

CHAPTER 25

SALINE WATER INTRUSION IN COASTAL AREAS: A CASE STUDY FROM INDIA

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ABSTRACT

An innovative method of control of saltwater intrusion into the coastal aquifers has been suggested in this paper. A new method consists of withdrawal by Qanat-well structures with reasonable compensation by rainwater harvesting by means of recharge ponds and recharges well. The salient features of the methodology are described by considering a design example adopted in the Contai Polytechnic Institute Campus of the district of Purba Midnapur in the state of West Bengal, India.

25.1 INTRODUCTION

Groundwater is the second largest reserve of fresh water on earth. About 2 billion people, approximately one-third of the world's population, depend on groundwater supplies, withdrawing about 20% of global water (600–700 km) annually—much of it from shallow aquifers (Patra et al., 2006). India cities located near coastlines with a large population can experience saline water intrusion due to over-exploitation of groundwater, causing this significant threat to freshwater resources. Sustainability strategies adopted to retard or halt the rate of saline water intrusion are necessary to protect the resources from further damage. The complexity of hydrogeological set up in the concerned area calls for scientific management techniques to be adopted in the groundwater development. This requires a clear understanding

of the hydrogeology of the area concerned, appreciation of the possible consequence of over or under developments and a coordinated approach of the planners, hydrogeologists, irrigation engineers, social scientists in the field (Bhattacharya et al., 2004). Excessive withdrawal of groundwater in coastal zones will lead to depression of water table with associated hazards like putting the well out of use, rendering the abstraction uneconomic with increased lift. A sustained regional groundwater drawdown below sea level runs the risk of saline water intrusion, even for confined coastal aquifers. A careful pumping and rest schedule may help in avoiding many such problems. An uncontrolled groundwater development may lead to a reversal of fresh water gradient thereby resulting in saline water ingress into the coastal aquifers. For example, reports of salinization of wells subjected to continuous heavy pumpage in the coastal district of Purba Midnapur, West Bengal, India though few, are not uncommon.

As suggested by various Scientists and Engineers, there are several established methodologies to control and minimize the problems associated with groundwater extraction followed by saline water intrusion. Some of the popular methods adopted are: the creation of a hydraulic barrier, rainwater harvesting, artificial recharge, canal irrigation, desalination, and reverse osmosis, etc. However, the author has developed an innovative, cost-effective technique to control saltwater intrusion into coastal aquifers; the techniques include withdrawal of coastal fresh water by means of qanat-well structures associated with artificial recharge through rainwater harvesting aided with percolation pond and recharge well. A case study on a selected location of the coastal zone of Purba Midnapur has been carried out. Adequate quantifications of the effectiveness of this new methodology have been incorporated, and relevant conclusions are drawn therefrom.

25.2 MATERIALS AND METHODS

25.2.1 NEW APPROACH FOR CONTROL OF SALINE WATER INTRUSION IN COASTAL AREAS

While a numerical simulation method like the finite difference or finite element scheme might be very illuminating from a research point of view, it is unlikely that field engineers will be able to capture the intricacies of such an approach. Keeping this in view; an innovative analytical method which is appropriate and at the same time easily implemental; is adopted as a new

approach for groundwater withdrawal and control of saline water intrusion in the study area.

It is evident that any withdrawal of groundwater from a coastal aquifer results in the advancement of the saltwater-freshwater interface from the shoreline towards to the point of withdrawal (Todd, 1976) unless the withdrawal is compensated by an equivalent artificial recharge. The rainwater harvesting is one of the most popular recharge techniques followed worldwide (UNEP Report, 2009). In the proposed methodology for reduction of saline water intrusion into the coastal aquifer and subsequent safe withdrawal of groundwater, the adoption of qanat-well structure associated with artificial recharge by rainwater harvesting through recharge ponds and recharge wells is hereby studied as one of the useful and cost-effective techniques. The salient features of the methodology are described by considering a design example adopted by the author in the Contai Polytechnic Institute Campus of the district of Purba Medinipur in the state of West Bengal.

25.2.1.1 ADOPTION OF QANAT-WELL STRUCTURE

The inland aquifers are suffering from the maladies of over-exploitation of groundwater by way of unscrupulous pumping; the coastal aquifers encounter the danger of seawater intrusion and saline water upconing. Due to saltwater intrusion, deep tube-well is not recommended because of the upconing problem. However, adoption of the shallow well is also inappropriate because of significantly lower discharge. It is well established (Raghu Babu et al., 2004) that adoption of qanats in such conditions not only yields higher discharge but also reduces the upconing problem significantly. Horizontal wells are more efficient than conventional vertical wells for environmental remediation of groundwater for a number of reasons such as:

- Greater reservoir contact with the well screen increases the productivity of the well.
- Geometry of the groundwater zone is conducive to greater access with a horizontal well than a series of vertical wells.
- Access to groundwater zones with vertical wells are often hindered by obstacles such as buildings, paved surfaces, or other topographical obstructions.

