EFFECT OF BUFFER STORAGE VOLUME AND STORAGE TIME ON BRACKISH ASR WELL RECOVERY BEHAVIOUR

BY

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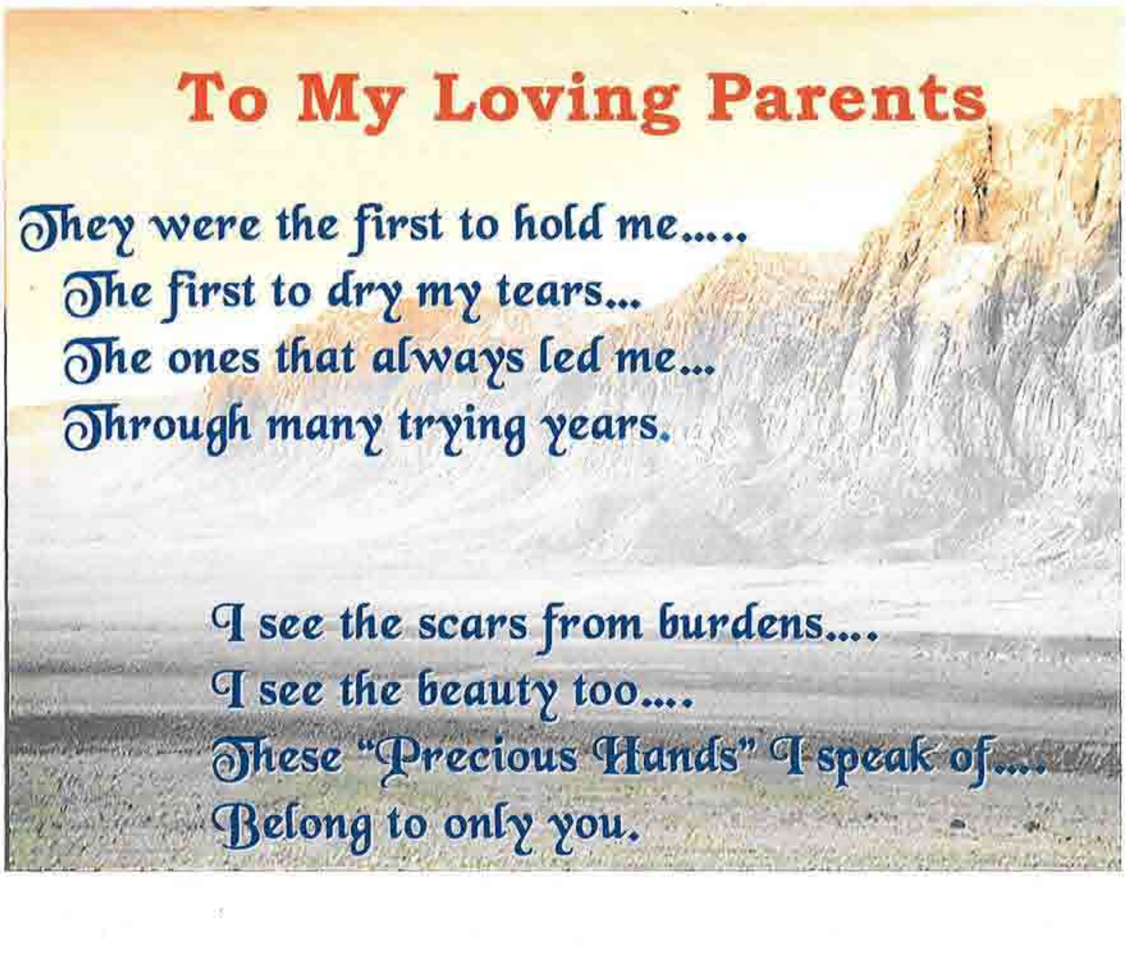

To My Loving Parents

They were the first to hold me.....
The first to dry my tears...
The ones that always led me...
Through many trying years.

I see the scars from burdens....
I see the beauty too....
These "Precious Hands" I speak of....
Belong to only you.

CERTIFICATE - I

This is to certify that this dissertation entitled **"Effect of buffer storage volume and storage time on brackish ASR well recovery behaviour"**, submitted for the degree of **Doctor of Philosophy** in the subject of **Soil Science** of the CCS Haryana Agricultural University, Hisar, is a bonafide research work carried out by **Mr. Vishal Goyal,** Admission No. **2001A40 D** under my supervision and that no part of this dissertation has been submitted for any other degree.

The assistance and help received during the course of investigation have been fully acknowledged.

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CERTIFICATE - II

This is to certify that this dissertation entitled **"Effect of buffer storage volume and storage time on brackish ASR well recovery behaviour"**, submitted by **Mr. Vishal Goyal,** Admission No. **2001A40 D** to the CCS Haryana Agricultural University, Hisar in partial fulfillment of the requirements for the degree of **Doctor of Philosophy** in the subject of **Soil Science** has been approved by the Student's Advisory Committee after an oral examination.

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(VISHAL GOYAL)

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Chapter I

INTRODUCTION

Aquifer storage recovery ASR is relatively a new water resource management technology, which has been put to wide range of uses (Pyne, 1995) including for improving groundwater quality for irrigation (Rattray, K. 1999; Herezeg *et al.,* 2000; Vanderzalm *et al.*, 2002). The ASR well is a dual purpose well sequentially used for both excess water injection in aquifer and for recovery of water during shortage. This technique is being increasingly utilized for reducing saline brackish aquifers for irrigation (Gerges *et al.,* 2002 a & b; Malik *et al.,* 2002a) and to prevent surface ponding in standing crops (Malik *et al.*, 2000) and for maintaining the desired water levels in fresh water aquifers (Pyne, 1995; Gale *et al.,* 2002; Pavelic *et al.,* 2002a) at relatively small cost. The economic development of ASR for improving native water quality is dependent upon recovery behaviour of the injected water after a given residence time. It is best described by the term recovery efficiency RE and the nature of the geo-physicochemical reactions taking place in aquifer. The RE is the volume of recovered water of useable quality relative to volume injected (Pyne, 1995). The RE is governed by movement and mixing of injected water in aquifer. The, hydrogeological and operational factors, which affects the movement and mixing of injected water in aquifers ultimately control the RE (Pyne 1995; Vanderzalm *et al.*, 2002). Aquifer factors include the transmissivity, porosity, thickness, heterogeneity, dispersivity, native groundwater quality and regional hydraulic gradient. Operational factors include quality of injected water, critical target water quality, storage time, buffer storage volume and ratio of recovery to injection rate.

However, success of ASR operations in such areas depends on availability of good quality water for injection and ability to recover useful quantities of good quality water. In India, the excess surplus rain, canal and river water available during summer wet period (July-Aug-Sept) may be injected to improve the quality of native brackish aquifer for irrigating subsequently for increasing crop productivity in winter dry periods (Oct-April) of scarcity. The brackish (EC > 2dS m^{-1}) groundwater in Haryana (India) is more than 53 % (Malik *et al.,* 2002b) and in different parts of country, it ranged from 32-83 % (Minhas and Gupta, 1992). Out of the total surface water potential of Haryana (14.8×10^9 m^3/annum) about 36% goes unutilized (Aggarwal and Roest, 1996). This shows that Haryana alone has a large potential for utilizing the excess fresh surface water for improving the underground brackish water using ASR technology.

In Haryana state of India, the problems, directly or indirectly, arising due to groundwater resources are over exploitations of good quality groundwater in northeastern zone resulting in fall of water table threatening the existence of irrigated agriculture due to depletion of resources. On the other hand the non-utilization of poor quality groundwater coupled with introduction of canal irrigation in other parts threatens the sustainability of irrigated agriculture with the potential problem of water logging and soil salinization. Improvement in the quality of water in the aquifer surrounding the ASR prompts the farmer to extract more groundwater for irrigation (Malik *et al.*, 2002a) thereby implementing the recommended conjunctive use strategy and helping to lower down the water tables in brackish groundwater zones.

Most of wells are cavity type in north India and were not found to clog when they were used to inject fresh water even of large, 900 mg/l, sedimentation load (Anonymous, 1993 and Malik *et al.*, 2002a). Cavity wells are shallow wells installed in aquifers (15 to 100 m deep) where an empty space is formed below the impermeable layer called a cavity; thus, the well is named a cavity well (Malik *et al.,* 2000).

