Chapter 3

Flow through Multiple Well Points System

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Additional information is available at the end of the chapter

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Abstract

Under natural geographical settings, there are regions all over the world where the native groundwater quality is brackish. However, recharging from the surface water bodies (i.e., rivers and canals) establishes freshwater lenses in the upper portions of these brackish aquifers. Skimming of these freshwater lenses is a viable technique for sustaining livelihood and agricultural practices in these regions. In the present chapter, various skimming methods have been discussed. In addition, one another type of problem has also been developed in certain pockets of these regions. The non-withdrawal of groundwater and the excess use of easily available surface water resources (i.e., canal water) have created severe water logging conditions. Subsequently, it leads to the creation of salt-affected soils. One of such areas located in the southwestern Punjab (India) was taken under study. Keeping the region's problems in mind and considering the merits and demerits of all the skimming methods, a much efficient and affordable technique named multiple well points system (MWPS) has been proposed. The continuous use of MWPS not only reclaimed the area but also improved the groundwater quality. The system was field tested and modified before recommending to the farmers. Later on, the MWPS's feasibility as a groundwater recharging system was also demonstrated in the field and the results have shown that it is a viable technique for reviving freshwater lenses in the region.

Keywords: brackish/saline aquifers, groundwater recharging, multiple well points system, skimming wells, well hydraulics

1. Introduction

Since ancient times, it is a natural tendency of humankind to settle near the perennial and freshwater resources. But for many millennia, humankind's capability to abstract groundwater was very little compared with the available resources [1]. With time the demand for freshwater increases due to rapid population growth and expanding economies in many parts of the world [2]. The mechanization advancements in the twentieth century, geological knowledge, well drilling, and pump technology made it more convenient to abstract groundwater from deeper aquifers [3, 4]. Globally, groundwater withdrawal ranges between 600 and 700 km^3/y [5]. In the past five-to-six decades, the overexploitation of fresh groundwater beyond sustainability limits has resulted in the widespread and progressive depletion of water level all over the world. As a result, the freshwater resources are becoming scarcer every year. The global warming and climate change is further threatening its security all over the world [6]. Moreover, the heavy withdrawal of freshwater in the regions surrounded by brackish/sea water is responsible for the intrusion of brackish/sea water into the freshwater aquifers [7]. It is not only the anthropogenic reasons that are responsible for the development of brackish aquifers, these may also occur naturally. Under natural geographical settings, there are regions all over the world where the native groundwater quality is brackish [8] and one of the possible reasons is the retention of ions from salt water trapped at the time of ancient marine transgression [9]. The vast stretches in the states of Rajasthan, Punjab, and Haryana of India and Indus basin of Pakistan are having brackish aquifers. Since the groundwater quality is not fit for domestic and agricultural purposes, alternate sources of freshwater were generated to fulfill the demand for potable supply in these regions. Keeping in mind the agricultural productivities of the regions, the governments of both the countries make lots of efforts to lay dense canal network by constructing hydroelectric projects and/or barrages on major rivers and their tributaries. It is a well-known fact that under all practical situations a huge quanti-

Figure 1. Photograph showing the water table at the ground surface (snapped in early 1980s).

ty of water is lost through seepage from the canal network (either lined or unlined) before reaching the destination. According to Wachyan and Rushton [10], a well-maintained canal with a 99% perfect lining reduces seepage to about 30–40%, but seepage cannot be controlled completely. By the time water reaches the field, around 45% of the actual volume of water supplied from the canal head seeps out [11]. In Indian conditions, the loss of water through seepage from unlined canals generally varies from 0.3 to 7.0 m^3/s per 10^6 m^2 wetted surface; which depends on the permeability of soil through which the canal passes, location of water table, distance of drainage, bed width, side slope, and water depth inside the canal [12]. Because of the excess seepage from the dense canal network (lined and unlined), deep percolation losses from surface irrigation practices, and in the absence of adequate drainage facilities, the water table has started rising in these regions. Consequently, the water table has risen from 3.65 m in 1930s to less than 1.20 m in 1980s in most of the lower Indus basin [13]. The situation was worse in certain pockets of Indus basin of India where the water table has virtually reached the land surface (**Figure 1**). As a result, the soils become severely alkaline (i.e., alkaline) in nature (**Figure 2**). These conditions have debarred the agricultural practices in the region.

Figure 2. Photograph showing the alkaline soils in the region (snapped in early 1980s).

Under these circumstances, the major challenges in front of the water resource managers were

a. to decline the water table and to improve the condition of soil in the areas where water is virtually standing on the surface (is termed as the *first type of problem*), and

b. to arrest the further rise of water table in the areas where water table is near to create water logging conditions (is termed as the *second type of problem*).

First type of problem: The reclamation process for this type of problem is comparatively difficult and takes longer period of time than the second type of problem. The main reason of high water table in the area is more inflow than the outflow. In general, the aquifers in these areas are very thin (i.e., near about 10 m). High water table conditions are further responsible for the creation of alkaline soils. It is a well-known fact that the presence of high sodium content in alkaline soils makes clay particles to remain in suspension and appear in the form of slurry. It makes the construction of trenches and installation of pipe drainage system difficult at the desired depth and suspects its workability. Therefore, the first requirement for reclaiming such areas was to decline the water table and to improve the soil conditions. In these conditions, only vertical drainage was possible as it was the only way by which the clay particles would be trapped in the upper part of the aquifer. The main advantage of the vertical drainage is that it lowers the water table to any desired depth which is not possible in the case of subsurface and pipe drainage system. Further, the increase in outflow from the aquifer creates space for the storage of seeped-out freshwater from the nearby canal.

Second type of problem: The sustenance of cultivation practices in these regions was vest in the condition that the existing groundwater could be used which will eventually lower the water table. This decision was based on the existence of those freshwater lenses which had established in varied thicknesses over the native brackish water due to the seepage from surface water bodies. Since the aquifer contains water of different densities in two layers, therefore, pumping the aquifer by merely placing the screen of a partially penetrating well in the freshwater zone will not serve the purpose as the development of discharge head in the aquifer may cause up-coning of fresh–brackish water interface to effective pumping zone of the well [14]. This phenomenon can be better explained by the Ghyben–Herzberg principle. Both the researchers have independently recognized the flotation of a steady-state, fresh groundwater lens on top of sea water [15, 16]. If h_f is the freshwater head above sea level and h_s is the depth to the sharp interface (i.e., considering immiscible fluids) below sea level, then for a system in static equilibrium the pressure at the interface due to the overlying column of freshwater must be equivalent to that due to the column of salt water (**Figure 3**). Considering ρ_f is the density of freshwater and ρ_s as that of saltwater, static equilibrium as shown in **Figure 3** can be expressed mathematically as

$$h_s \rho_s = \left(h_s + h_f\right) \rho_f \tag{1}$$

Rearranging the terms, Eq. (1) changes to

$$h_s = \left(\frac{\rho_f}{\rho_s - \rho_f}\right) h_f \tag{2}$$

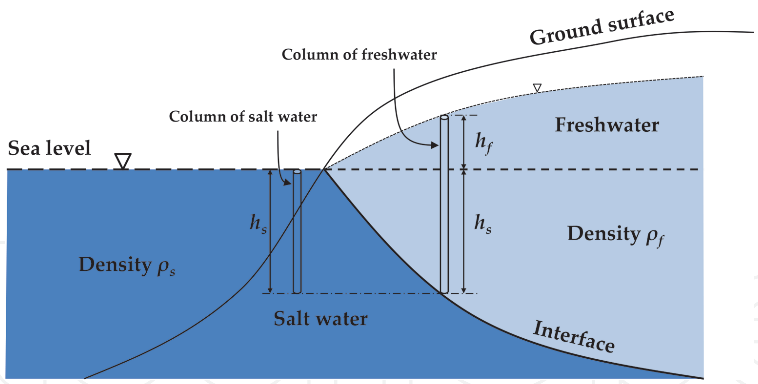

Figure 3. Schematic sketch explaining the Ghyben–Herzberg principle.

