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A Proposed Artificial Groundwater Recharge Scheme for Wadi Systems

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ABSTRACT. A series of field experiments and theoretical analyses of different infiltration-recharge processes in the alluvial system are presented. Theoretical analysis of one-dimensional vertical infiltration, lateral recharge, and recharge through the unsaturated wetting front were carried out. Field studies indicate that the soil heterogeneity and flood hydrograph characteristics have a prominent influence on the amount and duration of recharge. Infiltration-recharge equations for a clogged surface layer condition seem to be the best suited for estimation of recharge in most wadis in the Kingdom. In addition, it was shown that the infiltration-recharge process can be enhanced (35%) through artificial recharge schemes involving the construction of a series of inflatable-deflatable rubber dams across the wadi bed for the conditions in wadi Tabalah. These dams may be used to increased the duration and contact area of runoff and may result in a significant increase in the amount of recharge.

Introduction

Water resources are an important factor in the development of many arid countries such as Saudi Arabia. Currently, water demand for domestic, industrial and agricultural purposes is being met through exploitation of deep and shallow alluvial aquifers and desalination. In 1985, 88% of the water demand for various purposes was satisfied through the use of groundwater, while desalinization accounts for 5% and the remainder by surface and wastewater (MOP 1985, Abu Rizaiza and Allam 1989). Availability of modern technology and governmental incentives has led to a tremendous increase in agricultural activities resulting in the depletion of groundwater resources. However, the deep and shallow aquifers can be, at least, partially recharged through proper management of surface and reclaimed wastewater.

The Kingdom's mean annual surface runoff is estimated at 2025 million cubic meters, of which 45% infiltrates and recharges the groundwater aquifer, 30% is diverted for agricultural purposes, while the rest is lost by evaporation (El-Khatib 1980, Abu Rizaiza and Allam 1989). Runoff is available mainly in the western and southwestern regions of the country. Approximately 78% of the runoff in the Kingdom occurs in these regions (BAAC 1979, El-Khatib 1980). Frequent rainfall in this region, in combination with steep, barren slopes, results in large volumes of surface runoff, which recharge the groundwater aquifers, are stored behind dams, or are diverted for agricultural purposes.

Reclaimed waste water available for agricultural and industrial purposes is currently estimated at 200 million cubic meters. By the year 2000 it is expected to be about 600 million cubic meters (MOP 1985). This water can also be used to replenish the groundwater aquifers and later drawn upon to meet water demand.

Future long-term development and management policy will rely heavily on the efficient use of both surface runoff and reclaimed waste water, and artificial recharge schemes should be designed to make optimum use of these sources. This study explores some of the options available for artificial enhancement of the recharge process, suitable for a typical alluvial system such as Wadi Tabalah, in the southwestern region of the Kingdom. Based on field studies and theoretical formulations, along with their applications, recommendations are suggested for a suitable artificial recharge schemes, tailored to the arid climatic conditions of Saudi Arabia.

Background

Increasing attention has been focused on the use of artificial groundwater recharge schemes to supplement municipal and industrial water supplies, and to improve groundwater quality. Increasing demand for water calls for the implementation of efficient water management policies to preserve the longevity of the available resources, particularly in arid regions, where demand usually exceeds natural replenishment. Water conservation policies, in combination with well designed recharge schemes, which utilize surface runoff to enhance groundwater supplies, can be effective in helping the balancing of the system of supply and demand.

In arid regions, such as Saudi Arabia, natural recharge may occur through any one or a combination of three processes: direct infiltration of rainfall occurring over outcrop areas of the deep aquifer or alluvial areas, infiltration of flood flow through the wadi bed, or leakage from one aquifer to another. The amount of recharge is dependent on the frequency of rainfall-runoff events which are characterized by large temporal and spatial variation. Other factors that also influence the recharge process are contact surface area of the alluvium, type of bed material, aquifer outcrops, initial soil moisture, and thickness and type of deposits above the water table.

Various studies have been carried out to assess the water resources including the amount of recharge to deep and shallow aquifers in different regions of the Kingdom (Parson Basil 1968, Italconsult 1969, Sogreah 1968, 1970, Burdon 1973, BAAC 1979, Maclaren 1978, Al-Khatib 1980). These studies have reported a wide range of values and frequencies of recharge to shallow and deep aquifers, depending on the geographic location of the study area and the method of analysis.

The annual amount of recharge to the deep aquifers in the northern region was estimated to be between 2.7 and 8.3 mm (Parson Basil 1968), while in the central region it has been estimated to be between 1.0 and 1.5 mm (Sogreah 1968, BRGM 1982). In the southwestern region, the annual recharge to the deep aquifers is estimated to be between 14 and 39 mm (Italconsult 1969, Maclaren 1978). The range in values of estimated recharge depths for these regions may seem to be small, however, considerable volumes of water are actually available because the outcrop area usually cover hundreds of square kilometers, and infiltration can occur over the entire area. A feasibility study for the Saq aquifer, located in the central region, indicated that an annual amount of approximately 150 million cubic meters could be recharged to groundwater using appropriate artificial recharge methods over the outcrop area (Norconsult 1984).

Recharge to the shallow alluvial aquifers usually occurs from infiltration of surface runoff through the wadi bed. Large transmission losses of flood flow occur during the advancement of the flood wave along the main wadi channel. This may constitute a significant amount of recharge to the alluvial aquifer, depending upon the influencing recharge factors mentioned previously. The frequency of recharge to the shallow aquifers is limited in the Kingdom, with the exception of the western and southwestern regions, due to the irregularity runoff. However, conditions of shallow water table and course alluvial deposits make out of these regions potential sites for enhanced recharge programs. Various studies conducted by a number of consulting firms and researchers on the infiltration-recharge process in the alluvial system have produced widely variable estimates of the amount of recharge occurring through the alluvial system. These estimates have been used on transmission loss studies, empirical formulas, water balance and model studies (BAAC 1979). Some of these studies carried out in the alluvial system of the western and southwestern region (Italconsult 1969, Sogreah 1970, Maclaren 1978, BAAC 1979, DAA 1979) indicated that from 9 to 58% of the mean annual runoff was converted to recharge. A recent study in the Tabalah Basin (Abdulrazzak *et al.* 1989) indicated that as much as 70-75% of the mean annual surface runoff contributes towards recharge of the alluvial system. The large variation in the amount of recharge expressed as a percentage of runoff can be attributed to different methods of analysis (BAAC 1979), characteristics of the wadi bed materials, depth to the water table, available storage and soil moisture conditions. Favorable infiltration conditions in the alluvial wadi deposits, together with the areal rainfall, the potential for relatively large amounts of surface water, and the availability of increasing volumes of reclaimed waste water, make the western and southwestern regions highly suitable for the implementation of artificial recharge schemes.