Beljin and Losonsky (1992) provided a generalized solution, based on the work of Joshi (1986), for estimating steady-state discharge for withdrawal of

groundwater from a vertical aquifer by means of horizontal water well. The solution provided was given by:

$$Q = \frac{2\pi k_h Hs}{\ln\left[\left(\frac{\sqrt{1+\sqrt{1+64R^4/L^4}} + \sqrt{-1+\sqrt{1+64R^4/L^4}}}{\sqrt{2}}\right) \left(\frac{\frac{\beta H^2}{2} + 2\beta\delta^2}{Hr_w}\right)^{\beta H} \frac{L}{L}\right]} \quad (1)$$

where,

Q = Steady state discharge.

s = Drawdown above the well center.

L = Length of the horizontal well.

r_w = Well radius.

k_h = Hydraulic conductivity of the aquifer along the horizontal direction.

H = Aquifer thickness.

$$\beta = \sqrt{\frac{k_h}{k_v}}$$

k_v = Hydraulic conductivity of the aquifer along the vertical direction.

δ = Off-centered eccentricity of the well-center in the vertical aquifer plane.

R = Radius of the influence of the equivalent vertical well in the same aquifer for the same drawdown, which can be reasonably estimated using the available correlations (for example, Sichardt's formulae).

The above equation has been modified, applying the method of superimposition, to reasonably estimate the steady-state discharge by means of a 4-legged qanat. The final expression is obtained as:

$$Q_q = \frac{2\pi k_h Hs}{\ln\left[\left(\frac{\sqrt{1+\sqrt{1+4R^4/L_q^4}} + \sqrt{-1+\sqrt{1+4R^4/L_q^4}}}{\sqrt{2}}\right) \left(\frac{\frac{\beta H^2}{2} + 2\beta\delta^2}{Hr_q}\right)^{2\beta H} \frac{L_q}{L_q}\right]} \quad (2)$$

where, Q_q = Steady state discharge from the qanat.

L_q = Length of a qanat leg (Figure 25.1)

r_q = Inner radius of qanat legs

The maximum discharge from the qanat under full flow condition can be obtained by putting $s = d - 2r_q$ (neglecting the wall thickness of the qanat legs) in the Eq. (2). Thus,

$$Q_q(max) = \frac{2\pi k_h H(d - 2r_q)}{\ln\left[\frac{\sqrt{1 + \sqrt{1 + 4R^4/L_q^4}} + \sqrt{-1 + \sqrt{1 + 4R^4/L_q^4}}}{\sqrt{2}}\right] \left(\frac{\frac{\beta H^2}{2} + 2\beta\delta^2}{Hr_q}\right)^{2\beta H} \frac{1}{L_q}} \quad (3)$$

where, $Q_{q(max)}$ = Maximum possible discharge from the qanat.

d = Depth of the bottom surface of the qanat legs below the undisturbed water table.

Using Sichardt's formulae $R = 3000(d - 2r_q)k_h$ in Eq. (3), where all terms should essentially be in SI units, the Eq. (3) can be written as:

$$Q_q(max) = \frac{2\pi k_h H_f(d - 2r_q)}{\ln\left[\xi \frac{\left(\frac{\frac{BH^2}{2} + 2\beta\delta^2}{H_f r_q}\right)^{2\beta H}}{L_q}\right]} \quad (4)$$

$$\text{where } \xi = \frac{\sqrt{1 + \sqrt{1 + 4[3000(d - r_q)\sqrt{k_h}J^4/L_q]} + \sqrt{-1 + \sqrt{1 + 4[3000(d - r_q)\sqrt{k_h}J^4/L_q]}}}{\sqrt{2}}$$

Although upconing in case of qanat-well structures is apparently not practical specifically when the saltwater-freshwater interface is situated at a significant depth below the bottom of the structures, the upconing problem may be catastrophic for shallow depth of interface in the area near the sea. Therefore, the present analysis is extended considering upconing as well (Figure 25.2). After the recommendation of Dagan and Bear (1968):

$$Z_\alpha = \frac{Q_q}{2\pi \left(\frac{\rho_s}{\rho_f} - 1\right) K_h (H_f - d)} \quad (5)$$

where, Z_∞ = the value of Z at infinite time. The value of Q attains the maximum value when $Z_\infty = H_f - d$

$$Q_{q(max)} = 2\pi k_h \left(\frac{\rho_s}{\rho_f} - 1\right) (H_f - d) \quad (6)$$

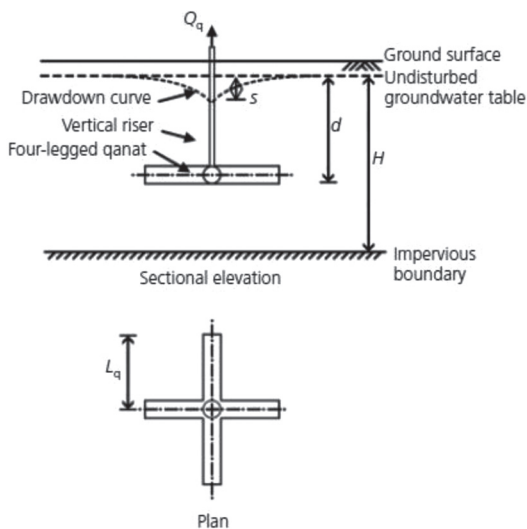


FIGURE 25.1 A typical 4-legged qanat.