According to Eq. (2), the up-coning of the interface depends on the density difference between the fresh and brackish water. For any operational discharge head value, decrease in density difference between freshwater and brackish/saline water leads the interface to rise higher [8], and which is synonymous to Wang's [17] results. Reclamation of such lands for sustaining livelihood is a major challenge for the scientists of India and Pakistan. Researchers from all over the world have also shown keen interest in the reclamation of such areas. Based upon the hydrogeological conditions of the areas, various water management techniques have been proposed. More specifically, the stress has been given to skim the available freshwater from the fresh–brackish/saline aquifers. In the subsequent sections, various types of skimming techniques are discussed.

1.1. Skimming tube well(s)

During the pumping of freshwater from fresh–brackish/saline aquifer, the pressure head in the vicinity of well is lowered which ultimately leads to the rise of brackish/saline water. This phenomenon is known as up-coning and is responsible for the increase in salt content of the pumped water. Obviously, the purpose is to pump the freshwater without much disturbing the brackish/saline zone. Therefore, the term "*skimming tube well*" may be defined as the *tube well to extract freshwater from the fresh–brackish/–saline aquifer by specifying the extraction rate so as to limit the rise of fresh–brackish/saline interface to reach effective pumping zone of the well* (**Figure 4a**). The performance of a skimming tube well depends upon the factors, viz., (i) relative thickness of the freshwater lens with respect to the brackish/saline water zone at the point of extraction, (ii) densities of freshwater and brackish-/saline water, (iii) screen length penetrating the freshwater zone, (iv) distance of skimming well from the recharging source (i.e., canal/ river), (v) diameter of the well, (vi) spacing between the adjoining skimming wells, and (vii) the aquifer parameters. Studies show that the single-bore skimming tube well technique is successful only in aquifer with the freshwater zone having thickness more than 30 m [18]. In the regions where the thicknesses of the freshwater zones are less than 30 m, the farmers' have to compromise either with the discharge rate or with the pumped water quality if they abstract groundwater through single-bore well. In such situations, a more practicable technique is to abstract water through a number of smaller capacity tube wells which are installed arbitrarily in circular array and are joined with a single pumping unit (**Figure 4b**). The complete pumping setup may be termed much appropriately as "*skimming tube wells system.*" Field experience shows that the number of tube wells in such type of system may vary from 2 to more than 16 [18]. However, based upon the performance studies on skimming tube wells system with reference to quantity and quality of pumped freshwater it was found that the double-strainer skimming well is most efficient [19]. Its basic reason is explained in Section 1.6.

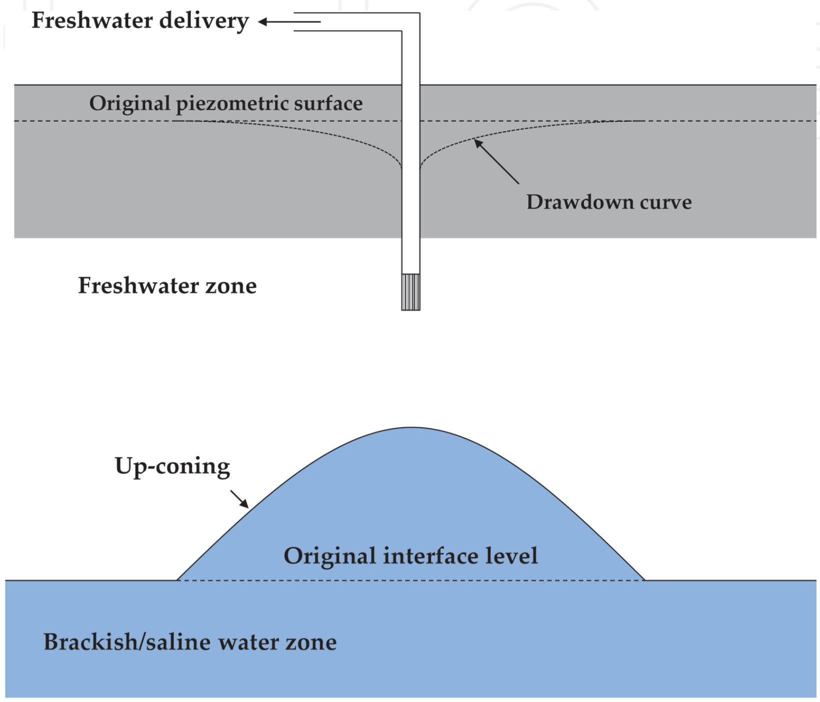

Figure 4a. Schematic sketch showing a skimming tube well.

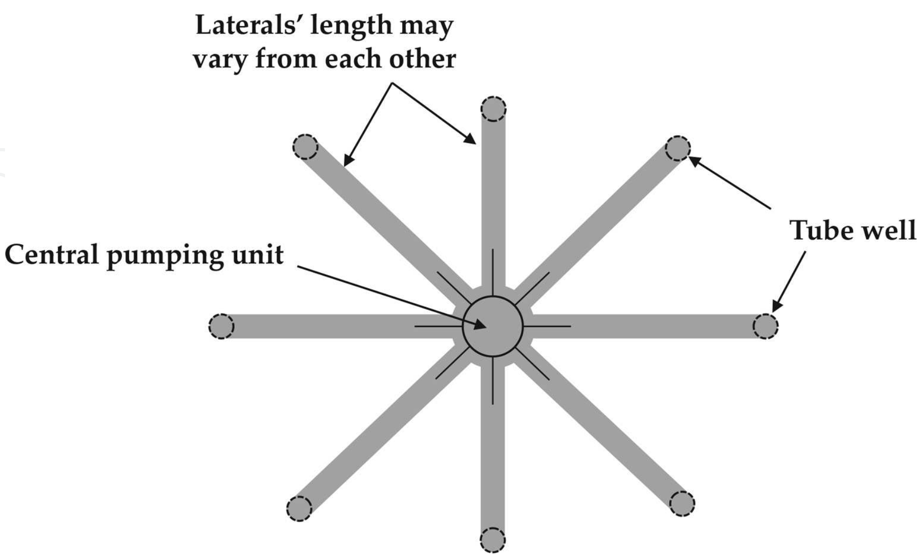

Figure 4b. Schematic sketch showing skimming tube wells system in which smaller capacity tube wells are installed arbitrarily in circular array and are joined with a single pumping unit.

1.2. Scavenger well system

To restrict the rise of fresh–brackish/saline interface to reach the effective pumping zone of the well, the adoption of scavenger well system is one of the possible solutions in which pumping from the production well is accompanied by brackish/salt water pumping from a scavenger well in the vicinity [20, 21]. In a scavenger well system, two wells (i.e., production well and scavenger well) are installed either in a single-bore hole (**Figure 5a**) or side-by-side bore holes (**Figure 5b**). The production well screens the freshwater zone whereas scavenger well taps the brackish/saline water zone. The development of discharge heads due to simultaneous pumping of these wells restricts the mixing of freshwater with brackish/saline water. The discharge rates of the two wells are adjusted in such a way that the up-coning caused by pumping from the production well could be countered by the down-coning of the interface caused by pumping from the scavenger well [20]. The resultant level of interface at any radial distance from the well can be evaluated from the difference of hydraulic heads of both production and scavenger wells considering both are working independently (**Figure 5a** and **b**). Ideally, this difference should be zero for keeping the interface at original level. Considering its pumped water quality, around 400 scavenger wells were installed in the lower Indus basin of Pakistan [13]. However, the concerns such as the mobilization of deep salts, disposal of pumped saline water, and the long-term negative environmental impacts due to seepage of saline water during its disposal were the major limitations on the sustainability of scavenger wells [13].