Field Studies

Successful implementation of artificial recharge schemes requires a detailed investigation of the infiltration-recharge mechanisms under ephemeral wadi conditions.

Determination of the factors influencing infiltration and recharge must be fully understood in order to select the appropriate artificial recharge scheme. Therefore, an experimental field site in the Tabalah basin was selected and instrumented with seven observation wells, four surface runoff recorders, and soil moisture and evaporation sensors, in addition to the existing hydrological network, as shown in Fig. 1.

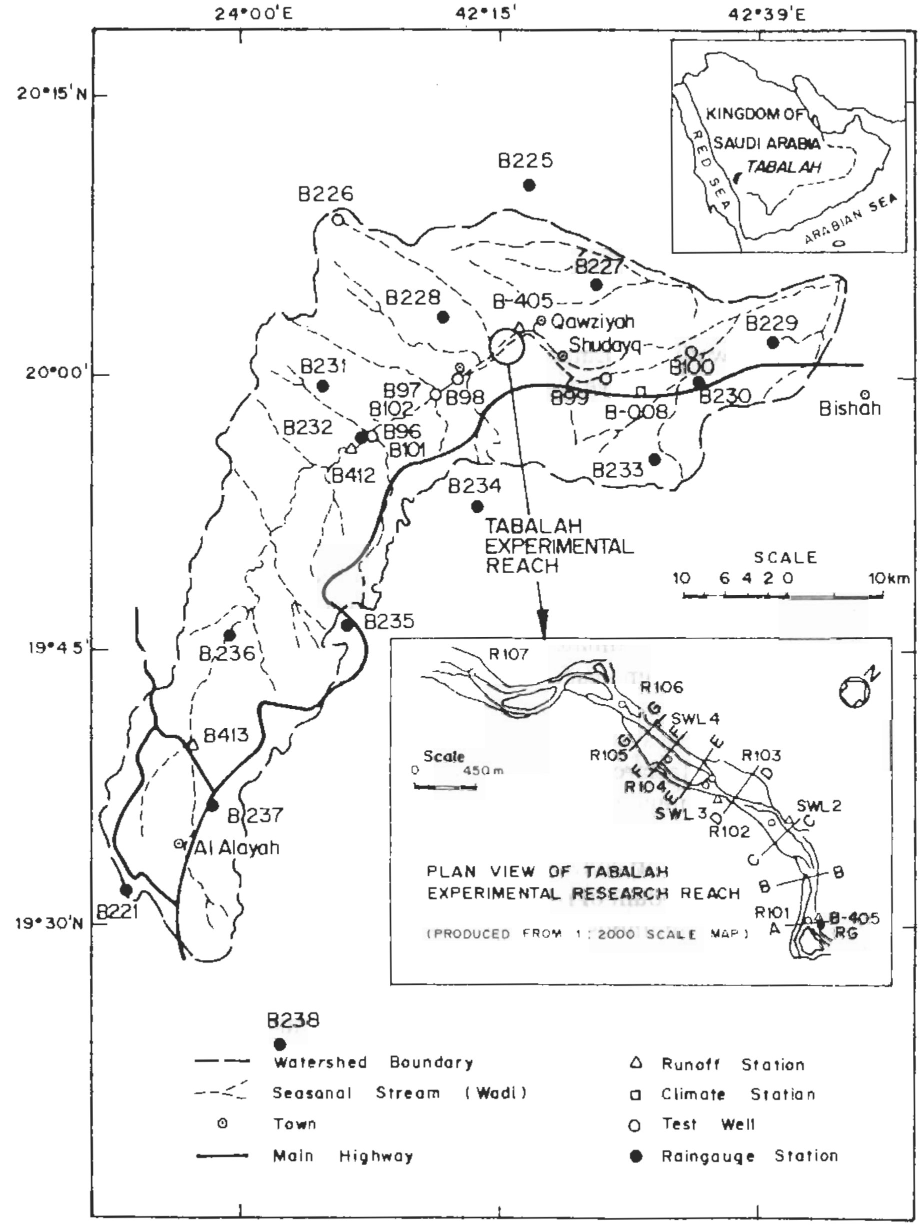

FIG. 1. Study area, Talabah areas.

Extensive soil sampling, infiltration tests and continuous groundwater monitoring programs were carried out in order to determine the factors influencing the infiltration-recharge process. The field study revealed that the alluvial deposits under the active wadi channel consist of sand and fine to coarse gravel in the upper portions of the basin, and increased silt and clay in the downstream portions (Abdulrazzak *et al.* 1986). The channel slope ranges from 0.5 to 0.8%. The alluvial wadi area is 24 km long, the width ranges from 50 m upstream to 300 m downstream, and the alluvial thickness ranges from 10-50 m. The water table depth below the surface fluctuates from 3 to 8 m (1986-89). Laboratory analysis of soil properties indicated that porosity (ϕ) values ranged from 25 to 35%; residual moisture content (θ_r) ranged from 2 to 4%, and moisture content at natural saturation ($\tilde{\theta}$) ranged from 25 to 30%. The hydraulic conductivity (K) of several soil samples collected through the alluvial profile, as well as several wadi cross-sections of the wadi (Fig. 1), was estimated in the laboratory using constant head parameter tests. The estimated values of hydraulic conductivity show considerable variation with depth and cross-section, ranging from 0.2 to 5.78 cm/min with a weighted average of 3.5 cm/min as shown in Table 1. This wide range in the hydraulic conductivity (K) can be attributed to heterogeneity of alluvial material. Samples were taken through the entire alluvial thickness for cross-sections *C*, *D*, and *G*, and the data are presented in Table 1.

TABLE 1. Hydraulic conductivities (K cm/min) at several cross-sections and depths (Abdulrazzak *et al.* 1986).