Geochemistry of ASR systems is very complex and is in the process of evolution as we learn from the experience at different sites. Prior knowledge of geochemical reactions occurring during mixing of injected water with groundwater in aquifer of varying mineral composition and pH conditions depending upon the climate of the area would help in installation, operation and sustaining the ASR system. Knowledge of precipitation of Iron, Manganese and Arsenic (Faust and Vecchiolli, 1974; Boochs and Barovic, 1981; Pyne, 1995; Meigs and Beauheim, 2001) in the aquifer by injecting pH and Eh optimized water may be utilized to reduce the toxicity of these heavy metals in drinking water and clogging in ASR wells. Similarly the knowledge of dissolution of calcite minerals in aquifer of semi arid regions can be utilized to increase the nutritive value of the recovered water and to increase the aquifer hydraulic conductivity.

Modelling water pressures heads around the ASR well would be helpful in quantifying the temporal and spatial rise or fall in water levels and also in assessing the environmental impacts (Gale *et al.,* 2002) on long-term basis for the planners and researchers. Successful planning and management of artificial recharge activity often requires consideration of different operational options under a given set of constraints. Simulation of models can integrate geological and hydrological information and helps in quantifying the influencing zone and to optimize the operational factors as buffer storage volume BSV and residence time $\bar{t}$ of the recharge water for the success of ASR technology. Farm scale water level responses are further complicated by the problem of surface unsaturated flows and aerial horizontal and vertical heterogeneities. To our knowledge, a few numerical modelling studies have been reported for cavity type ASR wells. A scientifically documented and evaluated (Diodato, 2000), HYDRUS-2D software package of (Simunek *et al.*, 1996) having extensive interface capabilities for simulating saturated and unsaturated water, solute and heat flow under bare and cropped condition, well suited for field heterogeneities would be used to predict the water level responses at a farm operating a cavity type ASR well on short term and long term basis.

Therefore objectives (**O**) of the study planned were:

O1: To quantify experimentally the effect of storage time, ST, and buffer storage volume, BSV on recovery efficiency and geo-physicochemical interactions in ASR well.

O2: Modeling of rise and fall of water pressure between brackish native and fresh injected water in ASR wells.

O3: To quantify the buffer storage volume for 100 % recovery efficiency

Chapter II

REVIEW OF LITERATURE

Water is power in 21st century (Pyne, 1995). Adequate storage is the key to sustainable water management. Effective water resource management in areas of water scarcity must include increased storage of water behind dams or in aquifers to save water in periods of water surplus for use in periods of water shortage. Storage in surface reservoirs is expensive and increasingly perceived as an unacceptable exchange of valued ecosystem. Systems to recharge aquifers through surface methods such as basins and in channel structures are functioning reasonably well, however their wide spread application is frequently limited by hydrogeologic constraints and the availability of land at reasonably cost. Aquifer storage and recovery ASR is a new, efficient and cost effective tool for water resources management and could be applicable wherever there are severe water supply challenges (Pyne, 1995). Use of ASR technique for irrigation and drainage process has a wide scope in India and need a fair trail. Pyne (1995); Kumar and Aiyagari (1997); Bower (1994, 1996, 1997); Malik *et al.,* (2000, 2002b) have worked on different methods of artificial recharge. Mishra and Seth (1988) studied the recharge from a river of large width to a shallow water table aquifer.

The literature on various aspects of groundwater recharge through ASR well is reviewed under following heads:

2.1 Recovery efficiency

2.2 Geo-physico-chemical interaction

2.3 Modelling of groundwater recharge

2.1 RECOVERY EFFICIENCY

The recovery efficiency RE is the volume of recovered water of useable quality relative to volume injected (Pyne, 1995). The economic development of ASR for improving native water quality is dependent upon recovery behaviour of the injected water after a given storage time. It is best described by the term recovery efficiency RE and the nature of the geophysical and chemical reactions taking place in aquifer. Gerges *et al.*, (2002a) reported 90 % of South Australian sites having too saline groundwater to use for irrigation prior to ASR. Recovery efficiency (RE) is known to vary enormously between sites. The various factors, hydrogeological and operational, which affect the movement and mixing of injected water in aquifers ultimately, control the RE (Pyne, 1995; Vanderzalm *et al.*, 2002). Aquifer factors include the transmissivity, porosity, thickness, heterogeneity, dispersivity, native groundwater quality and regional hydraulic gradient. Further, the dispersivity is a function of the ratio of pumping rate at the well to the regional flux (Silliman, 2001). Operational factors include quality of injected water, critical target water quality, storage time, buffer storage volume and ratio of recovery to injection rate. The results of the studies of Harpaz (1971) on limestone and sandstone aquifer in Israel showed that the groundwater movement and mixing at the edges of the body was much greater in limestone aquifer than in sandy aquifer. Increasing storage time may or may not decrease the RE in brackish aquifer (Harpaz, 1971; Pavelic *et al.,* 2002a) depending upon aquifer characteristic and the buffer storage volume (Pyne, 1998). Pavelic *et al.,* (2002b) have indicated that there is an optimum buffer storage volume for each site for acceptable recovery efficiency. Pyne (1998) demonstrate the improvement in RE that is possible during successive injection recovery cycles due to residual injectant providing a buffer against mixing with ambient groundwater. Harpaz (1971), Pyne (2002) and Gerges *et al.*, (2002b) have reported the decrease in RE on increasing the storage time and related it to the intense natural flow carrying the injected water body away and disperse it rapidly. Injecting water with large volumes results in high RE (Stevens *et al*, 1994; Howles *et al*, 1997; Pyne, 1998; Streetly, 1998; Malik *et al*, 2002a; Gerges *et al*, 2002a). Recovery efficiency is higher in confined aquifer than in unconfined aquifer (Dillon and Pavelic, 1996; Gerges *et al.*, 2002a). Movement of stored water is particularly important in ASR system where storage zone contain water of inferior quality. In order to quantify the recovery behaviour, it is necessary to estimate the fraction of ground water in the recovered water (Ragone and Vecchioli, 1975; Boochs and Barovic, 1981; Meigs and Beauheim, 2001; Pavelic *et al.*, 2002a). Chloride has been widely used as tracer to quantify the mixing fraction of native groundwater with the injected water in the situation where fresh water is injected into more saline aquifer (Ragone and Vecchioli, 1975; Le Gal La Salle *et al.*, 2002).

2.2 GEO-PHYSICOCHEMICAL INTERACTION

Hamlin (1987) studied hydraulic and chemical changes during water recharge by injection. During recharge, geo-physicochemical reactions can occur that may adversely affect aquifer permeability or cause changes in the quality of recovered water. Geochemistry of ASR systems is very complex and is in the process of evolution as we learn from the experience at different sites. Geochemical measurements and concepts that have proved particularly helpful in gaining understanding of underground processes are discussed here. Prior knowledge of geochemical reactions occurring during mixing of injected water with groundwater in aquifer of varying mineral composition and pH conditions depending upon the climate of the area would help in installation, operation and sustaining the ASR system. These chemical and physical changes are a function of recharge water quality, native groundwater quality, aquifer mineralogy, changes in temperature and pressure that occur during recharge and recovery. The most notable of the possible adverse geo-chemical reactions occurring in aquifer are dissolution (Martin and

Dillion, 2002; Gerges *et al.*, 2002b) or precipitation (Berner, 1978) of calcite, oxidation of pyrite (Faust and Vecchiolli, 1974; Pyne, 1995; Pavelic *et al.*, 2002b), ion exchange, reduction of sulphate, oxidation of organic matter and reduction of nitrate (Vanderzalm *et al.*, 2002; CH2MHILL, 1993). The sequential order of these processes is clogging, bacterial activity, ion exchange, adsorption, dissolution and precipitation.

Clogging

Physical clogging by total suspended solids (TSS) is perhaps the most important technical fatal flaw for ASR technology. Most of the work on ASR has been in preventing clogging of ASR wells (Pyne, 1995; Bower, 1997). In filter tubewell, some time, as little as 30 mg L^{-1} TSS, had significantly reduced the recharge rate (Pyne, 1995). Clogging of injection strainer wells due to sedimentation (Rahman *et al.*, 1969; Bichara, 1986), air entrapment (Harpaz, 1971; Huisman and Olsthoorn, 1982), bio-film coating (Rebhum and Schwarz, 1968; Schippers *et al.*, 1995; Pfeiffer *et al.*, 2002) and precipitation by oxidation of iron and manganese (Pavelic *et al.*, 2002b) and their declogging by back washing and redevelopment controlled acidulation (Gerges *et al.*, 2002a) have widely been reported. Most of wells are cavity type in north India and were not found to clog when they were used to inject fresh water even of large, 900 mg/l, sedimentation load (Anonymous, 1993; Taneja and Khepar, 1996; Malik *et al.*, 2002, 2002b,). Clogging has been reported to be major problem in most of the filter type ASR and injection wells (Rahman *et al.*, 1969; Bichara, 1986; Martin and Dillon, 2002; Pfeiffer *et al.*, 2002).