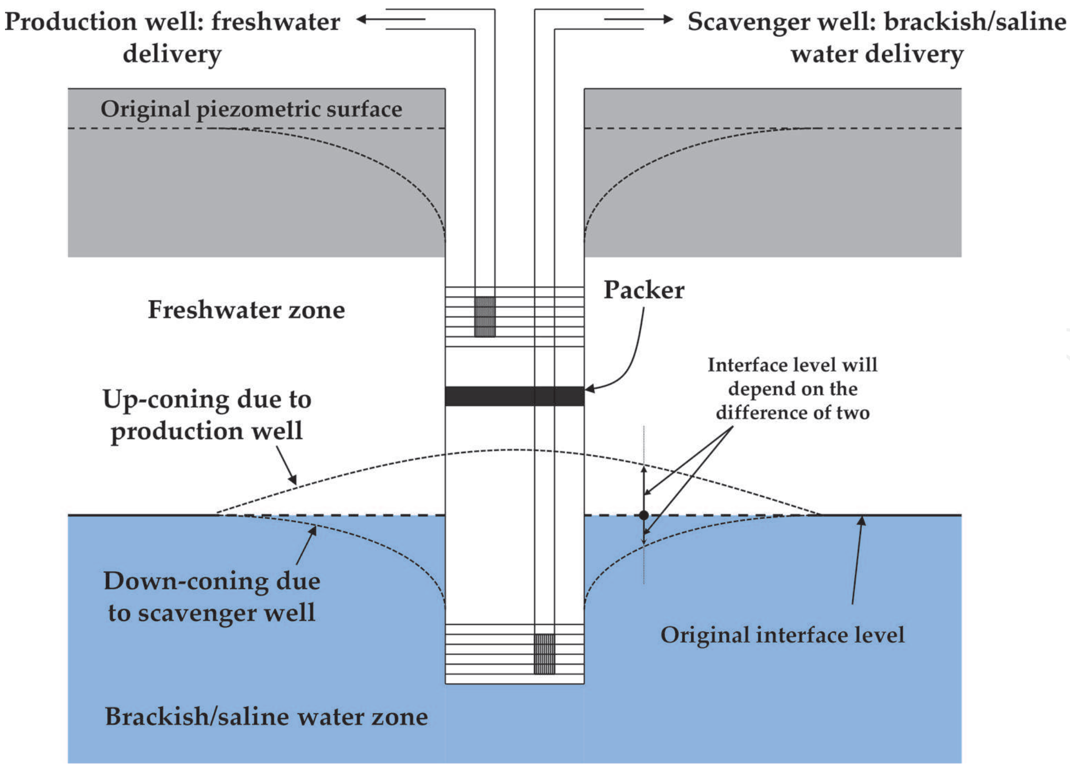

Figure 5a. Schematic sketch showing scavenger well system installed in a single-bore hole.

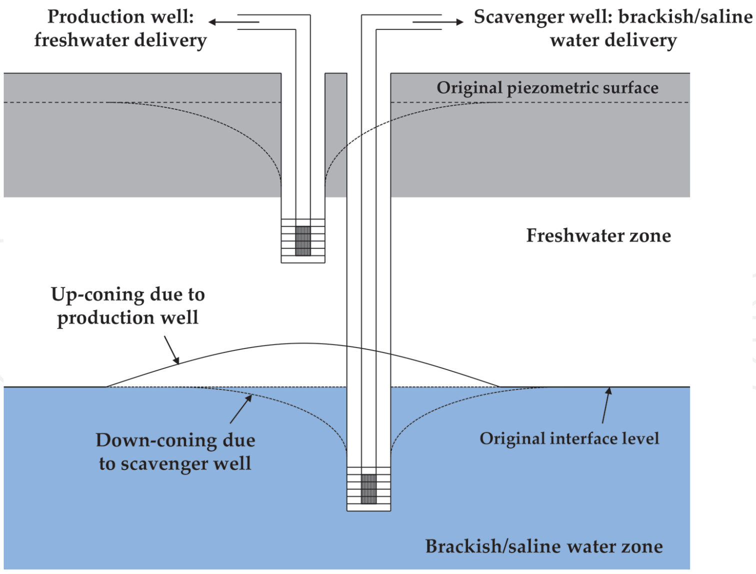

Figure 5b. Schematic sketch showing scavenger well system installed in side-by-side bore holes.

No doubt, the answer to these major limitations was given days back in 1965 by Jacob who proposed and patented a doublet well system (**Figure 6**) which was different from the present day scavenger well system in the sense that the scavenging discharge is pumped back to deeper formation [22], but its acceptability was restricted to thick aquifers only. From the above discussion it is clear that the adaption of scavenger well system for inlands depends upon the safe disposal of pumped brackish water. On the other hand, scavenger well system may prove to be best fresh-saline aquifer management practice in the coastal regions as the disposal of pumped saline water is comparatively easy by constructing reasonably long seepage-proof conveyance channels.

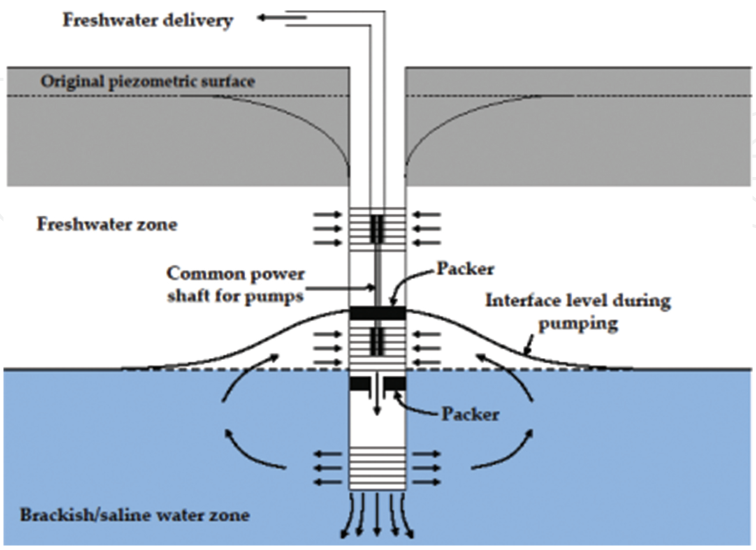

Figure 6. Schematic sketch showing the doublet well.

1.3. Recirculation well

The design of a recirculation well is somewhat similar to scavenger well (**Figure 7**). Unlike scavenger well, its lower screen is also kept in the freshwater zone. A part of the freshwater pumped from the upper screen is recirculated under gravity pressure into the lower screened chamber of the well which is separated from the upper through a packer. The injection of recirculated freshwater into the aquifer counters the up-coning of brackish/saline water mound beneath the well. Depending upon the position of lower screen with respect to interface, intermixing of injected freshwater may occur with the saline water. The establishment of flow pattern from the lower to upper screen takes this mixed quality water to freshwater zone, thus deteriorates the pumped water quality. Though the technique has been used in the petroleum industry [23], but the recirculation well's performance results in the water industry are not yet available [19].