Depths (m)	Cross-sections		
	C	*D*	*G*
0.2	0.9	–	0.8
1.0	0.2	2.0	3.9
3.0	4.8	2.4	3.8
5.0	4.9	4.7	1.0
7.0	2.8	5.0	1.8
9.0	4.0	5.0	3.5
11.0	3.8	5.4	2.2
13.0	3.4	5.7	1.9
Average K (cm/min)	3.1	4.3	2.4
Average I (cm/min)	0.9	1.7	0.8
Grain size d_{50} (mm)	0.7	–	0.58

Several infiltration tests were conducted at different cross-sections of the experimental reach, using a double ring apparatus, in order to estimate infiltration rate and soil moisture variation. The physical soil properties and infiltration test data are needed to recharge studies and design of artificial schemes. The average infiltration rate (I) from the constant head test (20 cm) ranged from 0.34 to 1.18 cm/min (Abdulrazzak *et al.* 1986). Additional tests were made with different head variations (45-87 cm) similar to stage flood hydrograph. Increasing in ponding depth generally resulted in higher infiltration rates, ranging from 0.84 to 1.38 cm/min. Cumulative infiltration depth test results are presented in Fig. 2. The average rate from all tests is estimated at 1.2 cm/min.

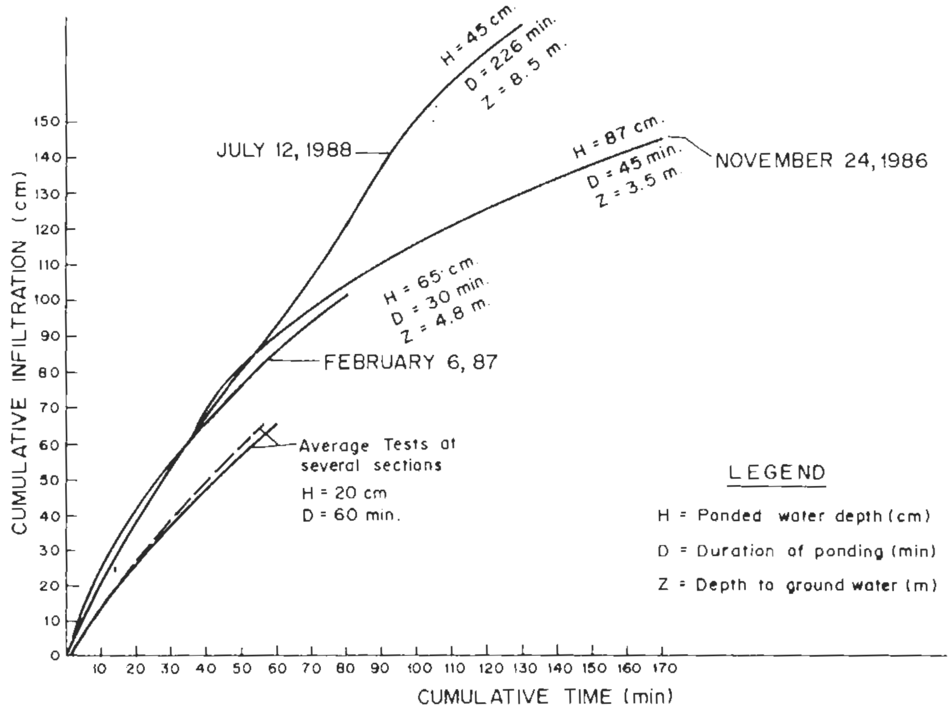

FIG. 2. Cumulative infiltration curves at Wadi Tab'alah.

Analysis of soil moisture data from sensors placed at different depths for various flood events, indicated that water movement in the soil profile occurs as unsaturated flow due to a fine sediment layer, which may be present on the soil surface. The soil moisture data, as well as the groundwater level rises, provide information about the wetting front movement in the soil profile. Wetting front propagation through the profile is estimated at 3.7 cm/min using soil moisture sensors, as compared to 2.7 cm/min estimated using the lag time between the time of occurrence of the flood flow and the start of water table rise (depth of 3 m) in the well. The lower value represents an integrated estimate for the whole soil profile. It seems that the wetting front advances at a slower rate than the hydraulic conductivity, as represented by the values in Table 1. For stage heights ranging from 27 to 118 cm, natural groundwater recharge may range from 11 to 145 cm (Abdulrazzak *et al.* 1987, 1988). The response of two typical observation wells for the given flood event on March 3, 1987, having a peak stage of 73 cm and a flood duration of 20 hr, is shown in Fig. 3. The groundwater data suggest that soil heterogeneity and location of wells in relation to the width of active channel flow influenced the water table rise readings which result from recharge events. Monitoring of water table response for several flood events (Abdulrazzak *et al.* 1986, 1987 and 1988), and for depths ranging from 1.04 to 5.08 meters, shows that the wetting front arrival varies from 0.5 to 4 hr. Data analysis of several runoff-recharge events observed during the various stages of recharge (1986-1989) indicated that maximum recharge occurs from 4 to 8 hours after the arrival of the wetting front of the water table (Abdulrazzak *et al.* 1987, 1988).

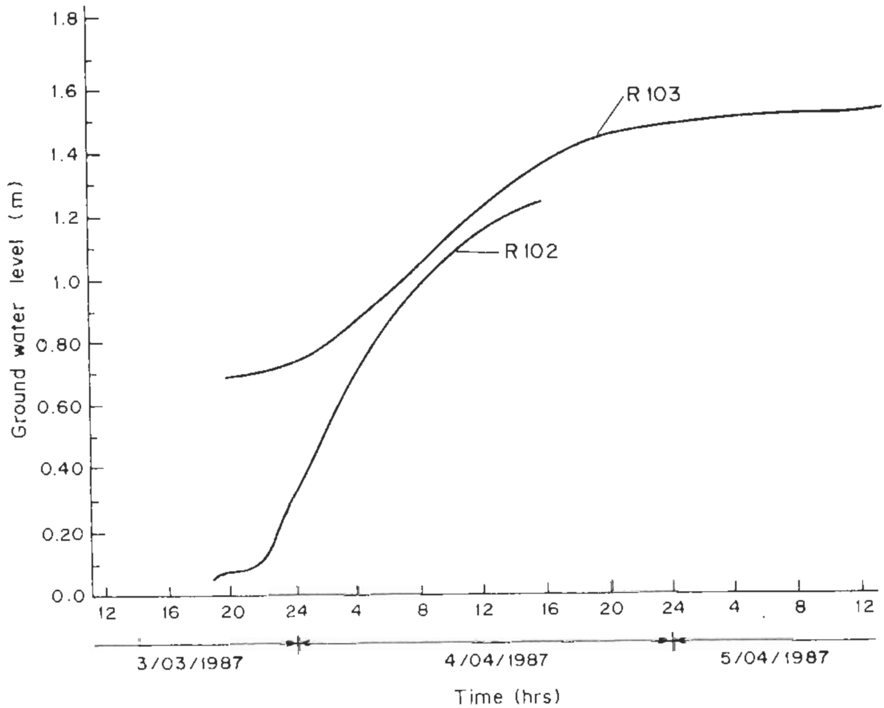

FIG. 3 Groundwater table rise at two wells in Wadi Tabalah.