2.2.2 Microbial activity

Pyne (1995) observed that bacteria are present in aquifer to a depth of 500 m or deeper. Bacteria can cause bio fouling and bacterial slimes can also reduce permeability around ASR well. Sulfate reducing bacteria are only one hundred of different type of bacteria that can cause biofouling. Temperature between 20 – 40 ^{0}C, pH between 7.6 – 8.6, total phosphorus exceeding 0.1 mg L^{-1}, nitrate exceeding 1 mg L^{-1}, dissolved organic carbon exceeding 5 mg L^{-1}, total iron exceeding 1 mg L^{-1}, dissolved oxygen exceeding 3 mg L^{-1} and a slow flow sequence strongly enhance bio fouling potential. The aquifer is considered to provide sustainable water treatment in addition to storage function. Miller *et al.*, (2002) reported the two major contaminant and pathogen attenuation processes in the subsurface, adsorption and biodegradation, of which biodegradation is considered as a sustainable attenuation process as adsorption capacity for persistent substances will be used up in long terms. Principle factors affecting attenuation rates of microbiological process appears to be temperature, salinity and native microbiota in storage zone (Pyne, 2002 and John and Rose, 2002). Haloacetic acid and their formation potential disappears in a few days due to aerobic bacterial activity (Pyne *et al.*, 1996). Trihalomethanes attenuate during a few weeks of ASR storage, primarily due to anaerobic bacterial activity (Pyne *et al.*, 1996; CH2MHILL, 2000). Nicholson *et al.,* (2002) and Toze and Hanna, (2002) demonstrate that ASR in anaerobic aquifer has capability for removal of pathogens and some other organic compounds over the storage periods. Dillion *et al.*, (2002) and Gerges *et al.*, (2002b) evaluate the degradation of bacterial toxins in saline aquifers.

Ion exchange

The ion exchange between aquifer soil and its water is governed by the concentration and valency of the cations. Pearson and Friedman (1970) have observed that clay minerals particularly kaolinite controls the concentration of alkali and alkaline earth element through cation exchange. The pH of the water is controlled by both the dissolution of H_2CO_3 and silica kaolinite equilibria (Faust and Vacchiolli, 1974). Calcium replacement on exchange complex would increase hydraulic conductivity and Na^+ on exchange complex reduce the aquifer hydraulic conductivity. Ca^{2+} replace Na^{+} on the clay lattice in a saline groundwater during injection process (Hamlin, 1987).

Dissolution

Dissolution of calcite by injecting low pH rainwater is important for increasing the calcium ion concentration. It may improve the transmissivity of the aquifer and also improve the quality of the water for irrigation. Pearson and Friedman (1970) reported that recovered water contains carbonate in aquifer free of carbonate minerals, and contains water whose chemistry was controlled by the CO_2 precipitation in the aquifer at the site Magothy. The CO_2 gas was evolved due to decomposition of organic matter in soil. Vanderzalm *et al.*, (2002) have also reported as large as 0.7 mmol L^{-1} of dissolution of limestone ($CaCO_3$) aquifer through CO_2 produced by oxidation of organic matter during injection of 250 ML reclaimed water and residence time of one year within the aquifer at Bolivar, South Australia. The low pH value of injected water as compared to that of native groundwater water may have caused dissolution of calcite ($CaCO_3$) present in the aquifer material (Malik *et al.*, 2002b) to form Ca^{2+} and HCO_3^- as:

$$CaCO_3 + H_2CO_3 \rightarrow Ca(HCO_3)_2 \rightarrow Ca^{2+} + 2\ HCO_3^-$$

Yadav (2002) reported that the high pH of injected water increased bicarbonate and decrease borate in recovered water. Storage of injectant can also affect the calcium and bicarbonate concentration, which increase by around 0.2 and 0.8 mmol L^{-1} respectively at ASR site in Bolivar (Vanderzalm *et al.*, 2002). The knowledge of dissolution of calcite and potash minerals in aquifer of semi arid regions can be utilized to increase the nutritive value of the recovered water (Malik *et al.*, 2002b) and to increase the aquifer hydraulic conductivity (Gerges *et al.*, 2002b; Martin and Dillon, 2002; Pavelic *et al.*, 2002a).

Oxidation and Reduction processes

Oxidation and reduction processes become evident with the onset of injection phase and the deviations from the injectant water quality are indicative of the reactive processes. Ragone and Vecchiolli (1975) observed the oxidation of pyrite by dissolved O_2 of the injected water according to the following reaction:

$$FeS_2 + 7/2\ O_2 + H_2O = Fe^{2+} + 2SO_4^{2-} + 2H^+$$

They observed that iron concentration increased from the range 0.14 to 0.30 mg L^{-1} to as much as 3 mg L^{-1} at 20, 100 and 200 foot distance observation well as the reclaimed water displaced native water. It indicated that source of iron was dissolved from iron mineral (Pyrite) present in the aquifer and it got dissolved while injected water carrying O_2 was moving towards the observation well.

Detailed study conducted by Pyne (1995) have indicated that as we go deep, the groundwater losses O_2, sulfate reducing bacteria become viable and can reduce the sulfate to disulfide, which then precipitates metal, particularly iron. This is a congenial environment for uranium deposition. Iron and manganese precipitation is caused by recharging through injection process by reacting with dissolved O_2 leading to the precipitation of iron into ferric hydroxide. They may decrease the hydraulic performance of the ASR well. However in a near future it is anticipated that work will commence to establish that effectiveness of ASR wells in removing arsenic during aquifer storage. The reaction mechanism is expected to involve co-precipitation of arsenic along with ferric hydroxide in aquifers containing low concentration of iron bearing minerals and recharged with water containing dissolved O_2. If successful, this approach may provide a low cost solution to many water utilities face with the prospects of expensive, above ground treatment processes for arsenic removed to meet new standards as arsenic toxicity problems in the state of Orissa and Bihar.

Pyne (1995) performed several recharge recovery test during a period of several months at site Chesapeake in USA when pH of the recharge water was sufficiently higher (7.4 to 9.4) and reported that no Mn problem were apparent in the recovered water. Mn concentration during recovery was less than 0.01 mg L^{-1}. Subsequent process changes at the water treatment plant reduce the pH (6.2 to 7.2) with the result that Mn concentration in the recovered water exceeded drinking water standards, reaching level of 0.25 to 1.28 mg L^{-1}. Remedial measure included recharging water be treated with sodium carbonate to raise the pH in the range of 8.0 to 8.2 or higher. The sodium carbonate helps to buffer the acidity remaining in the aquifer from a large volume of water recharge at low pH.

Vanderzalm *et al.* (2002) showed the reduction of nitrates for mineralizing organic matter by denitrification of around 0.1 mmol L^{-1} of the injected nitrate within 4 m from the injection well. Up to 90 % reduction in total-N at some sites of Florida has been observed during ASR storage (CH2MHILL, 1993). Similarly, phosphorus reductions in the range of 40 to 90 % have been observed at two injection well sites (St Peterburg and Gainesville in Florida), recharging treated wastewater in to fresh and brackish limestone aquifer (CH2MHILL, 1993). Cave and Tredoux (2002) reported the increase in k concentration over several season of artificial recharge from Atlantis and Calvinia sites in South Africa.

Modelling of groundwater recharge

Field and laboratory experiments will be essential to help address knowledge gaps on specific issues while modeling frameworks provide the predictive capability that is necessary to address complex problems (Dent, 2000). Models are essential for dealing with complex system, multiple interactions, competing demands, spatial and temporal variability, scenario analysis and extrapolation of experimental data and finding in both space and time (Dent, 2000). Modelling and scenario analysis are now well-accepted tools of the trade in many fields of endeavor, business, space exploration and industrial and aeronautical engineering. These tools are now becoming more widely accepted in some environmental and agricultural situations particularly in the hydrological, milling and industrial sectors. Significant progress has also been made in developing and applying soil and crop model within agricultural industries (Keating *et al.*, 1999; Inman-Bamber *et al.*, 2001; Carberry 2001; Mcowan, 2001). A scientifically documented and evaluated (Diodato, 2000), HYDRUS-2D software package of (Simunek *et al.*, 1996) having extensive interface capabilities for simulating saturated and unsaturated water, solute and heat flow under bare and cropped condition, well suited for field heterogeneities predicts the water level responses at a farm operating a cavity type ASR well on short term and long term basis.