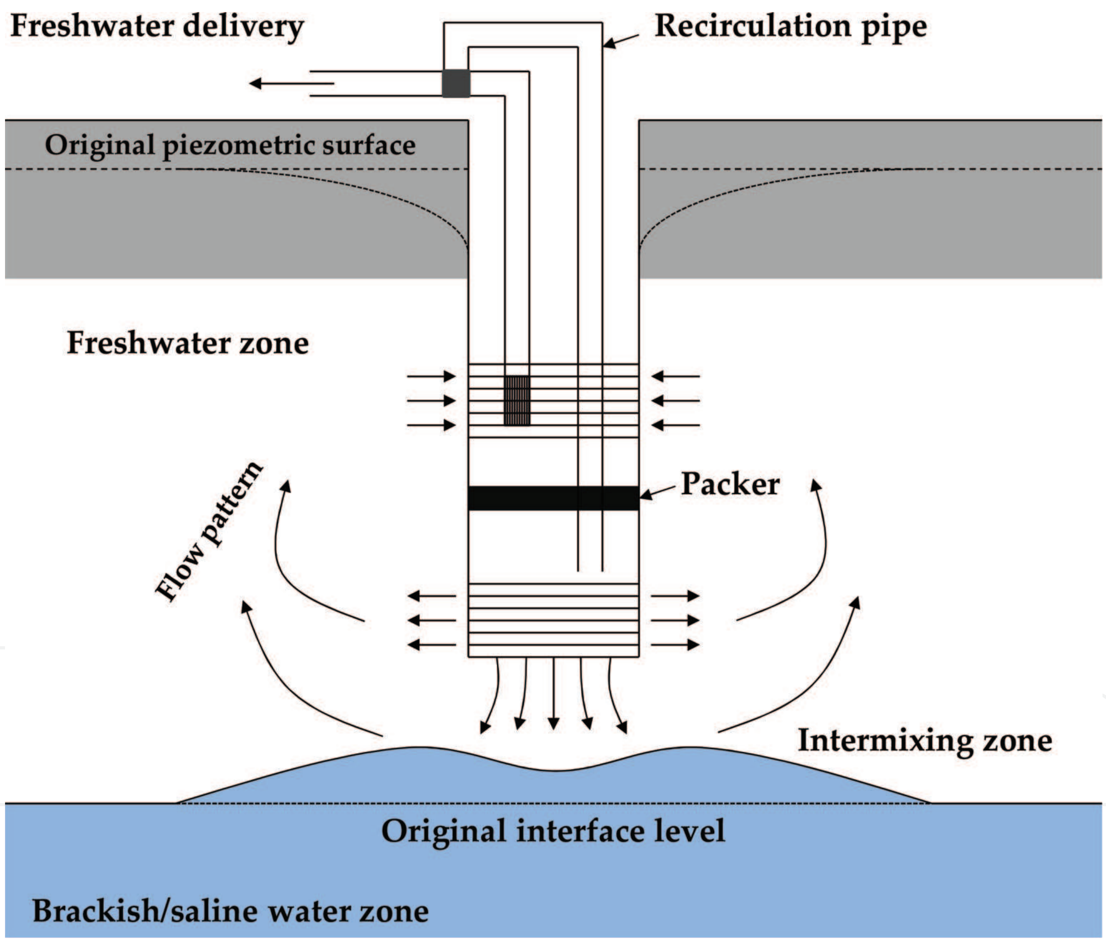

Figure 7. Schematic sketch showing recirculation well and its probable behavior while pumping.

1.4. Horizontal wells

To control the rise of interface to reach the effective pumping zone of the abstraction well, the only feasible option is to limit its discharge head [8]. For the purpose, horizontal wells can be used to abstract groundwater. Previously, the horizontal well is introduced for the remediation of contaminated groundwater [24] as in comparison to vertical well, horizontal well can influence a large planar area during remediation [25]. However, now these wells are gaining popularity for use in water supply and drainage fields. Rushton and Brassington [26] have grouped the horizontal wells into two configurations. The first one is the radial collector well in which a number of horizontal perforated pipes are connected to a shaft or caisson. The second configuration consist of a single perforated pipe which is placed in shallow unconfined aquifer with a suction pump located either toward the center or at one end of the horizontal well [27]. The horizontal wells can be differentiated from the fully penetrating vertical wells on the basis of the flow components around the wells [28]. The vertical flow components are more dominant near a horizontal well whereas flow patterns around a fully penetrating vertical well are horizontal (or two dimensional). No doubt, in case of partially penetrating or partially screened wells, the flow in the near vicinity of pumping/recharging well is strictly three dimensional in nature [29]. From the above discussion, it can be envisaged that the radial collector wells may be the suitable option in the regions under study. But, its installation is difficult and requires extreme precision. Field experiences show that the construction of shaft, particularly in alkaline soils is a very hard task [30].

1.5. Dug wells

The areas where freshwater zones are very thin (less than 5 m) and where soils are not alkaline in nature, dug well can be constructed for skimming freshwater. Sometimes, these are also referred as shallow hand-dug wells [31]. Though the yield of these wells is very less, even then the available water can be efficiently utilized by opting well-recognized pressurized irrigation systems. The yield of a dug well can be increased by increasing its diameter and penetration. Large diameter of well facilitates water storage and its construction. However, the well penetration is limited by the fresh–brackish/saline interface.

1.6. Multiple well points system

In Sections 1.1–1.5, various skimming techniques are discussed. The performance of any skimming technique depends on the persisting hydrogeological conditions of area and every technique may not be suitable under all set of conditions. The major drawbacks in all the above-mentioned techniques are stated below:

a. Skimming tube well (i.e., single-bore well) is not feasible in aquifer having very thin freshwater zone.

b. In skimming tube wells system, various studies have concluded that the groundwater procured with fewer number of bore holes is of better quality in comparison to more number of bore holes [19, 32]. With the increase in the number of skimming wells, various types of geometrical patterns are possible in which these wells can be installed in the field. All the patterns create different flow conditions in the aquifer and hence affect the freshwater skimming. However, the adoption of a particular configuration without considering the resultant flow pattern toward the wells becomes responsible for the deterioration of pumped water quality. It is explained schematically in **Figure 8**. It is a well-known fact that during pumping, the adjoining portion of the well screen is recuperated by the aquifer formation under influence. It is obvious that during the pumping of the system the recuperation of the aquifer formation with freshwater in the enclosed portions (as shown in **Figure 8b–d**) is minimal as the major portion of the freshwater moving toward the system is trapped by the wells before reaching the enclosed portions. Moreover, the interference of wells causes the drawdown to increase to maximum extent in the enclosed portion which in turn raises the interface to effective pumping zone of the wells. Combined effect of both these factors which comes into action with the start of pumping is responsible for the up-coning of brackish/saline water. On the other hand, in case of two and in-line tube wells system (**Figure 8a** and **e**), recuperation rate of freshwater is much higher than the other enclosed patterns and thus the procured groundwater quality is noticeably better than the other patterns.

c. The major limitations on the sustainability of the scavenger wells are the mobilization of deep salts, disposal of pumped saline water, and seepage of saline water from its disposal system. The acceptability of the doublet well system is also restricted to thick aquifers only.

d. Though the recirculation wells are more efficient than scavenger wells, the intermixing of brackish/saline water with the injected freshwater and the rising of this mixed quality water to freshwater zone are few undesirable features.

e. Extreme precision is required in the installation of horizontal wells. Moreover, its construction (specifically in alkaline soils) is a very hard task.

f. The low-yield of the dug wells restricts its adaption in surface irrigation practices. The available water's utilization is limited to well-recognized pressurized irrigation systems only.

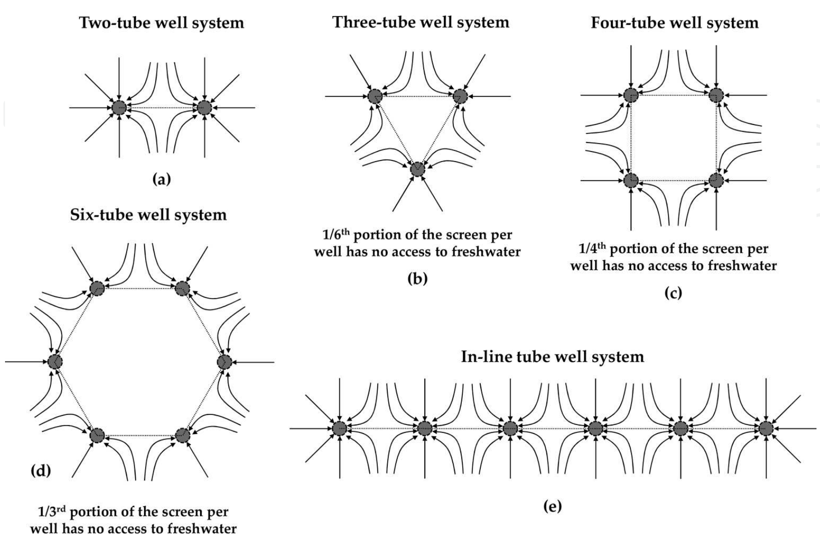

Figure 8. Schematic sketches showing general geometrical patterns in which skimming wells can be installed.