In general, the flood stage and duration, initial soil moisture, soil properties, porosity, hydraulic conductivity and active area of flow are the factors having the most influence on the infiltration-recharge process. Therefore, designs for artificial recharge schemes must take these factors into account.

Flood Hydrograph Characteristics

Flood flow hydrographs in arid regions, in general, and in Saudi Arabia in particular, is usually characterized by a rapid rise to peak flow, followed by a rapid decline over a short period, to a low stage succeeded by a long recession until the wadi returns to its original dry state. (FAO 1981, Abdulrazzak *et al.* 1986, 1987). Sustained flow is rare and prolonged base flow occurs from groundwater discharge when the water table is close to the surface. Peak flow caused by high intensity rainfall may occur within minutes, which is the situation observed during flood events in Wadi Tabalah. The stage hydrographs of several events recorded in the Tabalah basin are characterized by short time of rise to peak, ranging from 0.1 to 2.5 hr, and hydrograph time base ranging from 7 to 46 hr. Most of the observed flood events, however, have short durations. The stage hydrograph characteristics for events which occurred during the 1986-1987 season (Abdulrazzak *et al.* 1987), as well as depth to the groundwater table, are shown in Table 2. The maximum flood stage observed was 1.18 cm.

TABLE 2. Flood hydrograph characteristics for the Tabalah basin.

Date	Stage hydrograph				Peak discharge (m^3/sec)	Runoff volume $10^6(m^3)$	Groundwater depth (m)	Lag time of groundwater (hr)
	Time of rise T_r (hr)	Time of peak T_p (hr)	Time base T_b (hr)	Peak stage Y_p (m)				
7/4/86	13.83	0.10	18.0	0.60	23.65	0.279	3.74	0.50
13/4/86	18.83*	2.10(2)	20.0	1.18	72.30	1.672	3.42	1.80
23/4/86	16.67	0.50	9.5	0.58	25.05	0.279	2.32	0.36
7/5/86	13.50	2.50	40.8	0.35	8.50	0.048	2.30	0.73
30/7/86	13.33	0.10	13.0	0.50	40.00	0.318	2.72	0.77
31/7/86	16.00*	0.25(1)	10.0	0.30	12.60	0.037	2.65	0.20
21/3/87	21.00*	0.25	11.0	0.33	4.40	0.009	5.10	–
3/3/87	18.75	0.25	20.0	0.73	35.65	0.514	5.08	1.00
7/3/87	15.00	0.10	8.0	0.83	71.22	0.562	4.20	1.62
8/3/87	17.75	0.25	9.0	0.61	10.79	0.250	3.67	3.42
10/4/87	01.50	0.50(2)	46.0	0.77	48.30	2.970	3.58	–
15/4/87	17.50*	0.10	8.25	0.27	0.18	0.003	1.66	1.18
9/5/87	15.75	0.10(3)	12.0	0.71	29.40	0.316	2.21	0.83
11/5/87	04.75*	0.25(2)	18.0	1.04	196.80	2.960	1.81	1.82
23/5/87	02.50	0.50	7.0	0.49	2.90	0.073	1.18	0.58
24/5/87	19.25*	0.75(1)	11.5	0.55	5.68	0.133	1.04	0.03
Average	14.10	0.54-0.83	17.0	0.65	36.70	0.651	2.92	1.06

* – multi peak storms
(1), (2), (3), = order of peak

Based on the flood data for the major events presented in Table 2, it was possible to develop an approximate triangular stage hydrograph. The triangular hydrograph has a duration of 17 hr with time of peak of 0.7 hr. The average peak stage height was estimated at 0.65 m. This hydrograph can be used as the design hydrograph for recharge analysis for natural flood flow conditions and for artificial recharge schemes. Infiltration-recharge calculations will be based on this typical triangular hydrograph.

Considering the flood flow conditions, feasible alternatives to enhance the infiltration-recharge process could include increasing the duration of flow and broadening the contact area. Both of these methods could be achieved by using an artificial barrier, which would allow more infiltrated volume to contribute to aquifer storage.

Artificial Recharge Schemes

In general, it is suggested that a series of inflatable rubber dams 1-1.5 m in height, be constructed across the entire width of the main wadi channel, in order to regulate the flow for the purpose of recharge enhancement. These structures have been successfully used in recharge operations in the United States, particularly in California. The dams will serve as storage reservoirs, allowing more detention time, constant high head, and enhancing the infiltration-recharge process through increased contact area. Ponded water may last several hours after cessation of flow.

An artificial recharge scheme using the inflatable dams seems suited for the Kingdom's arid conditions, in comparison with schemes involving construction of storage dams or diversion of flow to adjacent areas. Flood control and recharge dams, which now number about 200 in the Kingdom (MAW 1984), were usually plagued by siltation problems and high costs associated with silt removal. It is known that arid land catchments produce high sediment (FAO 1981) and thus, dams built in these regions may accumulate a great deal of sediment, especially silt and clay. Diversion of flow to adjacent areas along the wadi coarse, for recharge purposes, involves cost for land acquisition and loss of some of the most fertile agricultural areas to inundation. Rubber dams, therefore, seem to provide the most feasible solution for modifying the stream bed and enhancing the infiltration recharge process. Deflation of the dams during flood stage rise will allow sediment, deposited from previous floods as well as that contained in the bed load, to be washed downstream. The dams can then be inflated during the period when infiltration rate is most likely to occur.

Inflatable rubber dam can be described as a sealed rubber tube, installed across a water course, which is raised by filling with air or water. This type of dam was originally conceived by Norman Imbertson in 1956, Chief Engineer of the City of Los Angeles, Department of Water and Power, who suggested inflatable gates (Bridgestone 1988). At that time, flash board and steel gates were used to divert water into recharge spreading basins. These gates required frequent replacement and incurred high operational costs.