Modelling water pressures heads around the ASR well would be helpful in quantifying the temporal and spatial rise or fall in water levels and also in assessing the environmental impacts (Gale *et al.,* 2002) on long-term basis for the planners and researchers. Successful planning and management of artificial recharge activity often requires consideration of different operational options under a given set of constraints. Information about soil hydraulic properties is needed for predicting and modelling water movement in the saturated and unsaturated zone of the soil. Numerous field and laboratory methods have been develop for estimating saturated and unsaturated soil hydraulic properties. Kool *et al.*, (1987) and Hopmans and Simunek (1999) gave over views of parameter estimation techniques and Feddes *et al.*, (1988) discussed data needs for model input and validation.One popular approach has been to use relatively simple analytical expressions for the hydraulic properties, such as the van Ganuchten-Mualem equations (Van Ganuchten, 1980). Observed field and/or laboratory soil hydraulic data are often used to derive parameters in these expressions by employing some type of fitting procedures. Direct, indirect or inverse methods may be used for this purpose.Temporal and spatial water pressure responses near ASR strainer wells have been modelled using analytical (Anonymous, 1993; Simpson *et al.*, 2003) in saturated flow conditions in homogeneous areas and numerical two / three dimensional approaches (Chiang and Kinzelbach, 1998; Williams, 2000; Kohfahl *et al.*, 2002; Jorgensen and Helleberg, 2002; Bogdanov *et al.*, 2003) under steady and transient saturated flow conditions for confined, unconfined and semi-confined aquifers in heterogeneous areas with fair degree of success.

Katia (2002) used the analytical model of Forchheimmer (1898) for nonleaky aquifer for homogenous soil to predict the spatial influence of recharge/discharge on rise and fall of water pressure in laboratory as well as field studies. Meritt (1986) in first detailed numerical modeling of 2D horizontal flow, have shown the significant loss in RE due to hydrodynamic dispersion, buoyancy stratification, dissimilar injection / recovery rates and multiple well configurations. Streetly (1998) studied a more detailed sensitive analysis for a radially symmetric homogenous aquifer and showed that recovery increases with increasing volume of the injected water plume. Huntley and Bottcher (1997) modelled a heterogeneous system in which significant reduction in RE observed as compared to equivalent homogenous system. Wright and barker (2001) calibrate the semi analytical model for two parameters i.e. characteristic block time and the ratio of the matrix to fracture porosity successfully when the model was applied to multiple ASR cycles.

Chapter III

Materials and Methods

Field studies to investigate the effect of buffer storage volume and residence time were carried out in a cavity type of ASR well located at soil research farm CCS HAU, Hisar.

3.1 HYDROGEOLOGY

The Haryana (India) soils are very deep > 200 m made from alluvial and aeolian deposits from rivers emanating from the Himalayas. The soils are anisotropic containing illite type of clay (Goyal *et al.,* 1990). Shallow aquifers fine and coarse sand in the depth range of 10 m to 135 m with well yield in the range of 1.5 to 30 L s^{-1}; and deep aquifers in the quartzite and limestone in the depth range of 136 to 450 m with well yield in the range of 1.5 to 150 L s^{-1} are in unconsolidated alluvium overlain by a non continuous clay layer. The groundwater occurs for the most part under water table conditions (Duggal, 1977; Anonymous, 2000). Depth to groundwater level varies from 1 m to more than 60 m below ground level, during the pre monsoon period and the quality of groundwater varies from less than 2 dS m^{-1} to more than 10 dS m^{-1}.

3.2 ASR FASCILITIES

The ASR site of highly brackish native water was selected at Soil Research Farm, Hisar, Haryana, (Plate-1), India (28°59' to 29°49' N latitude and 75°11' to 76°18' longitude at an elevation of 215 m above mean sea level) where an irrigation cavity type well was installed with the injection facility through a submersible pump by removing the check valve permanently while installing the pump. The inner pipe diameter and outer pipe diameters of ASR well (Figure 3.1) were 0.075 m and 0.275 m. The relevant ASR site characteristics are given in Table 3.1.

Table 3.1: Relevant ASR site characteristics

Site Characteristics	Value	Site Characteristics	Value
Effective porosity of aquifer(ne)	0.09	Native water EC	28.4 dS m^{-1}
Thickness of the aquifer (b)	15.0 m	Injected water EC	0.27 dS m^{-1}
Aquifer hydraulic conductivity (k)	1.04 m h^{-1}	pH of native water	8.4
Aquifer transmissivity (T)	15.65 m h^{-1}	pH of injected water	7.65
Regional hydraulic gradient (i)	0.0007	Storivity	1.28×10^{-4}
Total porosity	0.37	Specific capacity	6010 $m^3h^{-1}m^{-1}$
Fraction of injectant in recovered water at target time tr* (f *)	0.938	Average depth to water table	1.2 m

The site lithology and schematic diagram of ASR facility is shown in Figure 3.1. Water from canal was gravity injected into cavity type ASR well to create buffer storage volume BSV employing siphon system during August 2002. Buffer storage volume is the large initial storage volume, which forms the buffer zone between native brackish water and volume injected to be recovered Vi. Buffer storage volume in j th cycle BSV_j was estimated as:

$$BSV_j = Vi_j^* - Vi_j + BSV_{(j-1)} \quad (3.1)$$

where j denotes the number of ASR cycle, Vi_j^* = total volume injected in the cycle j

Residence time $\bar{t}$ of 70.83, 118.35 and 113.20 days were allowed at a buffer storage volume BSV of 14000 m^3 in 4th and 5th ASR cycles. In each cycle the volume injected to be recovered V_i was kept as 2000 m^3.

Residence time $\bar{t}$ was estimated for each cycle as:

$$\bar{t} = 0.5\,(t_i + t_r) + t_s \quad (3.2)$$

where t_i = injection time, t_r = recovering time, t_s = storage time between ti2 and tr1

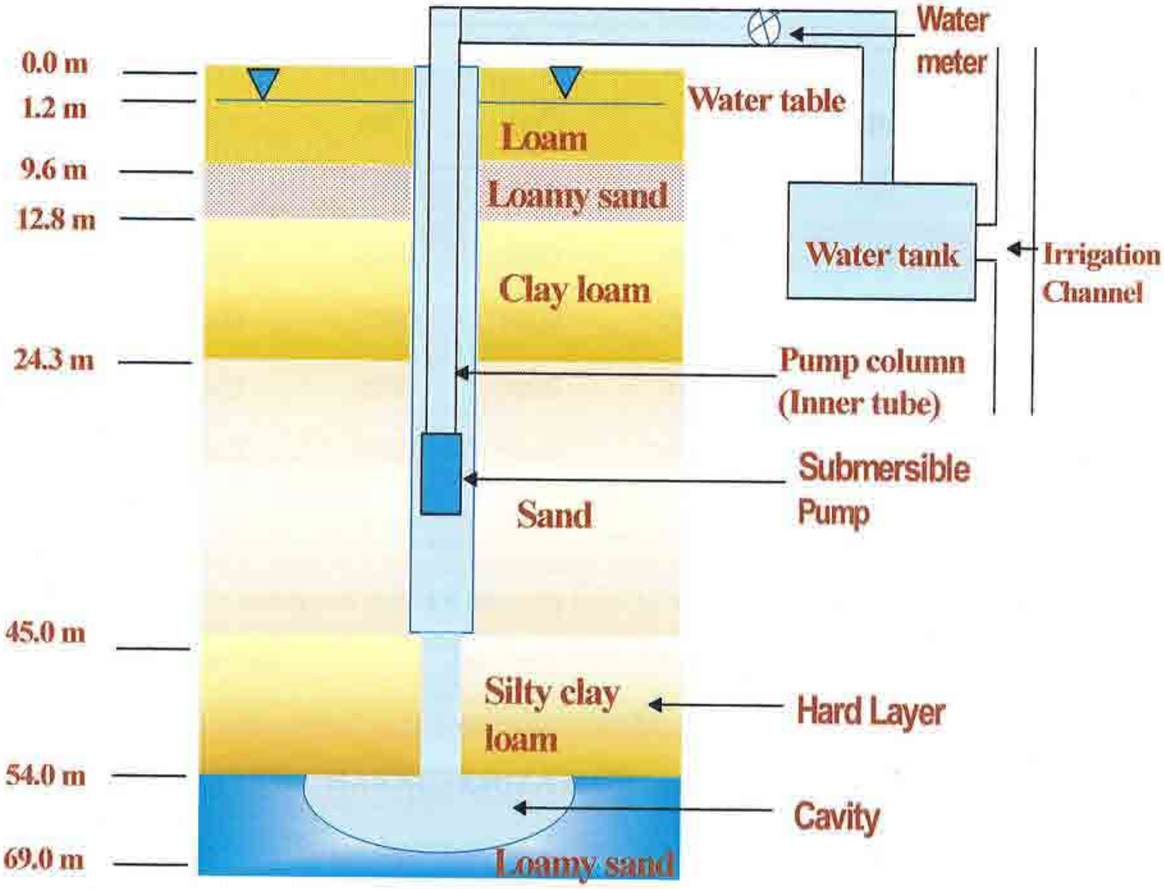

Figure 3.1: Schematic diagram of the ASR well

The details of the ASR cycle test programmed adopted in the study are given in Table3.2.