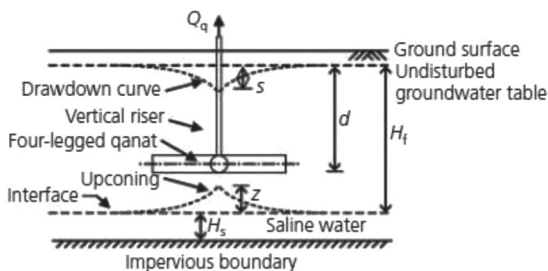


FIGURE 25.2 Withdrawal of groundwater by qanat in salinity affected aquifer.

The optimum values of $Q_{q(max)}$ shall be the least of the two values obtained from the Eq. (4) and (6). It is hereby mentioned that the design values of the depth of qanat-well structures are calculated as unrealistically high, therefore not feasible, the number of such qanat-well structures may be reasonably increased as required.

25.2.2 GROUNDWATER RECHARGE BY RAINWATER HARVESTING

A hybrid method considering ponds and recharge wells is adapted to: (i) combine the best of both, (ii) providing only ponds would eat up a huge amount of unnecessary spaces, and (iii) providing only wells would necessitate pressure injection

into the aquifer. Therefore, since due to space constraint in the locality under consideration, the full recharge may not be affected by the pond, recharge wells are needed. The withdrawal of groundwater by qanat should be suitably compensated by a recharge with rainwater harvesting, the salient features of this new approach with adequate quantification is described in the following subsections.

25.2.2.1 RECHARGE AREA

If fresh water in a coastal area is withdrawal regularly, the saltwater-fresh-water interface is progressively advanced horizontally as well as vertically unless the withdrawal is subsequently compensated by a suitable artificial groundwater recharge techniques. The method proposed herein includes rainwater harvesting by means of recharge ponds and recharge wells design.

Usually for a particular community, neglecting the area of recharge well,

$$A_t = A_{roof} + A_{road} + A_{pond} + A_1 \quad (7)$$

where, A_t = Total area of the community;

A_{roof} = Total roof cover area for all building in the community;

A_{road} = Total road area in the community;

A_{pond} = Total pond area of the community;

A_1 = Total area of vacant land in the community.

25.2.2.2 FACTOR OF SAFETY FOR RAINFALL RECHARGE

For a particular community in a coastal area, the net volume of freshwater withdrawal in a certain period of time should not exceed the available volume of recharge for that period. With this conception, the corresponding factor of safety for the particular community has been formulated for the volumetric constancy as:

$$F = \frac{\text{Volume of water annually available for recharge}}{\text{Volume of water annually extracted}} \\ = \frac{\left[(A_t - A_{roof})\eta + \alpha A_{roof} \right] R}{365WP} \quad (8)$$

where,

W = Average water consumption of people in the community in liter per capita per day = 140 lit/Capita/Day.

P = Population of the community.

R = Design annual rainfall in mm.

η = Recharge coefficient.

α = Fraction of rainwater collected at roof which is directed towards the recharge well.

It is hereby mentioned that this technique is most effective when the value of the factor of safety is slightly higher than unity. The excessively high value of the factor of safety may be necessitated adequate drainage facility in the area under consideration to avoid the undesirable circumstance like water logging and flooding. Conversely, when the value of the factor of safety is less than unity, the situation can be compensated either by reducing the withdrawal of groundwater or by increasing the catchments area for rainfall recharge.

25.2.2.3 PERCOLATION POND

The design precipitation chosen depends on the design return period of the precipitation. The longer the design returns period, the greater the precipitation. After recommendation by Sarkar (2007), the water collected from the roof area in the community is partly allowed to percolate through recharge chamber cum recharge well, and the remaining portion is stored for future usages like firefighting and domestic use, etc. Therefore, the total area of recharge pond for the community under consideration may be estimated reasonably considering the net volume of water to be stored in the pond during the monsoon period. Therefore,

$$A_p = \frac{[(A_t - A_{roof} - A_{road})\eta_1 + A_{road}]R_m}{1000 H_p - (1 - \eta_1)R_m} \quad (9)$$

where, A_p = Area of the Pond.

R_m = Design monsoon rainfall in mm.

η_1 = Runoff coefficient relevant to the area.

H_p = Depth of pond to be excavated.

25.2.2.4 RECHARGE CHAMBER WITH RECHARGE WELL

As already mentioned earlier Sarkar (2007) designed a rainwater harvesting scheme for TCS building Salt Lake, Kolkata, India. Following his

recommendations, the dimensions and number of recharge chamber fitted with 100 mm diameter recharge well for the community under consideration may be reasonably estimated by:

$$\frac{V_w N_w}{V_{ws} N_{ws}} = \frac{\alpha R A_{roof}}{\alpha_s R_s A_{roof s}} \tag{10}$$

where V_w = Volume of the recharge chamber in the community.
 N_w = Nos. of recharge chamber fitted with 100 dia. recharge well adopted in the community.

The suffix ‘s’ denotes the corresponding parameter for the relevant to Sarkar (2007). From the field investigation, SP reading is observed to move towards negative side indicating the presence of sand aquifer below. As observed, the average depth freshwater-saltwater interface is situated at a depth of about 40m below the ground surface. It is advisable not to go for ‘Deep Tube Well’ construction; Qanat-Well Structures is preferable in this situation. The input parameters necessary for design in the locality under consideration are summarized below in Table 25.1.