Keeping the region's problems in mind and considering the merits and demerits of all the above-mentioned skimming techniques, Shakya et al. [33] proposed the skimming of thin freshwater layers by a much efficient and affordable technique named multiple well points system (MWPS). The proposed system was capable to reclaim both types of problems (as mentioned in Section 1) persisted in the region. No doubt, skimming of freshwater was the basic objective but in comparison to other drainage technologies it can drain water logged soils by lowering the water table in wide spread region without disturbing much the deeper brackish water zone. The proposed MWPS was different from the skimming tube wells system [34] as mentioned in Section 1.2. In skimming tube wells system, different wells are installed almost in a circular array and are attached to the central pumping unit with separate lateral pipes of varied lengths (**Figure 4b**); whereas, MWPS constitutes several smaller capacities well points partially penetrating the aquifer and are arranged in a line connected to each other below the ground surface through single lateral and pumped centrally (**Figure 9**).

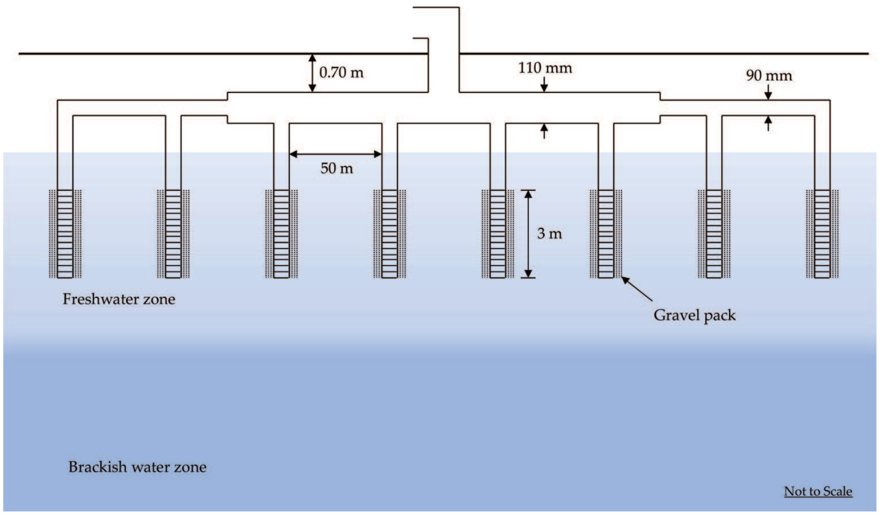

Figure 9. Schematic sketch showing multiple well points system with eight bores.

2. Study area

To examine the performance of conceived MWPS, an area which was out of cultivation was considered (as shown in **Figures 1** and **2**). The area is situated at a distance of 15 km from Ferozepur city on Ferozepur-Faridkot state highway No. 15 (**Figure 10**). The land of the project area belongs to three villages namely Golewala, Chak Kalan Tola, and Jhariwala (District Faridkot, Punjab, India). Project area falls in the arid zone having the minimum and maximum temperatures of 10 and 46°C during the months of January and June, respectively. The average values of the minimum and maximum relative humidity are 37 and 65%, respectively. The mean annual rainfall received in the region is about 400 mm. The topography of the area is leveled in general.

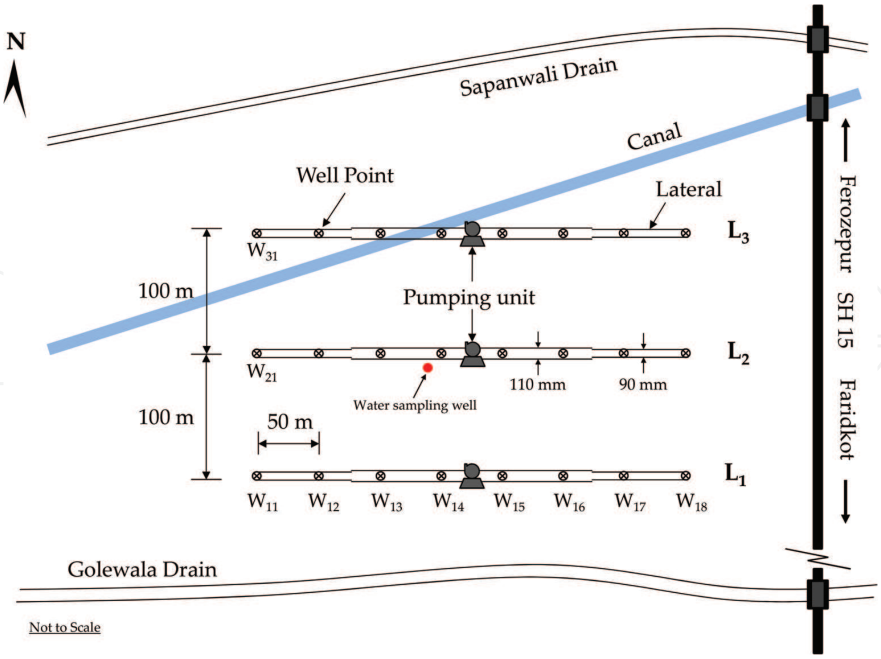

Figure 10. Schematic sketch showing the study area.

3. Characterization of underground water

Before the installation of MWPS, depth-wise analysis of the groundwater quality was performed. In **Figure 11** the change in electrical conductivity (EC) and residual sodium carbonate (RSC) with depth is shown. Perusal of **Figure 11** shows that the groundwater quality deteriorates with depth. Water can be considered fit for irrigation only if EC and RSC are less than 2 dS/m and 2.5 me/l, respectively. Though the salinity is within range but because of higher RSC,

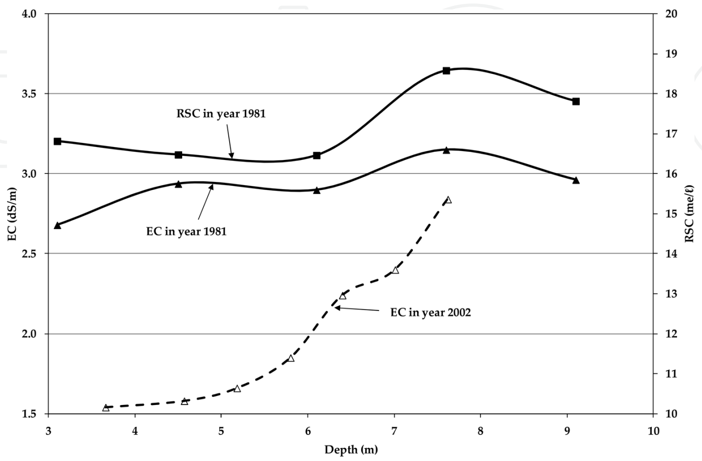

Figure 11. Change in EC and RSC of the groundwater with depth.

groundwater of the study area was not fit for irrigation. Hence, the project area was under the first type of problem.

4. Pumping test of the aquifer

A pumping test was conducted in a farmer's well which was existing in the project area. From the well log data, it was found that the depth of the soil at the location was 2.5 m and the aquifer was 10 m thick. Diameter of the well was 7.5 cm and it was installed in the said aquifer at a total depth of 10.5 m out of which 4.5 m was blind pipe of galvanized iron (GI). The well had a coir strainer of length 6 m. At a radial distance of 28.8 m from this well, another irrigation well of certain specifications was available which was used as a piezometer. Other than this available tube well, two more piezometers each of 9.0 m deep were installed at radial distances of 60 and 90 m from the test well, respectively. During the pumping test, the well was pumped at the rate of 10.82 l/s and drawdowns were recorded in all the three piezometers with respect to time. The change in drawdowns with respect to time at the three piezometric locations is presented in **Figure 12**. The recorded data were analyzed by the Walton method [35]. From the pumping test data, the average values of transmissivity T, hydraulic resistance c, and storage coefficient S were evaluated equal to 570 m^2/d, 17.04 d, and 0.0142, respectively [30]. The hydraulic conductivity of the overlying soil layers ranged from 1.4 to 2.0 cm/d.