Table 3.2: The ASR cycle test programme for the cavity type of ASR well

Cycle number j	BSV (m^3)	V_i (m^3)	V_i* (m^3)	t_i (d)	$\bar{t}$ (d)	t_r (d)
1	6000	2000	6000	12	7.2	2.4
2	10000	2000	6000	10.6	6.05	1.5
3	14000	2000	6000	25.6	13.55	1.5
4	14000	2000	2000	10.2	70.83	2.4
5	14000	2000	2000	9.17	118.35	1.54
6	14000	2000	2000	8.92	113.20	1.54

t_i = injection time, $\bar{t}$ = residence time, t_r = recovery time, Vi = volume injected to be recovered.
V_i* = Total volume injected

3.3 SOIL AND WATER CHARACTERIZATION

Soil samples from different layers taken during the installation of piezometers, were oven dried and ground gently with the pestle-mortar. The fraction remaining above a 2 mm sieve was identified as calcite concretions. The soil passed through the sieve was analyzed for different physico-chemical properties. Soil analysis was done with the standard methods. The relevant physico-chemical properties up to the aquifer are given in Table 3.3.

Water samples of recovery water as a function of recovery time and that of injected and native water were analyzed for temperature, organic carbon OC, cations (Na^+, K^+, Ca^{2+}, Mg^{2+}, NH_4^+, Zn^{2+}) and anions (CO_3^{2-}, HCO_3^-, Cl^-, SO_4^{2-}, BO_3^-) by standard methods. Percent error in ionic mass balance Em was calculated (Pyne, 1995) as-

$$Em(\%) = 100\left[\frac{\sum(EC_c - EC_a)}{\sum(EC_c + EC_a)/2}\right] \tag{3.3}$$

Where EC_c and EC_a are cation and anion concentrations in mmol$_c$ L^{-1}.

Table 3.3: Relevant soil physico-chemical properties of Hisar ASR site

Depth (m)	EC (dS m^{-1})	pH	Texture	CaCO$_3$ (%)	Concretion (%)	Gypsum (%)
0.0-9.6	1.20	8.2	Loam	8.0	32.1	0.014
9.6-12.8	1.19	8.5	Loamy sand	1.1	52.1	0.015
12.8-24.3	0.96	8.6	Clay loam	8.7	0.0	0.020
24.3-45.0	0.76	8.9	Sand	0.4	25.5	0.015
45.0-54.0	0.75	8.4	Silty clay loam	1.0	6.0	0.014
54.0-69.0	0.78	8.6	Loamy sand	4.1	0.0	0.014

3.4 NUMERICAL EXPERIMENTS

The windows based HYDRUS-2D package solves the modified form of Richard equation (1) for variably saturated flow numerically as:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x_i}[K(K_{ij}^{A}\frac{\partial h}{\partial x_j} + K_{iz})] - S \tag{3.4}$$

where θ is the volumetric water content ($L^3\,L^{-3}$), h is the pressure head (L), S is the sink term (T^{-1}), x_i ($i = 1,2$) are the spatial coordinates (L), t is the time (T), K_{ij}^{A} are the components of the anisotropy tensor K^A, and K is the unsaturated hydraulic conductivity (L T^{-1})

Calibration was done for first cycle having BSV 6000 m^3. Validation was done for the next two cycles of BSV 10000 and 14000 m^3 and three cycles of residence time $\bar{t}$ = 70.8, 118.35 and 113.20 d at BSV of 14000 m^3 as per field ASR cycle test programme (Table 2). In total 6 Hydrus 2D runs were carried out for simulating drawup and drawdown in 6 ASR cycles as given in Table 3.2.

The physical flow region involved a soil profile 500 m wide and 69 m deep with an exocentric elliptical cavity of 1m horizontal radius and 1m vertical radius at 54 m depth as shown in figure 3.2. No flux boundary condition was given at soil surface, bottom and lateral sides of the flow regions (Figure 3.2). One piezometer and observation well served as the observation nodes at the position shown in figure 3.2.

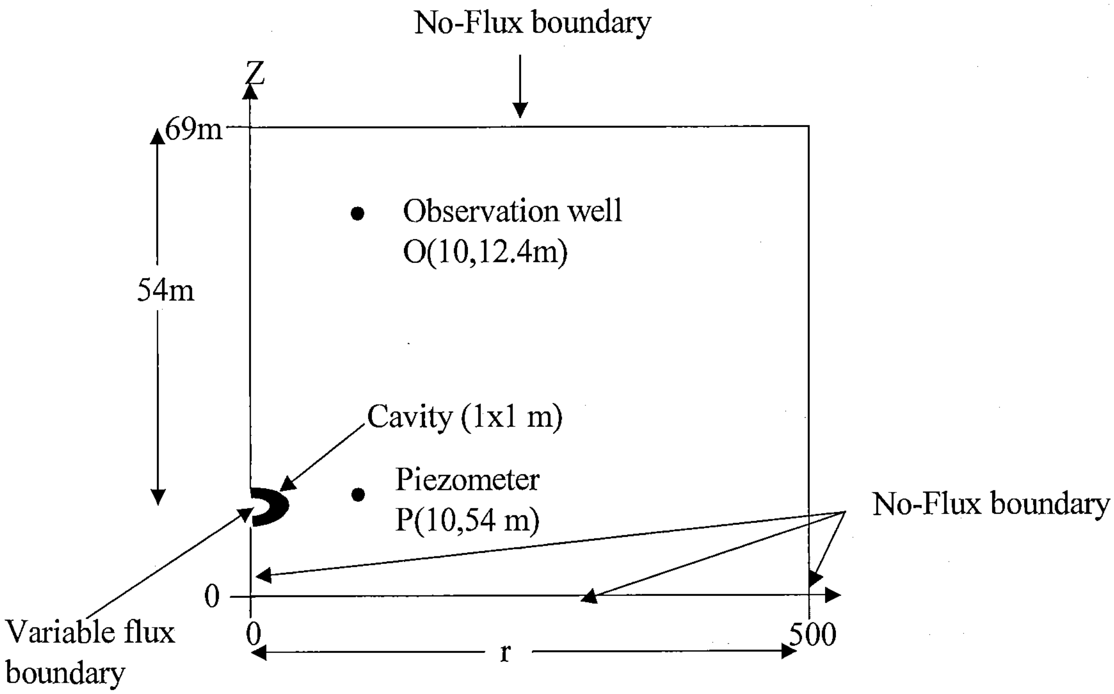

Figure 3.2. Schematic physical layout of the ASR system implemented in Hydrus 2D.

Experimentally observed recharge fluxes (-ve) and recovery fluxes (+ve) as a function of time served as a variable flux boundary condition for Hydrus 2D. The flux values are shown graphically in figure 3.3.

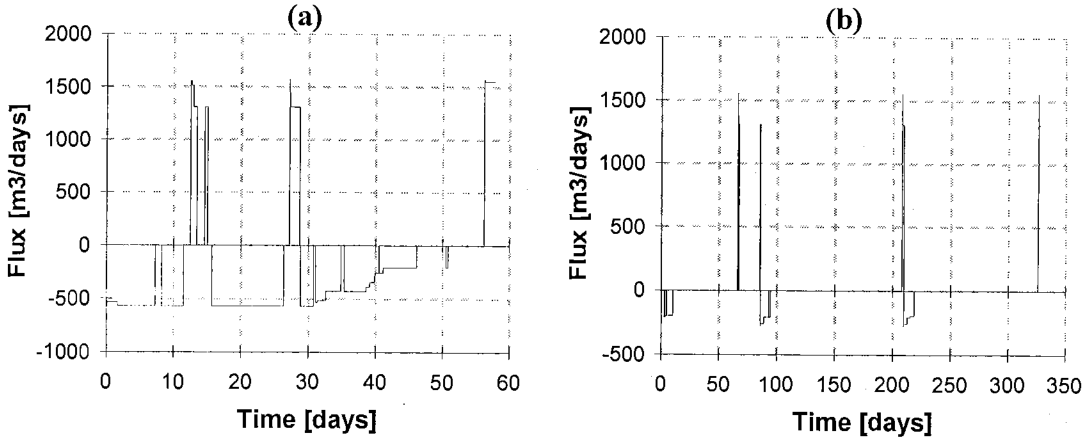

Figure 3.3: Recharge (–ve) and recovery fluxes (+ve) of (a) cycles having BSV-6000, 10000 and 14000 m^3 and (b) $\bar{t}$ = 70.8, 118.35 and 113.20 d

Parameter estimation

Soil water retention functions were derived from pressure head and water content data measured on pressure plate apparatus using Van Genuchten-Mualem equations (Van Genuchten, 1980) as:

$$\theta(h) = \frac{\theta s - \theta r}{[1 + |\alpha h|^n]^m} \qquad h<0 \tag{3.5}$$

$$\theta(h) = \theta s \qquad h \geq 0 \tag{3.6}$$

$$K(h) = KsSe^k \left[1 - \left(1 - Se^{k/m}\right)^m\right] \tag{3.7}$$

Where θ is the volumetric water content, h is the pressure head, α, n, m (=1=1/n), and k (=0.5) are empirical parameters, Se= $(\theta - \theta r)/(\theta s - \theta r)$ is the degree of saturation. For this purpose θr, is the residual water content and was set equal to air dry water content; and θs, the saturated water content, was set equal to the total porosity as calculated from the bulk density obtained in the h- θ measuring cores assuming particle density to be 2.65g cm^{-3}.