TABLE 25.1 Values of Variables Determined From Hydrogeological Investigation

Input Parameter	Values
Maximum design discharge, $Q_{g(max)}$	Calculated using Eqs. (4) and (6)
Aquifer thickness, H	40 m
Horizontal hydraulic conductivity, K_h	$3.512 \times 10^{-4} \text{ m s}^{-1}$ (Laboratory test)
Vertical hydraulic conductivity, K_v	$3.614 \times 10^{-4} \text{ m s}^{-1}$ (Laboratory test)
Conductivity contrast, $\beta = \sqrt{\frac{K_h}{K_v}}$	0.9857
Well eccentricity, δ	0
Population in Contai Polytechnic College Campus, P	300
Total Area of the College Campus, A_t	90,169 m ²
Total Roof Area including Student Hostels, A_r	12,000 m ²
Total road area, A_r	1010 m ²
Total area of pond, A_p	1204 m ²
Area of vacant land, A_l	75,955 m ²
Design annual precipitation, R	Various values are taken
Design monsoon precipitation, R_m	Various values are taken
Per capita water consumption, W	140 liters/capita/day
Recharge coefficient, η	Chosen from available literature
Runoff coefficient, η_l	-do-

25.3 APPLICATION OF NEW APPROACH

From the available groundwater data, the coastal areas in the district of Purba Medinipur mostly consist of unconfined aquifers, with the average freshwater table of 2–3 m below the ground surface (Goswami, 1968; Sarkar, 2005) and the average saline water and fresh water interface varies in the range of 0–100 m. The aquifer is unconfined having an average hydraulic conductivity of $k_h = 3.512 \times 10^{-4} \text{ m s}^{-1}$ and $k_v = 3.614 \times 10^{-4} \text{ m s}^{-1}$. From the available data (UNDP Report, 2006; WHO/UNICEF Report, 2010), the value of W (water demand) has been chosen as 140 liters/capita/day. The average population in the campus is 250. Considering a 20% increase, the value of P is taken as 300. On the basis of water demand per day for the College Campus with pumping operation per day such as 2 hrs., 3 hrs., 4 hrs., 5 hrs., the qanat-well structures with a different parameter such as length, radius, and depth of qanat is calculated using the Eq. (4). The $Q_{q(max)}$ is calculated as follows:

$$Q_{q(max)} = \frac{W P}{t \times 3600 \times 10^3} \quad (11)$$

where, t = hourly pumping rate in the college campus per day.

Using Eq. (4), the values of the depth of the qanat base for the chosen value of L_q and r_q is calculated. This value of 'd' is back-figured in the Eq. (6) to check for upconing. If the discharge calculated from the Eq. (6) exceeds the design discharge as estimated previously, upconing does not take place. Otherwise, the depth 'd' may be calculated by using Eq. (6). It is observed that at the College Campus, the upconing does not occur. As observed from Figure 25.3, the parameter d decreases following a curvilinear pattern with the length of leg L_q . The variation is quite sharp in the range of $1 \text{ m} \leq L_q \leq 3 \text{ m}$ and assumes a linear pattern for $L_q > 3 \text{ m}$. The above curves will be helpful for design Engineer to adopt suitable values of the qanat parameter r_q , L_q , d, and t considering other design aspects such as, maximum depth of water table, the feasibility of construction, etc.

25.3.1 RECHARGE STRUCTURES

25.3.1.1 RAINFALL RECHARGE

From the available literature (State Forest Report, 2008–2009 and Annual Climate Summary, 2010), the total annual rainfall in the district of Purba Medinipur of the state of West Bengal, India for the decade 2001–2010

varies in the range of 1296–2259 mm. For the design of recharge pond equipped with recharge-wells for the given community, the factor of safety F for recharge may be estimated using the Eq. (8), using the following data:

$$A_i = 90,169 \text{ m}^2$$

$$A_{ROOF} = 12000 \text{ m}^2$$

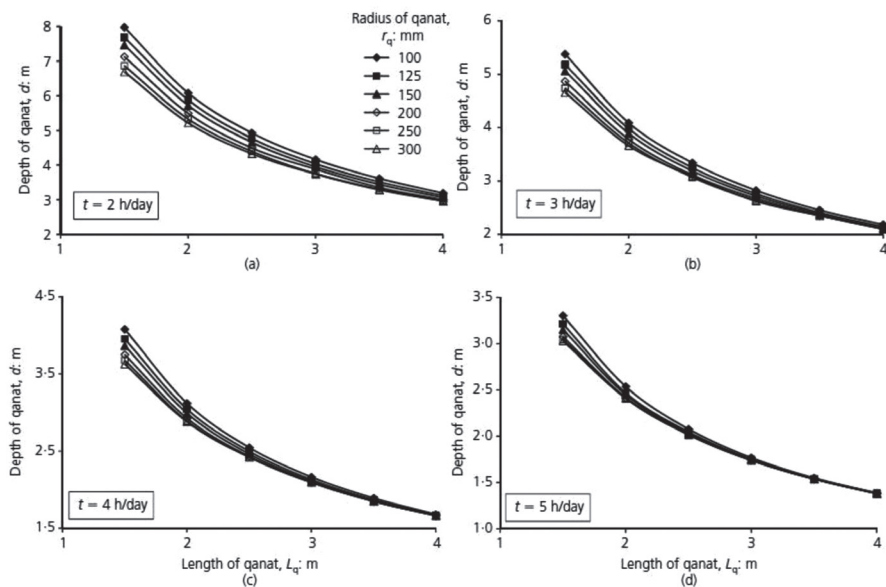


FIGURE 25.3 Variation of the depth of qanat at base versus length of qanat leg for pumping duration (in hours per day), t : (a) 2; (b) 3; (c) 4; and (d) 5.