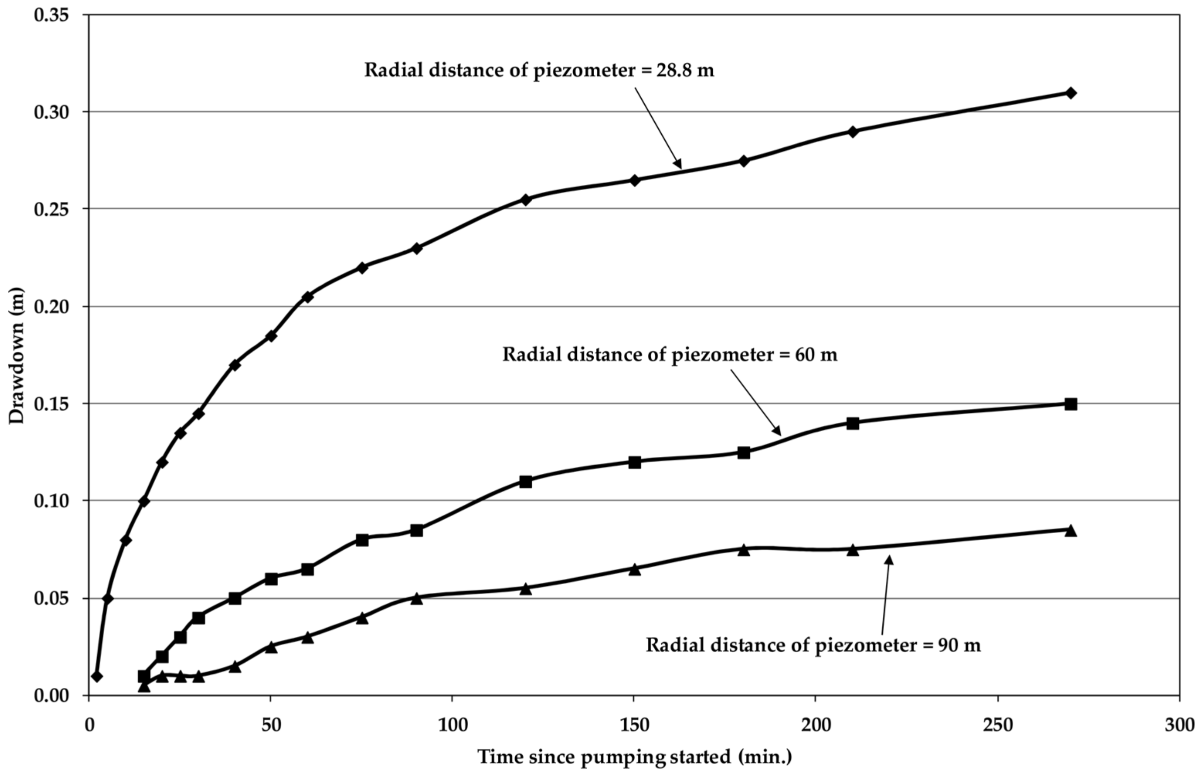

Figure 12. Change in drawdown with time at three piezometric locations while performing pumping test.

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5. Installation of multiple well points system

It was proposed to install a battery of 24 wells constituting three laterals L_1, L_2, and L_3 spaced 100 m apart. The well spacing along the laterals was considered to be 50 m with 8 wells on each lateral (**Figure 9**). The wells were installed by the local drillers. These wells were connected to each other at about 70 cm below the ground surface using 90 and 110 mm diameter PVC pipes by digging trenches. The screen of each well point had an effective perforated area of about 16% which is surrounded by pea size, clean, river bed, well rounded gravel pack of 30 mm thickness. In the middle of each 350 m long lateral, a T-section was provided which was raised to the ground surface such that it remained in level with the ground after placement of reflux valve. The centrifugal pumps were connected with the aforesaid outlet points of three laterals. In order to prime the lateral, a reciprocating pump was placed over the delivery of each centrifugal pump. Initially, the air from the lateral was removed through the reciprocating pump and when there was an adequate flow of water, centrifugal pump was started. Whenever, there was disruption of flow, reciprocating pump was operated and was stopped when there was continuity in flow. Before covering the laterals with soil, the complete system was tested for any leakage. From the desired discharge rate and available head values, the power requirement to operate the system was evaluated equal to ~4 hp (considering the working efficiencies of both centrifugal pump and diesel engine equal to 80% each). Therefore, three diesel engine operated pumps of capacity 5 hp each (nearest available higher size in the market) were installed on each lateral.

6. Behavior of multiple well points system and its applicability

For monitoring the drawdown distribution in an aquifer while pumping through MWPS, piezometers were installed close to each well point and at the midpoint of the well spacing along the laterals. Each piezometer was of diameter 40 mm and was installed at a depth of 6 m. The piezometers installed near to well points were given names in accordance with their nearness to the respective well points. The symbol W_{LN} indicates the Nth well point on the Lth lateral. The piezometers adjoining to the respective well points are named as P_{LN}. For example, P_{23} indicates the piezometer near to the third well point on the second lateral (i.e., W_{LN}). The piezometers installed at the midpoint of two adjacent well points along the lateral are named as $P_{LN-L(N+1)}$. For example, P_{23-24} represents the piezometer installed midway between the well points W_{23} and W_{24}. The lateral L_1 was discharging at a rate of 3110.4 m^3/d whereas the laterals L_2 and L_3 were delivering at a rate of 2419.2 m^3/d each. The available drawdown data were plotted and is presented in **Figure 13**. It is evident from **Figure 13** that the lowering of the water table is minimal at the four locations (i.e., in the center of the laterals at the outer boundary of the system). On the other hand, maximum lowering has been noticed around the central well points of middle lateral. Considering a section along the lateral lines L_1 or L_3 for the water table profiles, it is evident that the difference between the maximum water level at the midway between the wells and that of inside the wells was varied from 0.5 m at outer well to 0.72 m for central wells. These variations for L_2 lateral were found to vary from 0.47 m at outer well to 0.87 m for central wells.

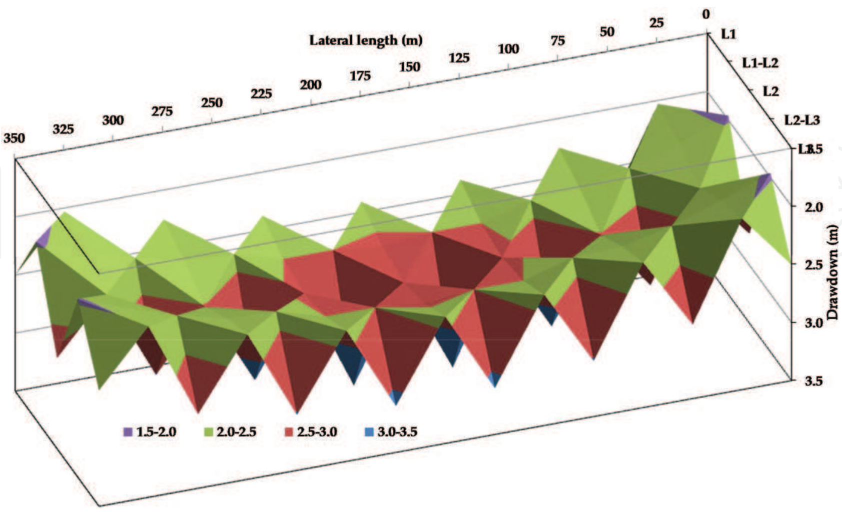

Figure 13. Behavior of multiple well points system while pumping.

Since the first type of problem was persisting in the project area, there was a need to control the water table first. Therefore, the pumping test was done with a schedule of 8 h of pumping and 16 h of recovery in a day for a week to observe the water table behavior in aquifer and soil. A residual drawdown of 17 cm in aquifer and 24 cm in soil was observed. It was also observed that the rise of water table in the soil during recovery is delayed with the passage of time. It could be explained as, once the water from soil is drained, rise would take place only after the pores of the soil are filled with water. It has imparted the delayed effect in rise of water tables in the soil. These encouraging results motivated us and long duration pumping of the aquifer was performed. Eventually, with the lowering of water table agricultural practices were started with the cultivation of paddy. Marginal quality water was used for irrigating the paddy which was achieved by mixing pumped water supply (through MWPS) with canal water. Studies show that the irrigation with marginal quality water does not affect the yield of paddy to much extent [30]. The motive was to continue pumping from the aquifer. In due course, groundwater quality in the upper portion of the aquifer started improving. In year 2002, groundwater samples were again analyzed for EC depth-wise and are presented in **Figure 11**. Perusal of the comparison clearly indicates that the there is a drastic improvement in the groundwater quality in the upper portion of the aquifer. The excellent performance by the MWPS has proven that it is a viable technology for the region and needs promotion.