Saturated hydraulic conductivity was estimated through inverse modelling technique using the experimental pressure heads h time pairs during the first ASR cycle from a piezometer (z = 54 m, r = 10 m); and observation well (z = 12.4 m, r = 10 m) by using the observed θr, θs, α, n, and m as fixed parameters. Estimation of hydraulic parameter through inverse modeling has become an accepted technique under field condition (Van Dam and Malik, 2003; Ghulam Ali *et al.,* 2004). The hydraulic parameters values are given in table 3.4 and figure 3.4 (a&b).

Table 3.4: Hydraulic parameters used in numerical experiments

Parameters	θr (m^3m^{-3})	θs ($m^3 m^{-3}$)	α (m^{-1})	n	K_s ($m\ d^{-1}$)
Loam (M1)	0.03	0.47	0.05	2.2	1.00
Loamy sand (M2)	0.05	0.43	0.10	2.5	5.00
Clay loam (M3)	0.07	0.54	0.015	2.1	0.05
Sand (M4)	0.03	0.40	0.07	2.7	1.00
Silty clay loam (M5)	0.06	0.50	0.13	1.7	0.20
Loamy sand (M6)	0.05	0.40	0.10	2.5	8.20

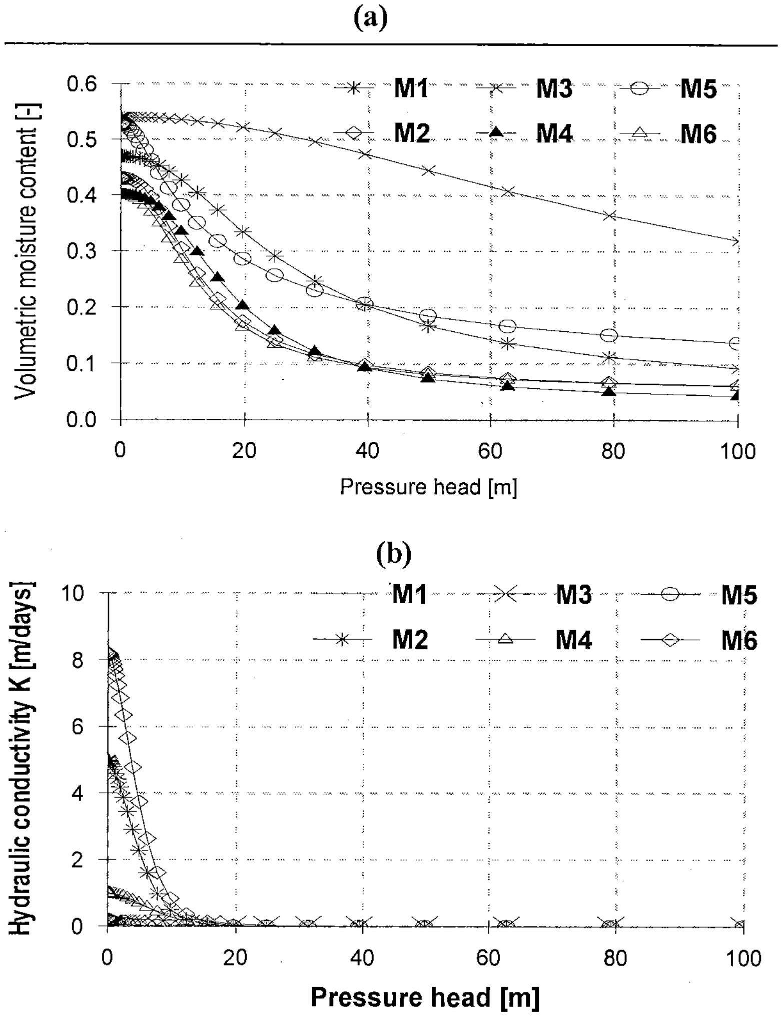

Figure 3.4: Soil hydraulic properties for ASR site lithology.

Statistical test

Statistical tests to assess simulation performance were:

Modelling efficiency (ME)

$$ME = 1 - \frac{\sum_{i=1}^{n} (O_i - S_i)^2}{\sum (O_i - \overline{O})^2} \tag{3.8}$$

where Oi and Si represent the observed and simulated values, n represents the number of observed and simulated values used in the comparison, and $\overline{O}$ the observed average:

$$\overline{O} = \sum_{i=1}^{n} \frac{O_i}{n} \tag{3.9}$$

one is considered to be the best modelling efficiency. Negative values of modelling efficiency are considered as unacceptable (Ghulam ali *et al.*, 2004) and

The root mean square error RMSE:

$$\mathrm{RMSE} = \sqrt{\left(\frac{1}{n}\sum_{i=1}^{N} [O_i - S_i(b)]^2\right)} \tag{3.10}$$

Analytical model

Forchheimer solved the steady state equation of groundwater flow for a cavity-well with spherical bottom situated on top of a confined aquifer for drawdown and drawup as:

$$s = \frac{Q}{2\,\pi\, Kr} \tag{3.11}$$

where s = Drawdown or drawup of pressure head (m)

Q = Recharge or discharge rate ($m^3\ d^{-1}$)

K = Aquifer hydraulic conductivity ($m\ d^{-1}$)

r = radial distance from the cavity (m)

Paired t test was applied to compare the pressure head generated numerically and analytically at radial distances as:

$$t_{cal} = \frac{d}{\sqrt{S^2\left[\frac{1}{n_1} + \frac{1}{n_2}\right]}} \tag{3.12}$$

d is the difference of mean defined as:

$$d = X_1 - X_2$$

$$S = \sqrt{\frac{n_1 x S_1^2 + n_2 x S_2^2}{(n_1 + n_2 - 2)}} \tag{3.13}$$

n and S are the numbers of comparable paired points and standard deviation and their subscript are indicative of their respective experimental and predicted values and S is the standard deviation of mean and t_{cal} is calculated t value.

Chapter IV

RESULTS AND DISCUSSION

Results are discussed under the following heads:

4.1 Effect of buffer storage volume and residence time on recovery efficiency and dispersivity

4.2 Geo physicochemical Interactions

4.3 Modelling of groundwater recharge

4.1 EFFECT OF BUFFER STORAGE VOLUME AND RESIDENCE TIME ON RECOVERY EFFICIENCY AND DISPERSIVITY

4.1.1 Injected and recovery rates:

Injection rates were less than recovery rates due to shallow groundwater level condition at the ASR site. Recovery rates remained fairly constant in each cycle at an average value of 60.21 $m^3 h^{-1}$. The injection rates were fairly constant up to the third cycle at an average value of 23.23 $m^3 h^{-1}$ (Figure 4.1).

However, injection rates decreased slowly to 13.29 $m^3 h^{-1}$ in 3rd and 4th cycle. The underlying reason could be the relative positions of pheretic and piezometric surfaces.