Japan has played a prominent role in the history of inflatable dams; there are over 1000 of these dams and gates in use in Japan, and more than 300 rubber dams have been installed throughout the world (Bridgestone 1988). A sample of dams, built by Bridgestone (1988) for various purposes throughout the world, is shown in Table 3.

Inflatable dams, that were originally constructed, employed the use of water to raise the rubber tube body. Recently, however, pneumatic type dams are being used more frequently as they can be raised and lowered more rapidly. Air filled dams provide quicker raising and lowering by a simple method, eliminating the need for a water storage reservoir. Less material is required, depending on the height of the dam, as well as minimal maintenance (Bridgestone 1988). The problem of oscillation and abrasion of the lower part of the rubber dam against its foundation during heavy overflow, which can be exaggerated in the air filled dams, was overcome by using a thicker rubber material and construction of a fin on the upper face of the dam.

TABLE 3. Sample of rubber dams built throughout the world (after Bridgestone 1988).

Year	Height (m)	Length (m)	Application	Location
1979	1.50	40.0	Tidal barrier	Okayama, Japan
1982	1.00	16.0	Irrigation	Hianan, Taiwan
1982	2.75	30.0	Water supply	Sheung, India
1982	2.20	25.0	Irrigation	Zhanghia, Taiwan
1982	1.30	8.0	Irrigation	" "
1983	2.00	37.0	Irrigation	Luzon, Philippines
1984	0.60	125.0	Irrigation	Khon, Thailand
1984	1.80	10.0	Irrigation	Taitung, Taiwan
1985	0.60	125.0	Irrigation	Khon, Thailand
1985	2.44	22.4	Water supply	Calif., USA
1985	2.38	30.5	Groundwater recharge	Calif., USA
1985	2.44	177.4	Research	Pen., USA
1985	2.20	32.0	Recreation	Seoul, S. Korea
1986	2.50	22.9	Hydroelectricity	Washington, USA
1986	1.80	107.2	Irrigation	Queensland, Australia
1986	2.44	177.4	Recreation	Pen., USA
1986	1.50	54.0	Irrigation	Gon Leu, Taiwan
1987	1.60	8.0	Flood control	Shing, Taiwan
1987	1.53	35.7	Water supply	Pen., USA
1987	1.83	61.0	Groundwater recharge	Calif., USA
1987	2.13	61.0	Groundwater recharge	Calif., USA
1987	2.13	39.6	Groundwater recharge	Calif., USA
1987	1.83	61.6	Hydroelectricity	New York, USA
1988	2.44	88.7	Recreation	Pen., USA

Inflatable rubber dams have been known to have a wide range of water control applications. They can be used as head gates; in supplying water for irrigation, for groundwater recharge basins, for hydropower, for increasing the crest height of concrete dams, as boat locks and tidal barriers.

Inflatable dams usually consist of a few basic components; a rubber tube body, an inflation-deflation system, and an anchoring system built on a simple foundation, as shown in Fig. 4. The rubber body consists of layers of laminated rubber and nylon ranging from 10-16.5 mm thick depending on the height of the dam. Usually an ethylene propylene-dienthon monomer combination is mixed with the rubber to make it highly resistant to ozone, sunlight and weathering (Bridgestone 1988). The estimated lifetime of the rubber body is 30 years, based on actual experience, age testing, and long experience with a variety of rubber products (Bridgestone 1988).

The inflation-deflation system is composed of pipes connected to the dam body, and either an air or water pump as well as an automatic deflation system. The automatic deflation system is designed to operate when the water level behind the dam reaches a preset trigger level. The maximum height possible for a rubber dam is 5 m, and there is no limit on length. The maximum recommended overflow is 1.4 times

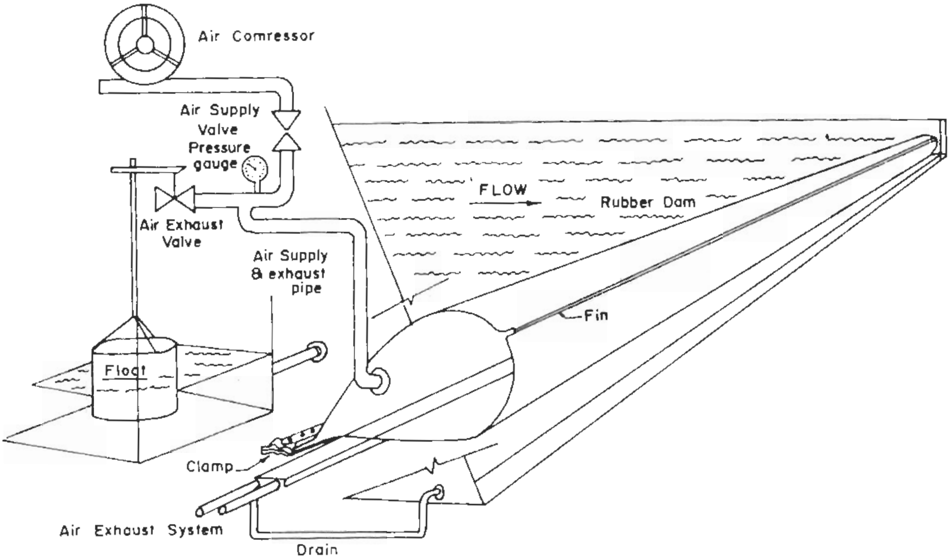

FIG. 4. Basic components of inflatable rubber dam.

the height of the dam.

The management and operation of the proposed rubber dam scheme can be implemented through telemetry techniques. Water level sensors could be placed at each dam to monitor changes in stage level. Real time data on stage can be sent *via* radio signals to each of the hydrology offices and the office operator will, in turn, send the signal to inflate or deflate the rubber dam.

Mechanism of Infiltration-Recharge from Rubber Dam Operations

The construction of inflatable rubber dams across the wadi bed may activate three possible infiltration-recharge mechanisms as follows :

1. One dimensional vertical infiltration from the entire width of the wadi channel, Fig. 5a.
2. One dimensional vertical infiltration from the active flow channel to the water table, with subsequent lateral groundwater, Fig. 5b.
3. One dimensional vertical infiltration with lateral groundwater flow as for No. 2 above, except that clogging of the surface layer with fine sediment eventually causes a reflected saturating front moving upward to fill the remaining pore space under the infiltration basin, Fig. 5c.