The value of the recharge coefficient η may be reasonably estimated from the available literature (Wu and Zhang, 1994; Chaturvedi, 1936; Kumar, 2002). Wu and Zhzng (1994) calculated the effective precipitation P_e and the total amount of recharge P_e produced by P_e . By performing a regression analysis on P_e and R data available in China, a functional relationship between them was obtained as:

$$R_e = 0.87(P_e - 27.4) \quad (12)$$

where R_e = Infiltration Recharge in mm;

P_e = Effective Rainfall in mm.

Chaturvedi (1936) derived an empirical relationship to arrive at the recharge as a function of annual precipitation in Ganga-Yamuna doab basin as follows:

$$R = 2.0 (P - 15)^{0.4} \quad (13)$$

where, R = net recharge due to precipitation during the year (inch);
 P = annual precipitation (inch).

The formula of Chaturvedi (1936) was later modified further by Kumar and Seethapathi (2002), and the modified form of the formula is:

$$R = 1.35 (P - 14)^{0.5} \quad (14)$$

As observed from Figure 25.4, the factor of safety increases linearly with an increase in annual precipitation, which is well in agreement with the Eq. (8). Also, the curves relevant to those of Chaturvedi (1936) and Kumar and Seethapathi (2002) almost coincide. Both the magnitudes and the slope of the curve relevant to that of Wu and Zhzng (1994) are significantly high.

25.3.1.2 PERCOLATION POND

The runoff should be assessed accurately for designed the recharge structures and may be assessed by the following formula.

Runoff = Catchments area x Rainfall x Runoff coefficient

Runoff coefficient plays an important role in assessing runoff availability, and it depends upon the catchments characteristics. It is the factor that accounts for the fact that not all rainfall falling on catchments can be collected. Some rainfall will be lost from the catchments by evaporation and retention on the surface itself. The required area of recharge pond decreases in a hyperbolic manner with the depth of pond to be excavated, which is well in agreement with Eq. (9).

Recharge chamber with recharge well: The relevant calculations for recharge chamber with recharge well are described below. As observed from Figure 25.5, the number of recharge chambers N_w decreases fairly exponentially with the volume V_w of the recharge chambers. The rate of decrease is pronounced in the range of V_w , 5, beyond which a stabilizing tendency is noted.

Appropriate Engineering Design: The appropriate site-specific engineering design is suggested by the author following the analysis described above in details.

Qanat-well Structure: The following parameters are suggested:

- $t = 3$ hours.
- $r_q = 125$ mm

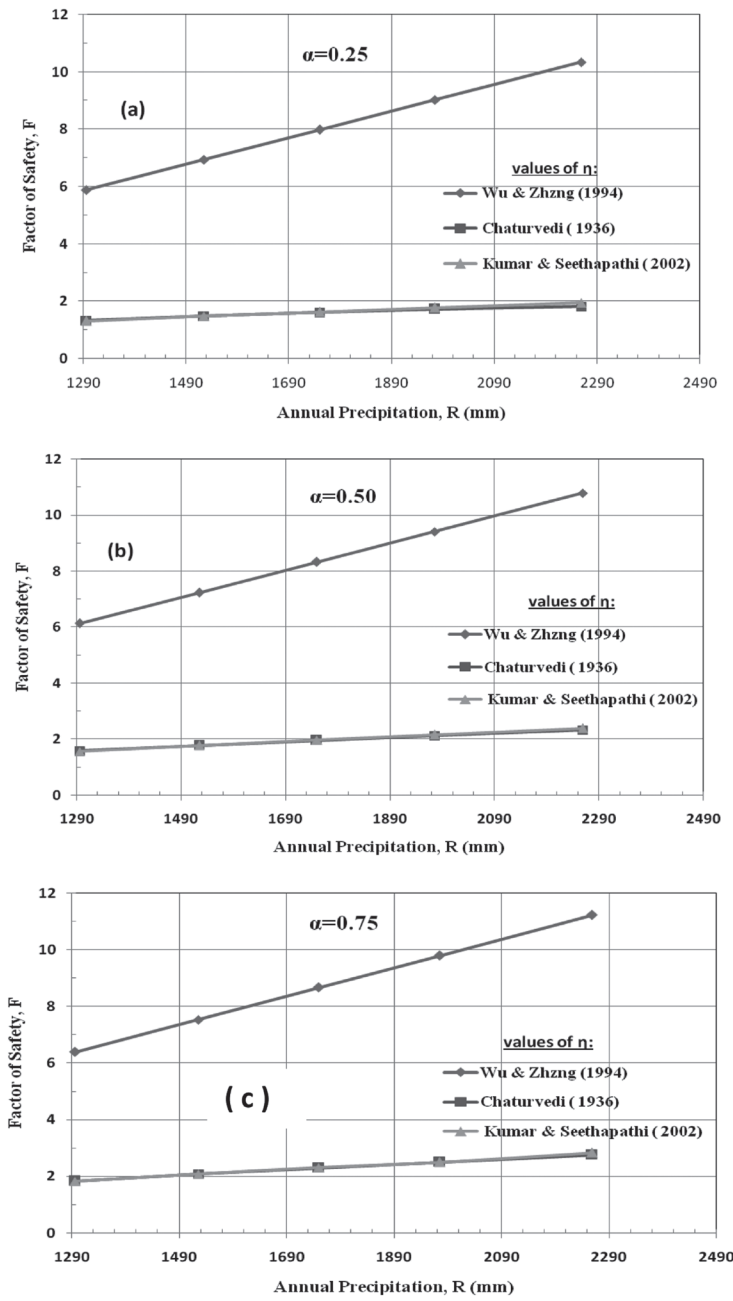


FIGURE 25.4 Variation of the factor of safety F with annual precipitation R for: (a) $\alpha = 0.25$. (b) $\alpha = 0.50$, and (c) $\alpha = 0.75$.

- $L_q = 2.5\text{ m}$
- $d' = 3.25\text{ m}$

(For future safety provision, 2 qanat-well structures are recommended for alternative use). Therefore, design depth of the qanat below G.L. = $d +$ maximum depth of G.W.T. = $3.25 + 3 = 6.25\text{ m}$

Factor of Safety: The factor of safety for minimum and maximum rainfall are obtained as

Rainfall	Factor of Safety
Minimum	6.135 (after Wu and Zhzng, 1994)
	1.586 (after Chaturvedi, 1936)
	1.565 (after Kumar and Seethapathi, 2002)
Maximum	10.786 (after Wu and Zhzng, 1994)
	2.321 (after Chaturvedi, 1936)
	2.387 (after Kumar and Seethapathi, 2002)

For the Indian condition, the recommended value as per Kumar and Seethapathi (2002) is mostly suitable. It is also mentioned here that the value of factor of safety under minimum rainfall in the last 10 years should not fall below 1.0., therefore satisfactory in terms of reasonable compensation of withdrawal of groundwater. Also, under maximum rainfall in the last 10 years, the factor of safety exceeds 2.0, which may introduce sufficient pushback of saline water interface. It should also be mentioned here that for the excessively high value of factor of safety, adequate drainage should be facilitated at the site towards nearby stream channel.

Area and depth of Percolation Pond: The design rainfall data has been chosen as $R_M = 367.1\text{ mm}$. The depth of the pond is chosen as $H_p = 3\text{ m}$. Therefore, the area of pond required may be interpolated as, $A_p = 1202.436\text{ m}^2$. Hence, in the Contai Polytechnic College Campus, 4 ponds of area 301 m^2 each are provided, the depth of each pond is 3.0 m . Figure 25.6 illustrates the plots of recharge pond area versus pond depth for monsoon precipitation of (a) 350 mm , (b) 500 mm , and (c) 750 mm .

Recharge Chamber with Recharge Well: Adopting a total roof area in the site as 12000 m^2 , $\alpha = 0.5$ and $R = 2259\text{ mm}$ (maximum rainfall in last 10 years), keeping the recharge chamber dimensions as: $L = 2\text{ m}$, $B = 2\text{ m}$, $H = 1.2\text{ m}$, the number of recharge chamber with recharge well has been obtained as $N_w = 12$. It is also mentioned that the dimension of the recharge wells adopted here are as per the recommendation of Sarkar (2007) and are as follows:

Diameter of the well	100 mm
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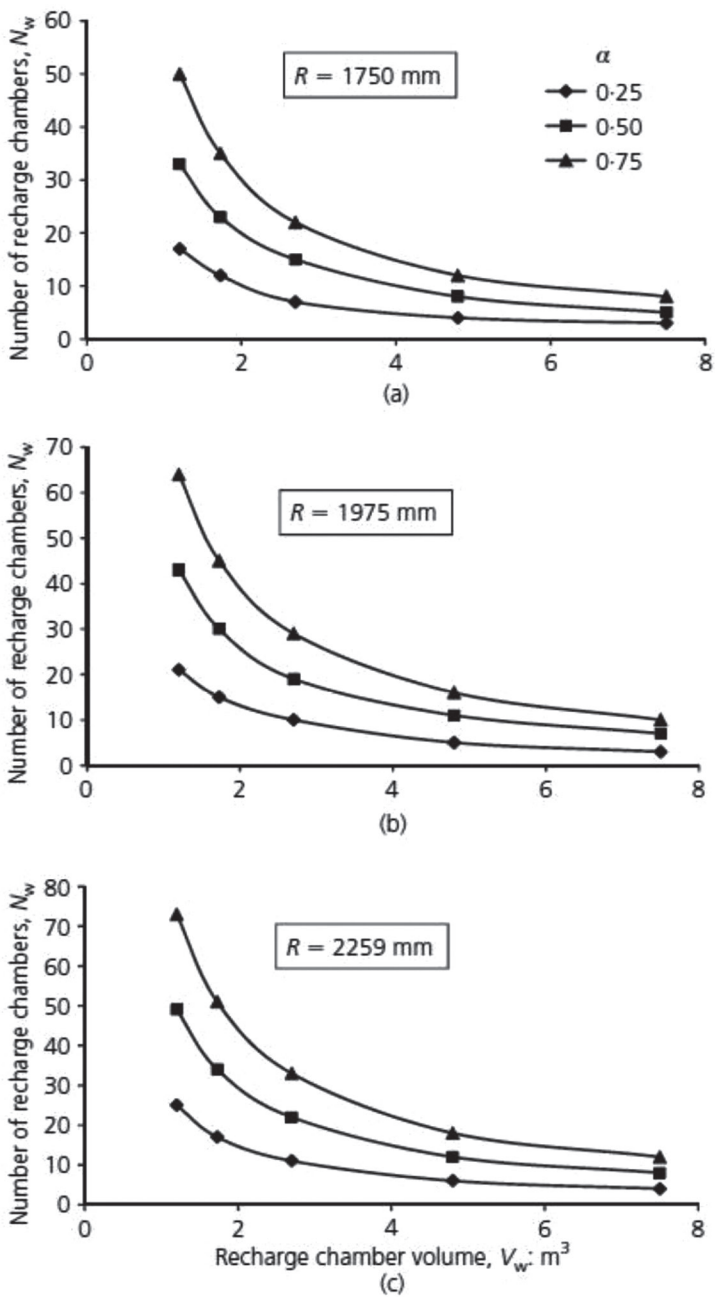