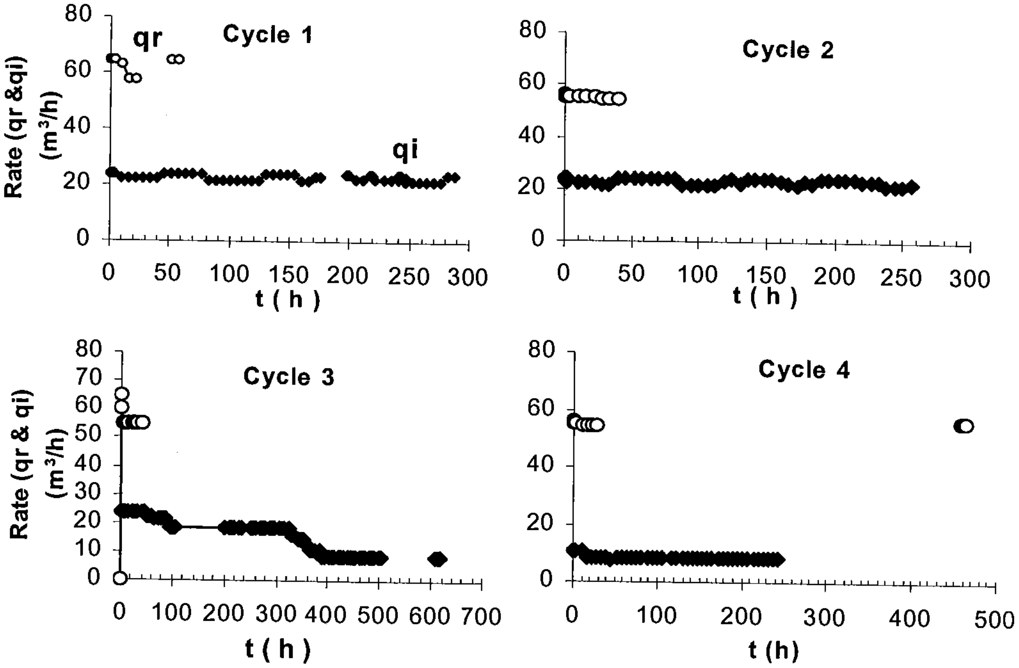

Figure 4.1: Injection qi and recovery rates qr in indicated cycles as a function of time

The data given in Table 4.1 showed that up to cycle 3 the pheretic surface lay over and above the piezometric surface by more than 0.26 m making a case for vertically downwards drainage favoring the injection process. In cycle 3 & 4, the reverse was true i.e. the peizometric surface lay over and above the pheretic surface making a case for vertically upward seepage disfavoring the injection process. The difference between dwp and dwo as given in column 5 of Table 4.1 varied with cycle number showing an interplay of different opposing factors like seepage from irrigation channel, injection in ASR well and irrigation in nearby field on one hand and canal dry period and recovery from ASR well on the other hand. Nevertheless, the study clearly showed that injection could be done in a cavity type ASR well under shallow water table condition even when depth to water table depth was 0.54 - 2.08 m near canals and in monsoon season. Clogging also does not seem to be responsible for the decrease in injection rate in 3rd and 4th cycle, as recovery rates remained unaffected with successive ASR cycles.

Table 4.1: Average injection rate and depth to piezometric surfaces dwp and pheretic water surfaces dwo at 10 m radial distance from ASR well

ASR Cycle	Injection rate ($m^3 h^{-1}$)	dwp (m)	dwo (m)	(dwp-dwo) (m)
1	23.23	0.89	0.64	0.25
2	23.23	0.70	0.54	0.16
3	13.29	1.28	1.59	-0.31
4	13.29	1.25	1.26	-0.01

4.1.2 Recovery behaviour

Recovery percentage I

It is defined as the percentage recovered water volume V_r at any recovery time tr to the volume injected to be recovered V_i as:

$$I = \left[\frac{\int_{tr1}^{tr2} qr(t)\,dt}{\int_{ti1}^{ti2} qi(t)\,dt} \right] = \left[\frac{V_r}{V_i} \right] \quad (4.1)$$

where ti1= time that injection starts, ti2= time that injection ends, tr1= time that recovery starts, tr2 = time that recovery ends, qr (t)= recovery rate as a function of time, qi(t) = injection rate as a function of time, V_r = volume recovered between recovery time tr1 to tr2 and V_i = volume injected between injection time ti1 to ti2.

Recovery efficiency RE

The instantaneous recovery efficiency IRE represents the recovery percentage I at target time t_r* to meet the target instantaneous EC_r (t) criteria for the recovered water. The integrated recovery efficiency CRE would therefore, represents the recovery percentage (I) at target time t_r** to meet the target integrated EC_{rw} (t) for the recovered water. It may be expressed mathematically as:

$$RE = \left[\frac{\int_{tr1}^{trt} q_r(t)\,dt}{\int_{ti1}^{ti2} q_i(t)\,dt} \right] = \left[\frac{V_r^*}{V_i} \right] \tag{4.2}$$

Where, V_r* = total recovered volume at target time trt. In this study desired water quality (electrical conductivity, EC) of the recovered water for irrigation purpose was taken as 2 dS m^{-1}. The EC_r (t) and EC_{rw} (t) are instantaneous and integrated (weighted average) electrical conductivity as function of time t in the instantaneous recovered water sample ΔV_r and in the cumulative recovered volume of recovered water V_r and EC_i, and EC_n are concentrations of given parameters in injected and native water. The EC_{rw} (t) can be estimated as:

$$EC_{rw}(t) = \left[\frac{\int_{tr1}^{tr2} EC_r(t) qr(t)\,dt}{\int_{ti1}^{ti2} qr(t)\,dt} \right] = \frac{\sum EC_r(t)\Delta V_r}{\sum \Delta V_r} \tag{4.3}$$

where ΔV_r is the instantaneous recovered water volume in any given recovery time interval.

Instantaneous recovery efficiency is useful when the recovered water is put to direct use such as for drinking or irrigation. The integrated RE is useful when the recovered water may be stored in the storage tanks just before use and for quantifying the geo-chemical interactions.

4.1.3 Effect of buffer storage volume on recovery efficiency

The integrated electrical conductivity of recovered water EC_{rw} as a function of recovery times was estimated from equation (4.3). The EC_r and EC_{rw} of the recovered water increased with I (Figure 4.2 a&b) signifying that there was increasing mixing as the recovered water was withdrawn radially away from the well (Pyne, 1995).

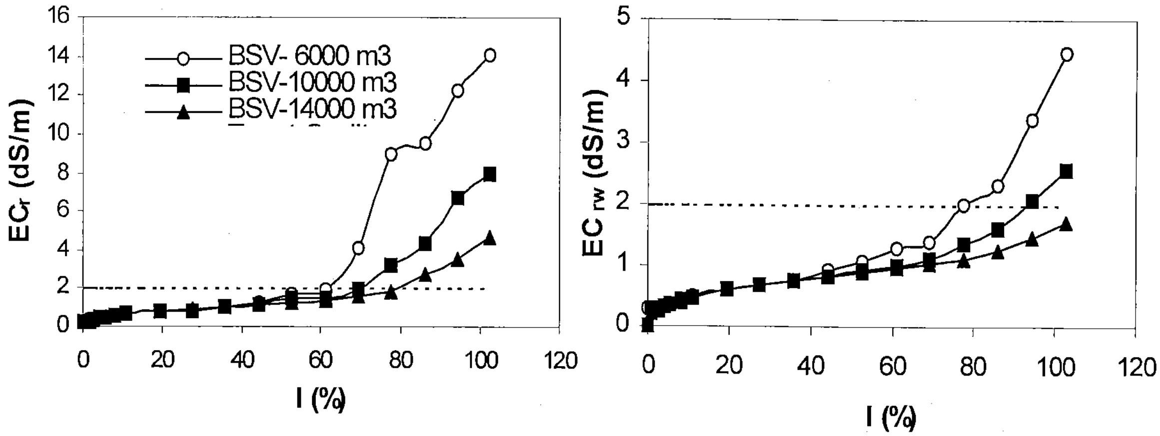

Figure 4.2: (a) Instantaneous electrical conductivity EC_r and (b) integrated electrical conductivity EC_{rw} of the recovered water as a function of recovery percentage I at indicated buffer storage volume BSV

It further showed that EC_{rw} increased relatively slower with I than EC_r signifying high integrated recovery efficiency than instantaneous recovery efficiency. In these figures the dotted line showed that 2 dS m^{-1} was taken as the target water quality for irrigation purposes (Package and Practices, 2004).

The recovery efficiency RE described in equation (4.2) at target EC* of 2 dS m^{-1} as a function of BSV is shown in figure 4.3.