Vertical Infiltration from the Wadi Bed

Most of the major wadis have wide beds, and infiltration during artificial recharge operations would essentially be vertical. Results of two-phase flow studies (Ahuja

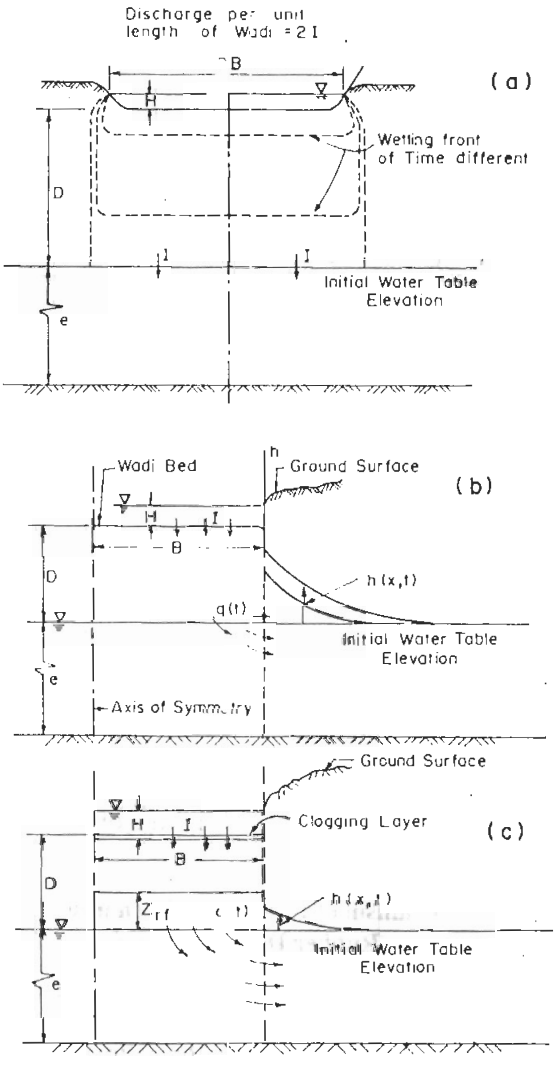

FIG. 5. Schematic view of recharge from a wadi bed.

1974, Morel-Seytoux and Khanji 1974, Parlange 1975) have indicated that the Green and Ampt model gives an adequate representation of the actual flow process, as far as the infiltration rate is concerned. This is particularly true when the depth of ponding is large. The infiltration rate, before the wetting front reaches the water table, can be calculated according to the Green and Ampt equation, as follows :

$$I = \widetilde{K} \left[\frac{(\widetilde{\theta} - \theta_i)\ (H + H_c) + W}{W} \right] \tag{1}$$

where I is the infiltration rate, K is the hydraulic conductivity at natural saturation, H is the ponded depth, H_c is the effective capillary drive, $\tilde{\theta}$ is the water content at natural saturation, θ_i is the initial moisture content and W is the cumulative infiltration depth. The effective capillary drive decreases with high initial moisture content and depth to the water table. The Green and Ampt approach assumed that the water content behind the wetting front is close to natural saturation, and the wetting front travels at a velocity approximately equal to the vertical hydraulic conductivity K_v as it reaches the water table. However, the Green and Ampt formula is suited for conditions where the water table is at a great depth.

One Dimensional Infiltration with Lateral Groundwater Flow

As artificial recharge operations continue, the wetting front may reach the water table, causing both the infiltration and recharge rates to decline. Abdulrazzak and Morel-Seytoux (1983) have shown that a decrease in the rate of recharge results from groundwater mound buildup. These conditions may occur when there is a wide wadi bed and flood flow covers the active flow channel. However, the channel width to be inundated will depend on the magnitude of flood flow and initial moisture content.

Once the wetting front begins to merge with the saturated groundwater body, incoming recharge from infiltration basins will move laterally below the water table. When the merger is complete, lateral aquifer recharge will take place at the vertical plane at the edge of the infiltrating area. The amount of recharge $[q = q(t)]$ is related to the infiltration discharge IB (per unit length of the infiltration basin) at the moment the wetting front reaches the water table and the mound extends outside the infiltration basin. Resistance to infiltration will increase proportionately as the groundwater mound develops. Fortunately, the mound also tends to dissipate due to the hydraulic head gradient in the lateral direction, which moves water away from the zone of recharge. Physically, the amount of infiltration will become very small as the water table rises towards the surface.

A method for estimation of recharge under such conditions has been addressed by Abdulrazzak and Morel-Seytoux (1983) where the recharge rate per unit width of the channel $q(t)$ can be calculated using the following equation :

$$q(t) = IB \ \exp \frac{(IB)^2 \kappa t}{[T(D + H)^2]} \ erfc \ \frac{IB(\kappa t)^{1/2}}{T(H + D)} \tag{2}$$

where κ is the aquifer diffusivity T/ϕ, T is the transmissivity, ϕ is the effective porosity, B is the half width of the channel, H is the ponding depth, D is the depth to the water table, and *erfc* is the error function complement.

One Dimensional Vertical Infiltration and Lateral Groundwater Flow Under Conditions of Surface Clogging

In cases where there is a superficial surface layer of the fine sediment, infiltration from the recharge basins or wadi bed is unsaturated. Field observation by the authors and Dames and Moore (1988) indicated that a thin layer of fine sediment consisting of silt and clay usually occurs at the wadi bed. Consequently, the infiltration-recharge process under the conditions of a clogged surface layer seems to represent the actual conditions. Therefore, theoretical analysis of the infiltration-recharge process with a clogging layer will be specifically addressed below in relation to its influence on the artificial recharge scheme involving rubber dams.

The unsaturated infiltration-recharge process, resulting from clogged surface layer, has recently been addressed by Morel-Seytoux *et al.* (1988). It is postulated that the infiltration rate I is less than the vertical conductivity K_v of the zone below the clogging layer. In the soil profile, below the clogged thin layer, the infiltration flux I is unsaturated and water content is less than the moisture content at natural saturation.