FIGURE 25.5 Variation of recharge chamber volume with number of chambers for (a) $R = 1750$ mm, (b) $R = 1975$ mm, (c) $R = 2249$ mm.

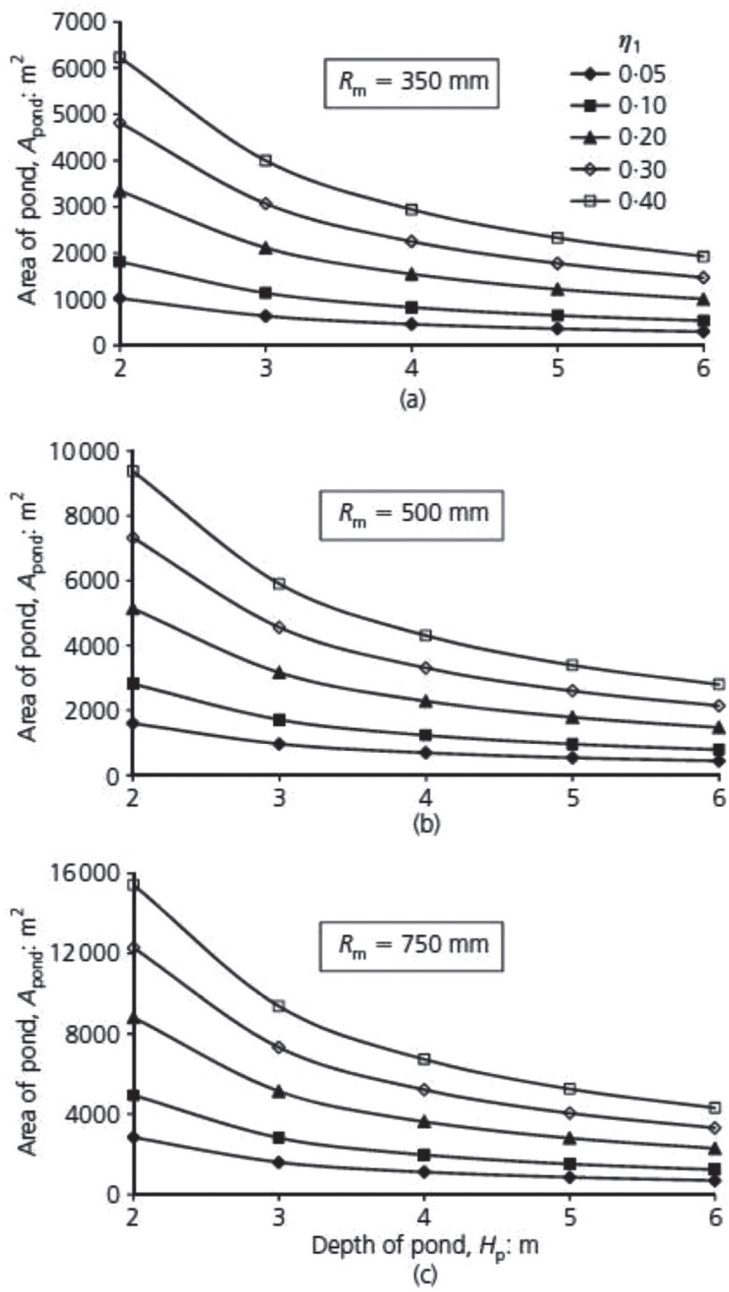


FIGURE 25.6 Plots of recharge pond area versus pond depth for monsoon precipitation of (a) 350 mm, (b) 500 mm, and (c) 750 mm.

Strainer dia in the aquifer	100 mm
Length of strainer	12 m
Dia of the inlet strainer placed in the recharge chamber	150 mm
Length of 150 mm strainer	800 mm

As per design recommendation, the plan of the site provided with the new methodology has been given in Figure 25.7. The Contai Polytechnic College Campus area is shown with the location of qanat-well structures, percolation ponds and recharge chambers with recharge wells. The cross-section of recharge well adopted and methodology of recharge through recharge wells and recharging chambers are also shown in the Figure 25.7. It is hereby mentioned that the parameters for recharge, well, etc. used in the design are highly site-specific. Successful application of the entire methodology is possible only when the design parameters are adequately chosen for a specific site.