7. Recommendation based on experimental results

In order to propagate the use of MWPS in the region, a smaller system with four-well points spaced at 6 m in a line connected horizontally at about 1 m below the land surface, pumped centrally was found to give technically satisfactory performance (i.e., no mixing of floating good quality water with the underlying poor quality groundwater) and economically viable results. Each well point has a screen length of 3 m which has 16% effective perforation and surrounded by pea size, well rounded clean river bed gravel envelope. Blind pipe may be adjusted according to the depth of aquifer. The details are shown in **Figure 14**. After watching the enthusiastic results of the project area, farmers of the region have adopted the recommended MWPS with four-well points on a large scale. As per the survey of Faridkot district in year 2000–2001, around 1400 MWPSs have already been installed [36]. From the analysis of water quality samples taken from some selected MWPSs, it was found that these are withdrawing good quality water that is fit for irrigation. Farmers themselves have admitted that they are using MWPS from last 10 years and have not noticed any deterioration in pumped water quality. Moreover, the adoption of MWPS has also lowered the water table in the region.

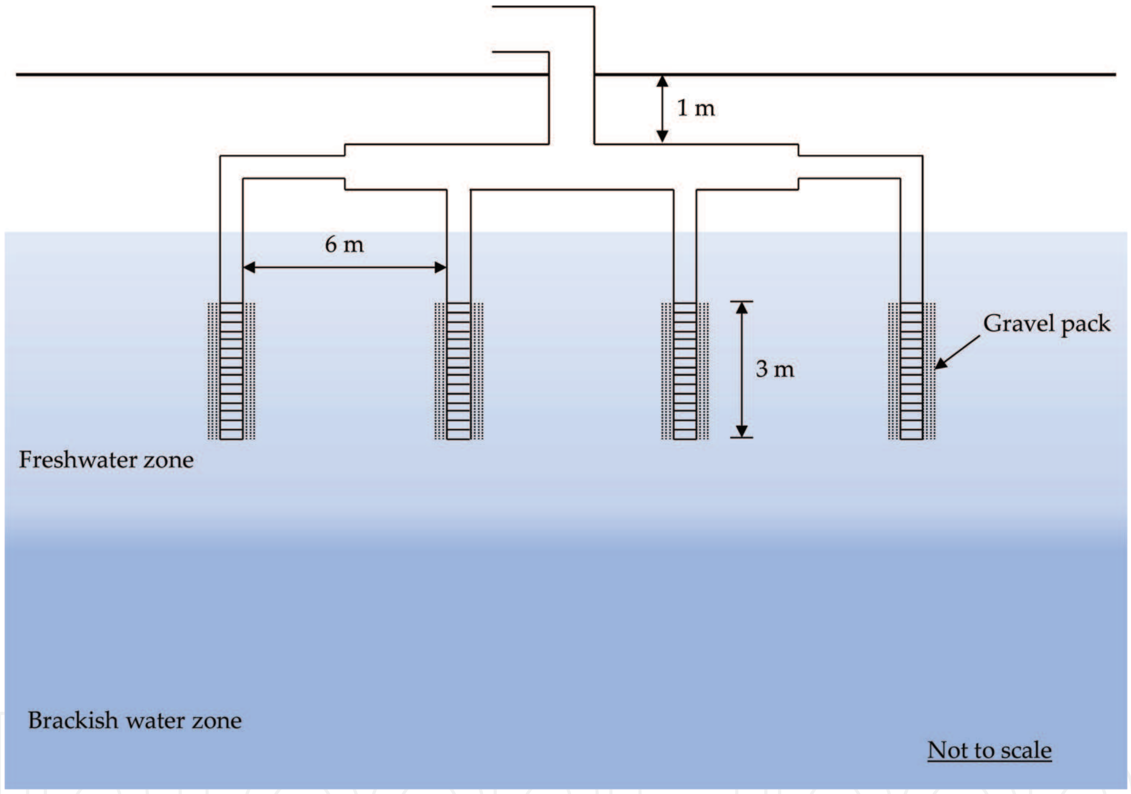

Figure 14. Multiple well points system with four bore holes.

8. Groundwater recharging through MWPS under constant head conditions

It is already mentioned in Section 7 that farmers of the region have adopted the MWPS in big way and their dependency on canal water has declined considerably. It is also true that these freshwater lenses are very limited and are now under stress. For long-term sustainability of these limited freshwater lenses, enhancement in freshwater recharging rate is required. Therefore, we have conceived an idea to recharge the freshwater zones with surplus canal water when available during the monsoon season through the existing MWPSs in the region [37]. Aquifer storage recovery (ASR) is worldwide recognized technique for managing brackish/saline aquifers [38] in which freshwater when available is stored in the aquifer and later on recovered for use. However, our proposal was little different from this basic technique. In the ASR technique, recharging of the brackish/saline aquifer is generally performed with the fully penetrating well of high capacity in which the injected freshwater displaces the saline water. As a result, considerable portion of the stored freshwater gets salinized before its recovery. The native groundwater movement and the buoyancy effect are the two factors which are responsible for the irrecoverable portion of stored freshwater. With the use of multiple partially penetrating wells in a single bore hole, the freshwater losses can be reduced considerably [39]. In this modified ASR technique, freshwater is injected in the deeper portion of the aquifer whereas its recovery is made from the shallow well. On the other hand, as the MWPS operates under limited head conditions and it penetrates only the upper portion of the freshwater zone of the aquifer through smaller capacity wells, it causes minimum disturbance to the denser native brackish water which is flowing in the lower portion of the aquifer [8]. The recharged water gets an opportunity to store in the wide-spread portion of the aquifer. Hydraulic head distribution in the aquifer while recharging through MWPS is shown in **Figure 15**. While evaluating this, we have considered the recharging rates through individual laterals equal to the pumping rates as mentioned in Section 6. Perusal of **Figure 15** indicates that the freshwater got an opportunity to store in the upper portion of the aquifer and it causes minimum disturbance to deeper brackish water zone.

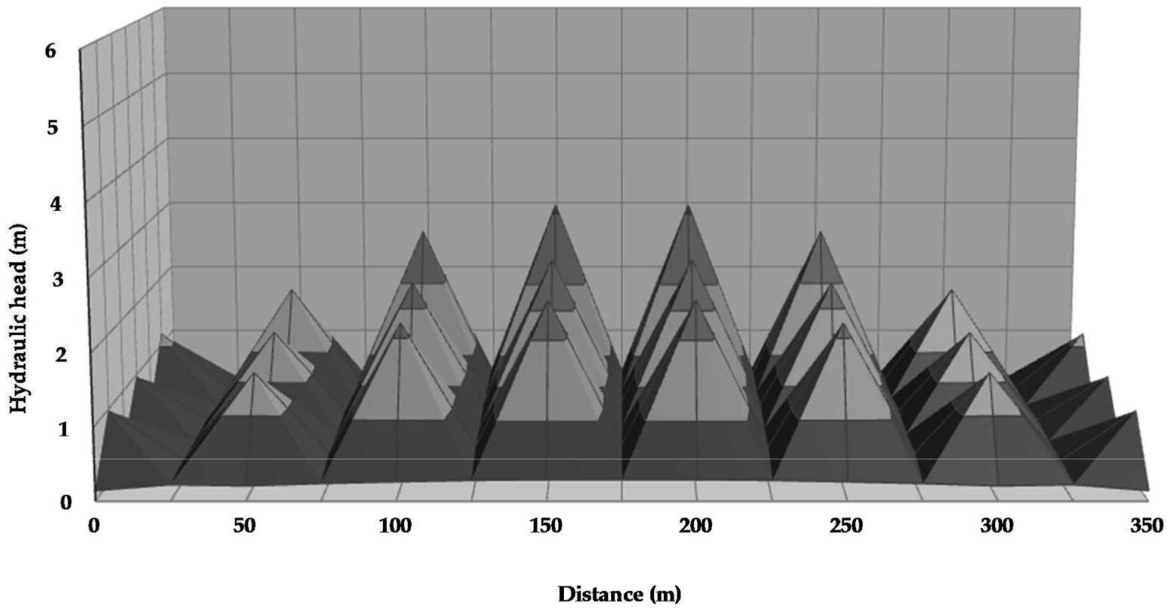

Figure 15. Hydraulic head distribution in the aquifer while recharging through MWPS.