The analysis of the infiltration process before the wetting front reaches the water table, for the case of clogged surface layer, can be addressed by the application of Morel-Seytoux's (1983) integral equation. The infiltration rate I for heterogenous medium under a variable ponding depth (Morel-Seytoux 1983) is as follows :

$$I = \frac{K_v[(\tilde{\theta} - \theta_i)(H_c + Z_c + Y(t)) + k_{rw}(\theta)\, W]}{(\tilde{\theta} - \theta_i)(K_v/K_c)\, Z_c + W} \tag{3}$$

where K_v is the hydraulic conductivity in the vertical direction, $Y(t)$ is the stage ponded water depth time variation at the soil surface, K_c is the hydraulic conductivity of the clogging layer, Z_c is the thickness of the clogging layer, and $k_{rw}(\theta)$ is the relative permeability (Morel-Seytoux 1983). Other terms in the equation were defined previously. The infiltration rate can be estimated by equation (3) until the wetting front reaches the water table.

As soon as the unsaturated wetting front reaches the water table, a hdyraulic connection between the infiltration basin and the aquifer is not immediately established. Since the arrival of the percolating flux is unsaturated, a fraction of it will be reflected as it hits the rising water table. The available pore spaces become saturated as a result of the reflected flux, and the increased weight of the water below the recharge zone will induce lateral movement of groundwater away from the developing mound. As a result, a fraction of the descending unsaturated flux is transmitted laterally to recharge the aquifer, and contributes to groundwater storage.

The groundwater configuration, as a result of this flow condition, is represented in Fig. 5c. The mound profile below the basin is approximated by the position of reflected front Z_{rf} above the initial water table level and by the profile $h(x,t)$ in regions outside the recharge basin. The governing equations (Morel-Seytoux *et al.* 1988) for the reflected front Z_{rf}, mound profile $h(x,t)$ and lateral recharge rate $q(t)$ are as follows :

$$Z_{rf} = \frac{It}{(\tilde{\theta} - \theta_o)} - \frac{1}{(\tilde{\theta} - \theta_o)B} \int_o^t q(t)dt \tag{4}$$

$$h(t) = \frac{2}{\sqrt{\phi T \pi}} \int_o^t \sqrt{t-\tau}\, \frac{dq(\tau)}{d\tau}\, d\tau \tag{5}$$

$$q(t) = K[Z_{rf}(t) - h(t)] \tag{6}$$

where K is the effective conductivity related to the horizontal and vertical conductivities K_h and K_v, to the half width B of the basin and the saturated aquifer thickness e and I is the percolation flux at the water table, and θ_o is the transmission zone moisture content less than $\widetilde{\theta}$ the moisture content at natural saturation :

$$K = K_h \Big/ \left[1 + \frac{K_h e}{K_v B} \right] + K_v \Big/ \left[1 + \frac{K_h B}{K_v e} \right] \tag{7}$$

The characterized integro-differential equation for lateral recharge rate $q(t)$ is as follows :

$$(\widetilde{\theta} - \theta_o)\, Bq(n) + K \sum_{v=1}^{n} q(v) + \frac{2(\widetilde{\theta} - \theta)\, KB}{\sqrt{T\phi\pi}} \sum_{v=1}^{n} [q(v) - q(v-1)]\; \Delta(n - v + 1) = KIBn$$

for $n = 1, 2, 3 \ldots N$ (8)

where $q(n)$ is the value of $q(t)$ at discrete integer values of a selected period of time, and N is the total time horizon of interest. The discrete $\Delta\ (m)$ kernel is defined as :

$$\Delta(m) = 2/3\, [m^{3/2} - (m - 1)^{3/2}] \tag{9}$$

where $m = (n - v + 1)$

Recharge Analysis

Theoretical infiltration-recharge models have previously been presented for a variety of field conditions, however the recharge model for the clogged surface layer seems to represent the conditions expected in most wadis of the Kingdom. Consequently, recharge analyses using recharge equations were undertaken to demonstrate that the construction of inflatable rubber dams across the wadi bed would enhance the natural recharge process. Two hypothetical cases were investigated: estimation of recharge under expected natural flood flow conditions using triangular flood hydrographs, and in the presence of inflatable rubber dams across the wadi channel. The inflatable rubber dam will help to maintain a constant head of water for a duration longer than that under natural conditions.

Since the application of equation (8) concerns only the commencement of recharge, estimation of the arrival of the wetting front at the shallow water table is required. The wetting front arrival time can be estimated by the infiltration equation (3).

Field studies of Tabalah basin provide some of the required input parameters for the application of the infiltration and recharge equations (3 and 8). The estimated input parameters consist of soil porosity ($\phi = 0.30$), soil moisture variation ($\theta = 0.02$-0.25), depth to water table (D = 3-8 m), triangular stage hydrograph characteristic (T_p = 0.75 hr, T_b = 17 hr, and Y_p = 0.65 m), channel width ($2B$ = 40-100 m), saturated aquifer thickness (e = 12 m), and horizontal hydraulic conductivity (K_h = 1.2 cm/min). The additional required input parameters were estimated by a trial and error calibration procedure using the data of several field infiltration tests as shown in Fig. 2 and observed groundwater level rises due to flood events during the period 1986-1988. The result of calibrations indicated that the estimated values of the remaining parameters are as follows: residual soil moisture (θ_r = 0.03), moisture content at natural saturation ($\widetilde{\theta}$ = 0.25), vertical conductivity (K_v = 0.4 cm/min), hydraulic conductivity and thickness of clogging layer (K_c = 0.25 cm/min, and Z_c = 5 cm), effective capillary drive (H_c = 10 cm), and percolation flux (I = 0.6 cm/hr). From the application of the infiltration equation (3), the wetting front arrival at the water table, which is assumed to be at a depth of 4 to 5 m, would take 1.5 to 2 hr. Consequently, the recharge analysis indicates that the recharge process commenced 2 hr after the initial rise of the flood stage and continued for 15 hr of the triangular hydrograph recession. Following the merger of the wetting front with the saturated groundwater body, the lateral recharge rate can be estimated by using equation (8) for natural flow conditions as well as for artificial recharge schemes employing the use of inflatable rubber dams.

The amount and rate of recharge under natural flood flow conditions was estimated, taking into consideration the assumed linear decrease in the channel width, as a result of the stage hydrograph recession during a 15 hr period. Using equation (8) and the physical and hydraulic soil parameters, the rate and amount of lateral recharge was estimated for two percolation fluxes (I = 0.6 and 3.0 cm/hr) with initial channel widths of ($2B$ = 40 m) and linear decrease to a 10 m width as shown in Table (4). The recharge volume estimated for a width ($2B$) of 40 meters, and a percolation flux rate of 0.6 cm/hr was 0.37 m^3 per unit of wadi length.