25.4 CONCLUSIONS

The following significant conclusions are drawn:

An innovative method has been developed by the author for coastal zone groundwater management which involves withdrawal by qanat-well structures associates with equivalent artificial recharge by rainwater harvesting through percolation pond and recharges well. If adequately applied and design the proposed methodology is expected to be quite useful and convenient, for the unconfined condition of the coastal aquifers. As the suggested methodology has been applied to a selected coastal site located at Purba Midnapur district to study the various quantitative aspects of the method, it was observed that depth of qanat d decreases following a curvilinear pattern with the length of leg L_q . The variation is quite sharp in the range of $1\text{ m} \leq L_q \leq 3\text{ m}$ and assumes a linear pattern for $L_q > 3\text{ m}$.

The factor of safety for rainwater recharge in the selected location increases linearly with an increase in annual precipitation. Also, the curves relevant to those of Chaturvedi (1936), and Kumar and Seethapathi (2002) almost coincide. Both the magnitudes and the slopes of the curves relevant to that of Wu and Zhzng (1994) are significantly high. This technique is most effective when the value of the factor of safety is slightly higher than unity. The required area of recharge pond decreases in a hyperbolic manner with the depth of pond to be excavated.

The number of recharge chambers N_w decreases fairly exponentially with the volume V_w of the recharge chambers. The rate of decrease is pronounced in the range of $V_w < 5$, beyond which a stabilizing tendency is noted. It is

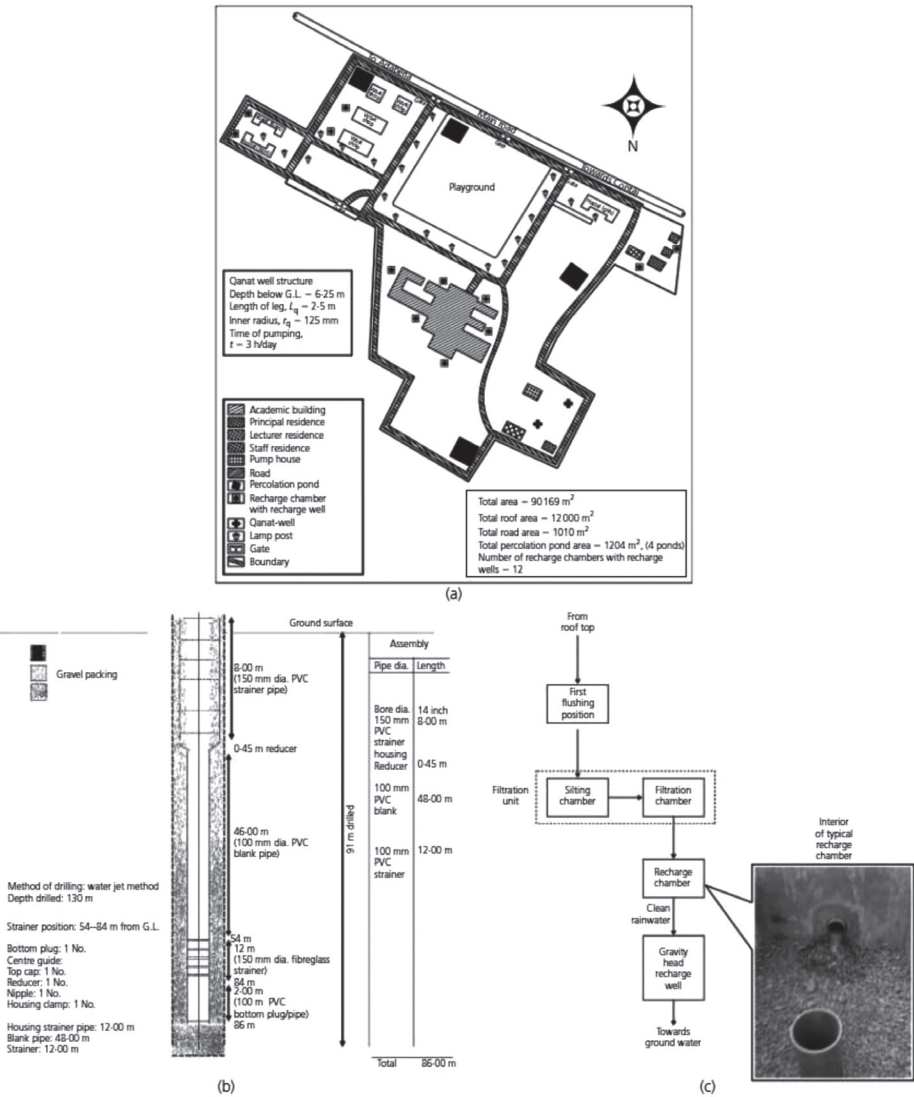


FIGURE 25.7 (a) Contai Polytechnic College Campus area showing the location of qanat-well structures, percolation ponds and recharge chambers with recharge wells; (b) Cross section of recharge well adopted; (c) Methodology of recharge through recharge wells and recharging chambers.

hereby mentioned that the model suggested is highly site-specific. Successful application of the entire methodology is possible only when the design parameters are adequately chosen for the particular site under consideration.

KEYWORDS

- **coastal environment**
- **geotechnical investigation**
- **management and control of saline water intrusion**
- **mathematical analysis**
- **quantitative analysis**

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