phenomena vary during the year as temperature of injected water changes.

- Clogging may also occur due to gas or air bubbles in the water, especially in shallow wells with low water pressure. It is essential to prevent underpressure in recharge pipes, valves and connections. This problem can be overcome by the use of small diameter recharge pipes in order to ensure the "pipe-full conditions

- Mixing of chemically dissimilar waters causes these waters to react and to form precipitates. Another form of clogging is caused by the swelling of clay particles which may be present in the target aquifer.

The most economical way to operate artificial recharge by injection consists of using dual purpose wells (injection and pumping) so that cleaning of the aquifer may be achieved during the pumping period. However, a pretreatment to eliminate the suspended matter is always necessary.

2.6.4 Conjunctive Use of Surface and Groundwater As Part Of Integrated River Basin Management

The increasing acuteness of water scarcity problems, worldwide, requires the adoption of a double approach of water supply management and water demand management.

Governments tend to consider river basins as water resources management units and as a spatial basis for the formulation of water management strategies integrating all cross-sectoral issues such as water resources conservation, environment, water resources allocation, water demand management, etc. The conjunctive use of surface and groundwater is one of the strategies of water supply management which has to be considered to optimize the water resources development, management and conservation within a basin, and artificial recharge of aquifers is certainly one of the tools to be used for that purpose.

The use of the river basin as the spatial unit for analyzing the interactions and interrelations between the various components of the system, and for defining the water management policy, is well justified, and is increasingly becoming common practice:

- In **China**, river basin plans have legal status and development projects are required to be consistent with the provisions of the plans;

- In **Indonesia**, the Government recently adopted new water management policies in order to prepare spatial management plans and to link water and land use through river basin plans, to centre water management at the river basin level, and to centralize water management responsibilities through a more effective participation and collaboration of beneficiaries;

- In **Italy**, a 1989 law introduced the river basin as a management unit to regulate the programmes of the various sectoral and regional institutions;

- In the **United Kingdom, Spain, France**, and in most European countries, water resources management is now essentially centred on river basins.

The adoption of an integrated river basin management approach for elaborating policies and strategies of water resources development, management and conservation would help consider the water resources as one system and would avoid a water resources development approach focused only on surface water. This approach also facilitates the management of the resource itself, allowing a better understanding, by water users, of the hydrological issues involved.

Research is still needed, however, to understand better, and to quantify the role of watershed management and particularly of soil and water conservation practices in the water cycle. The development of GIS techniques could certainly help assess the overall water resources within a river basin and the effect of various human interventions such as water conservation practices over large areas, large dams or small dams.

2.6.5 Irrigation scheduling

Irrigation scheduling is the process used by irrigation system managers to determine the correct frequency and duration of watering.

The following factors may be taken into consideration:

- Precipitation rate of the irrigation equipment - how quickly the water is applied, often expressed in inches or mm per hour.
- Distribution uniformity of the irrigation system - how uniformly the water is applied, expressed as a percentage, the higher the number, the more uniform.
- Soil infiltration rate - how quickly the water is absorbed by the soil, the rate of which also decreases as the soil becomes wetter, also often expressed in inches or mm per hour.
- Slope (topography) of the land being irrigated as this affects how quickly runoff occurs, often expressed as a percentage, i.e. distance of fall divided by 100 units of horizontal distance (1 ft of fall per 100 ft (30 m) would be 1%).
- Soil available water capacity, expressed in units of water per unit of soil, i.e. inches of water per foot of soil.
- Effective rooting depth of the plants to be watered, which affects how much water can be stored in the soil and made available to the plants.
- Current watering requirements of the plant (which may be estimated by calculating evapotranspiration, or ET), often expressed in inches per day.
- Amount of time in which water or labour may be available for irrigation.
- Amount of allowable moisture stress which may be placed on the plant. For high value vegetable crops, this may mean no allowable stress, while for a lawn some stress would be allowable, since the goal would not be to maximize production, but merely to keep the lawn green and healthy.
- Timing to take advantage of projected rainfall
- Timing to take advantage of favourable utility rates
- Timing to avoid interfering with other activities such as sporting events, holidays, lawn maintenance, or crop harvesting.

The goals in irrigation scheduling is to apply enough water to fully wet the plant's root zone while minimizing overwatering and then allow the soil to dry out in between watering, to allow air to enter the soil and encourage root development, but not so much that the plant is stressed beyond what is allowable.

In recent years, more sophisticated irrigation controllers have been developed that receive ET input from either a single on-site weather station or from a network of stations and automatically adjust the irrigation schedule accordingly.

Other devices helpful in irrigation scheduling are rain sensors, which automatically shut off an irrigation system when it rains, and soil moisture sensing devices such as capacitance sensors, tensiometers and gypsum blocks.

2.7 Flood control

Flood control methods are used to reduce or prevent the detrimental effects of flood waters. Flood relief methods are used to reduce the effects of flood waters or high water levels.

Floods are caused by many factors or a combination of any of these generally prolonged heavy rainfall (locally concentrated or throughout a catchment area), highly accelerated snowmelt, severe winds over water, unusual high tides, tsunamis, or failure of dams, levees, retention ponds, or other structures that retained the water. Flooding can be exacerbated by increased amounts of impervious surface or by other natural hazards such as wildfires, which reduce the supply of vegetation that can absorb rainfall. Periodic floods occur on many rivers, forming a surrounding region known as the flood plain.

During times of rain, some of the water is retained in ponds or soil, some is absorbed by grass and vegetation, some evaporates, and the rest travels over the land as surface runoff. Floods occur when ponds, lakes, riverbeds, soil, and vegetation cannot absorb all the water. Water then runs off the land in quantities that cannot be carried within stream channels or retained in natural ponds, lakes, and man-made reservoirs. About 30 percent of all precipitation becomes runoff and that amount might be increased by water from melting snow. River flooding is often caused by heavy rain, sometimes increased by melting snow. A flood that rises rapidly, with little or no warning, is called a flash flood.

Coastal areas are sometimes flooded by unusually high tides, such as spring tides, especially when compounded by high winds and storm surges.

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