Thus, as suggested earlier, the recharge process may be enhanced through the construction of inflatable rubber dams across the wadi bed, which allows a constant water level and longer duration of flow than under normal conditions. It is suggested that the dam be inflated two hours from the commencement of flow in the wadi, maintaining a constant head of water for 15 hr, for a channel width ($2B$) of 40 m. The dam should be kept inflated for an additional 15 hr during flow recession, where the linear width is decreased from 40 to 10 m. The result of calculations is presented in Table 5 using the same soil and aquifer parameters as under natural recharge conditions. The volume of recharge is estimated to be 0.51 m^3. Further analysis of a study of the influence of percolation flux to the water table and the effect of width of the wadi channel for hypothetical cases was presented in Tables 4 and 5. The increases in the recharge rates are proportional to the increases in the percolation rate.

The effects of use of a rubber dam on the recharge rate and amount are presented in Table 5. The result indicate a higher rate and volume of recharge resulting from

TABLE 4. Recharge rate and volume without inflatable dam for various widths.

Cum. Time (hr)	Half width B(m)	Cumulative recharge rate $q(t)$m^2/hr	
		I = 0.6 cm/hr	I = 3.0 cm/hr
0	20	0.0000	0.0000
1	19	0.0081	0.0406
2	18	0.0142	0.0711
3	17	0.0192	0.0958
4	16	0.0232	0.1160
5	15	0.0264	0.1322
6	14	0.0289	0.1446
7	13	0.0307	0.1533
8	12	0.0316	0.1582
9	11	0.0318	0.1590
10	10	0:0311	0.1553
11	9	0.0293	0.1465
12	8	0.0263	0.1315
13	7	0.0218	0.1084
14	6	0.0154	0.0769
15	5	0.0064	0.0322
Total recharge volume (m^3)		0.3700	1.8500

use of the inflatable rubber dams than would ordinarily occur under natural conditions. The analysis showed a recharge volume of 0.51 m^3 in comparison to a value of 0.37 m^3 under the natural flood flow conditions with an increase of 35%. Therefore, use of the rubber dam can lead to enhancement of the natural recharge process. However, it should be kept in mind that the analysis was made for a simple case, and further investigations may be necessary in order to account for the variation in input parameters on the recharge rate and amount.

Conclusion

Application of various infiltration-recharge equations under a variety of field conditions was discussed in this study. Field studies reveal the magnitude of variation in the physical and hydraulic soil properties and infiltration rates reflecting the heterogenous nature of the alluvial deposits, and their influence on the recharge process. The recharge model presented for conditions of clogged surface layer seems to be suited for most wadis in the Kingdom, and the southwestern region in particular. The flood flow characteristics, as well as the soil heterogeneity of arid environments such as Wadi Tabalah, reflect the difficult task of modeling the infiltration-recharge process.

This research illustrates, through the two case studies presented, that natural recharge would be enhanced by at least 35% through the construction of a series of inflatable rubber dams of 0.5-1.0 m height for the Tabalah basin, as well as other similar watersheds.

TABLE 5. Recharge rate and volume with inflatable dam for various widths.

Cum. Time (hr)	Half width B(m)	Cumulative recharge rate $q(t)\mathrm{m}^2/\mathrm{hr}$	
		$I = 0.6\,\mathrm{cm/hr}$	$I = 3.0\,\mathrm{cm/hr}$
0	20	–	–
1	20	0.0082	0.0408
2	20	0.0144	0.0719
3	20	0.0196	0.0981
4	20	0.0242	0.1208
5	20	0.0282	0.1408
6	20	0.0317	0.1587
7	20	0.0250	0.1748
8	20	0.0379	0.1895
9	20	0.0406	0.2029
10	20	0.0430	0.2152
11	20	0.0453	0.2266
12	20	0.0474	0.2371
13	20	0.0494	0.2469
14	20	0.0512	0.2560
15	20	0.0529	0.2646
16	19	0.0524	0.2622
17	18	0.0517	0.2587
18	17	0.0506	0.2531
19	16	0.0490	0.2452
20	15	0.0464	0.2344
21	14	0.0441	0.2204
22	13	0.0405	0.2027
23	12	0.0361	0.1806
24	11	0.0307	0.1534
25	10	0.0240	0.1201
26	9	0.0159	0.0794
27	8	0.0059	0.0294
28	7	0.0036	0.0110
29	6	0.0020	0.0100
30	5	0.0010	0.1000
Total recharge volume (m^3)		0.5100	2.5100

It is suggested that a series of pneumatic type dams be constructed along the main channel. These dams can serve as storage reservoirs, allowing more retention time and larger contact area and thus enhancing the infiltration recharge process. Use of the proposed type of dam may overcome the problem of siltation which is usually associated with arid environments. In addition, these dams are simple to operate, require minimal maintenance, and are harmonious with the natural environment.

Finally, a pilot project using a single dam should be carried out in the experimental study reach or at a sight where reclaimed water is being discharged into a wadi bed, to assure its feasibility and practicality.

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الاستعاضة الاصطناعية للمياه الجوفية من رسوبيات الأودية

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تشتمل الدراسة على إجراء تجارب حقلية وتحليل نظرى لعملية تسرب المياه فى التربة ، والاستعاضة الناتجة عنها للمياه الجوفية عن طريق مياه السيول . وقد ناقش التحليل النظرى عملية السريان الرأسى للمياه فى التربة والاستعاضة الناتجة عنها وخصوصا الاستعاضة غير المشبعة .

وقد أظهرت التجارب الحقلية أن لاختلاف مكونات رسوبيات الأودية والخصائص الهيدرولوجية لحدوث السيول وتكرارها تأثيرًا كبيرًا على كمية استعاضة المياه الجوفية . وحيث إنه فى الغالب توجد طبقة قليلة النفاذية على مجرى سطح الوادى ، فإن المعادلات المقترحة لهذه الحالة يمكن تطبيقها على معظم أودية المملكة .

وقد أظهرت النتائج الخاصة بتطبيق معادلات التسرب والاستعاضة غير المشبعة عن طريق تشييد سدود مطاطية ، زيادة في كمية الاستعاضة بمقدار ٣٥٪ عن الحالة الطبيعية . ويُقترح إقامة مثل هذه السدود لما لها من مميزات عديدة حيث إنها سوف تؤدى إلى زيادة المساحات المغمورة ومدتها ، وسوف تساهم بدرجة كبيرة فى زيادة كمية استعاضة المياه الجوفية وتكرارها .