Other than the theoretical investigations, field study was also conducted to monitor the change in quality of aquifer while recharging with freshwater. In the field study, canal water was allowed to recharge the aquifer through MWPS under constant head conditions. Radial flow filter was used for removing turbidity from the canal water (**Figure 16**).

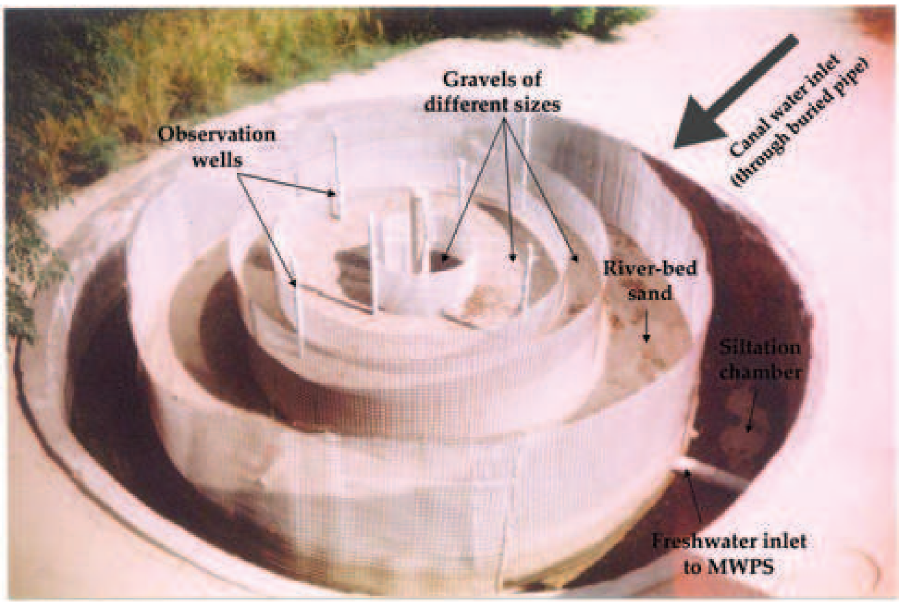

Figure 16. Radial flow filter for removing turbidity of canal water before recharging through MWPS.

For monitoring the change in quality of groundwater due to recharging, a water sampling well of length 9.144 m having diameter 10.16 cm was installed at a radial distance of 3.27 m from the well point W_{24} (**Figure 10**). The perforated length of the observation well was 6 m. For critically analyzing the effect of recharging on the quality of brackish water, it was necessary to collect water samples depth-wise with minimum disturbance. For this purpose, a specialized water sampler was fabricated. In spite of this, for achieving accuracy, considerable time was given between consecutive samplings. Before starting the recharging operation, groundwater samples from various depths were collected and analyzed for EC and pH. The recharging operation was continued for net 65 days and on its completion, water samples were collected from the same depths and were again analyzed for EC and pH. Comparison of the change in groundwater quality due to freshwater recharging is shown in **Figures 17** and **18.** Perusal of both the figures indicates that the recharging of freshwater in fresh–brackish aquifer through MWPS is a viable technique for reviving freshwater lenses in the region. However, for planning any recharging project through MWPS, theoretical investigations are required *a priori*. Realizing this need, Vashisht and Shakya [8] have proposed a semianalytical solution for evaluating hydraulic head distribution and recharging rate in a single leaky aquifer while recharging freshwater under constant head conditions through MWPS. The proposed solution was based on the introduction of a new relation termed as "position-oriented *opportunistic proportion*." The most important advantage of recharging through MWPS is that it covers the wide-spread region of the aquifer without disturbing much the native brackish water. The developed hydraulics for MWPS may be considered as the backbone for planning and execution of policies for managing brackish groundwater aquifers in the region.

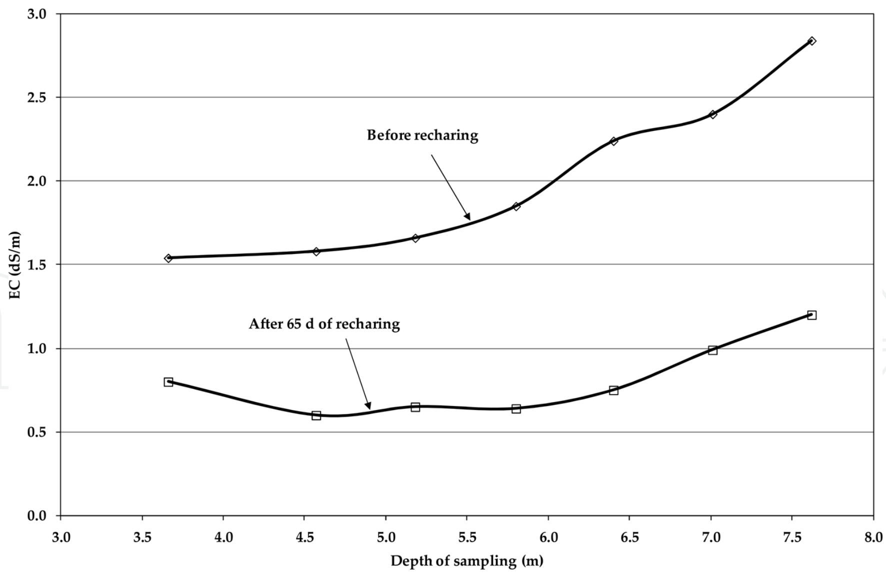

Figure 17. Change in EC of groundwater depth-wise after recharging canal water through MWPS.

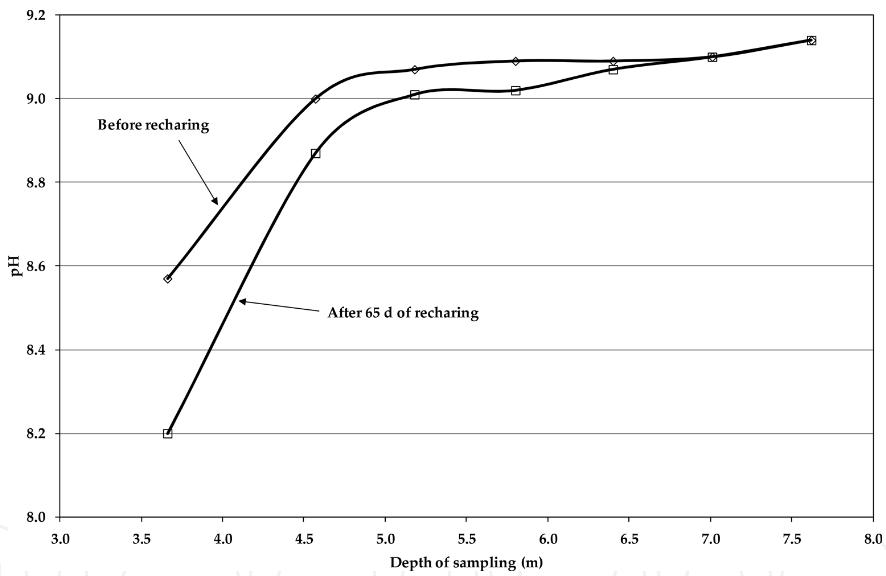

Figure 18. Change in pH of groundwater depth-wise after recharging canal water through MWPS.

9. Conclusion

Long-term field investigations were made on the MWPS for checking its performance as a drainage system, a skimming system, and a recharging system. On the basis of the field results and theoretical investigations, it is concluded that MWPS is a viable technique for managing brackish aquifers of a region.

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