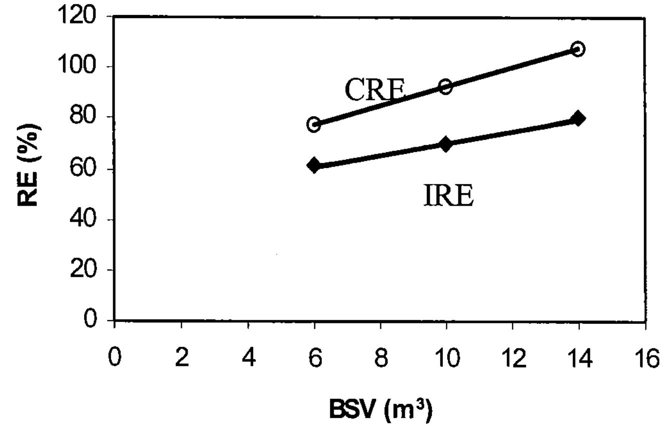

Figure 4.3: Instantaneous recovery efficiency IRE and integrated recovery efficiency CRE as a function of buffer storage volume BSV

It showed that both instantaneous recovery efficiency IRE and integrated recovery efficiency CRE increased with BSV linearly as:

$$\mathrm{IRE} = 54.708 + 3.8125\ \mathrm{BSV}, \qquad r^2 = 0.9999 \qquad (4.4)$$

$$\mathrm{CRE} = 46.233 + 2.465\ \mathrm{BSV}, \qquad r^2 = 0.9956 \qquad (4.5)$$

The observed IRE and CRE at EC* of recovered water 2 dS $m^{-1}$was 80.2 % and 108 % at BSV of 14000 m^3 (Table 4.2). The CRE was higher than IRE at each BSV. It suggested that the minimum BSV required to maintain the acceptable CRE of 100 % was 14000 m^3 at residence time of 13.5 days. Pyne (1995) has reported recovery efficiency varying form 25 – 100 per cent at different sites in Florida depending upon BSV, aquifer water quality and aquifer hydraulic characteristics.

Table 4.2: Recovery efficiency and dispersivity parameters at different buffer storage volume BSV and residence time $\bar{t}$.

Cycle No.	BSV (m^3)	$\bar{t}$ (d)	IRE (%)	CRE (%)	α (m)	α_{rd}	RMSE
1	6000	7.20	61.0	77.5	0.291	0.004	0.10
2	10000	6.05	69.5	93.0	0.245	0.011	0.13
3	14000	13.55	80.2	108.0	0.235	0.011	0.14
4	14000	70.83	50.1	76.6	0.360	0.170	0.12

IRE = instantaneous recovery efficiency, CRE = integrated recovery efficiency, α = longitudinal dispersivity, α_{rd} = relative dispersivity, RMSE = root mean square error.

The recovery efficiency at different target value for EC* (2, 4 & 6 dS m^{-1}) of irrigation water was estimated from figures 4.2.

It showed that the RE increased linearly with the increasing target EC* of the recovered water as:

$$\text{IRE} = 55.833 + 3\ \text{EC*} \quad ; \quad r^2 = 0.9453 \qquad (4.6)$$

$$\text{CRE} = 62.33 + 8.375\ \text{EC*} \quad ; \quad r^2 = 0.9739 \qquad (4.7)$$

Malik *et al.,* (2002a) also reported 80 % IRE at native water quality of 2.65 dS m^{-1}. The IRE and CRE as a function of target water quality are presented in Figure 4.4.

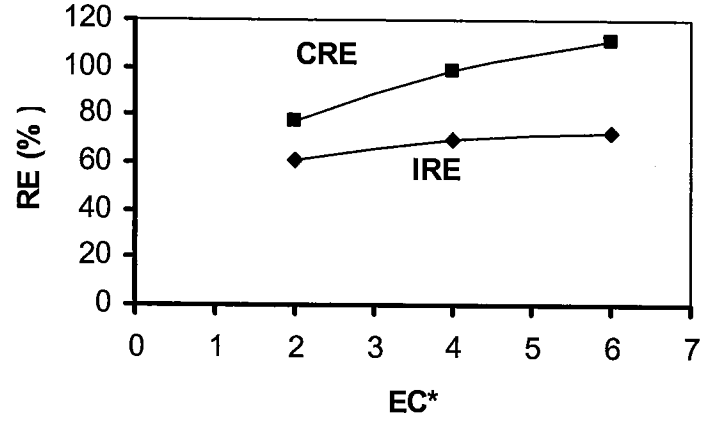

Figure 4.4: Instantaneous recovery efficiency IRE and integrated recovery efficiency CRE as a function of target EC*

It thus implies that higher RE may be achieved from a given ASR cycle for salt tolerant crops. The RE often improves with subsequent injection cycles and may reduce when the storage time is too long.

4.1.4 Effect of residence time on recovery efficiency

The recovery efficiencies at different residence time $\bar{t}$ as estimated from Figure 4.5 are presented in Table 4.2.

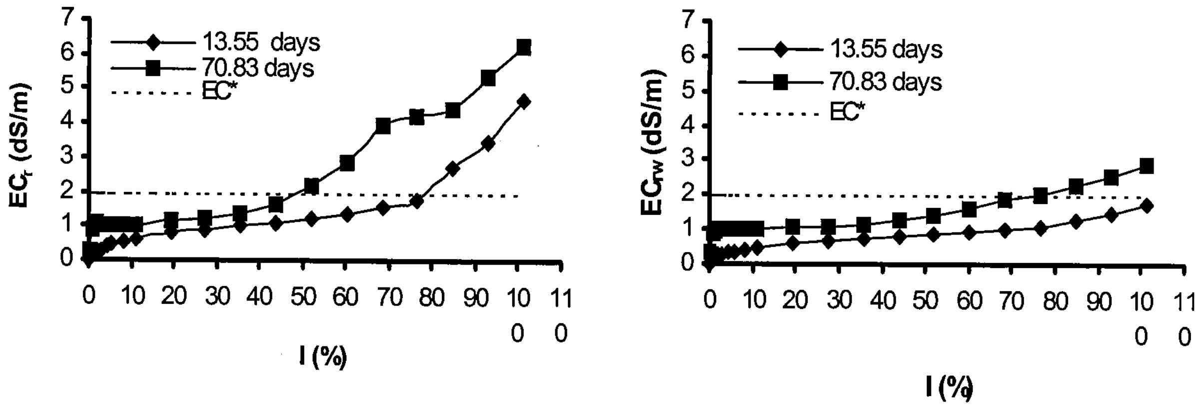

Figure 4.5: (a) Instantaneous electrical conductivity EC$_r$ and (b) integrated electrical conductivity EC$_{rw}$ of the recovered water as a function of recovery percentage I at indicated residence time $\bar{t}$.

The recovery efficiency IRE and CRE decreased with increasing residence time $\bar{t}$ of 57.25 d (Figure 4.5) in 4th ASR cycle by 30.1 and 31.4 % respectively as compared to 3rd cycle (Table 4.2). It may be because of more operation time available for dispersive parameters. Pavelic *et al.*, (2002a) and Pyne, (1998) had also reported the decrease in recovery efficiency with increasing storage time in brackish aquifer depending upon aquifer characteristic and the buffer storage volume.

4.1.5 Analytical experiment for dispersivity

We define mixing fraction *f (t)* according to Pavelic *et al.*, (2002a) as:

$$f(t) = \frac{C_{rw}(t) - C_n}{C_i - C_n} \qquad (4.8)$$

f (t) = fraction of the injectant present in the recovered water at any time t, C_{rw} (t) = integrated solute concentration in the recovered water at any recovery time, C_n = solute concentration in the native water, C_i = solute concentration in the injected water.

where C is a conservative solute, $C_i \neq C_n$, and further defining f* = f (tr*)

Chloride, fluride, EC & deuterium are commonly used to determine f. However f* the minimum f for an acceptable quality of recovered water, is reached when any solute species in the recovered water exceeds its maximum permissible value for its beneficial use. The previous studies (Pyne; 1995 and Pavelic *et al.*, 2002a) have shown that two main processes significantly influence recovery 1) Dispersion 2) the regional movement of the injected water bubble. The radial extent of an idealized cylindrically shaped injected water bubble around the ASR well can be approximated from the volume of pore space occupied by the injectant:

$$r_m = \sqrt{\frac{V_i}{\pi \; n_e \; b}} \qquad (4.9)$$

Where n_e = effective porosity of the aquifer, b = thickness of the aquifer, r_m = radius of the injected water bubble.

The relative dispersivity (α_{rd}), a factor of mixing of the injected water with the native water was described as ratio of the longitudinal dispersivity (α) to the radius of the injected water bubble r_m (Pavelic *et al.*, 2002a) as:

$$\alpha_{rd} = \frac{\alpha}{r_m} \qquad (4.10)$$

Analytical solution for dispersivity

Analytical model to predict f (t) as a function of I was used to estimate the dispersivity for each site. The one-dimensional radial solution of Gelhar and Collins, (1971: Eqn. 42) was applied to estimate α. The equation is given as:

$$f(t) = \frac{1}{2} \operatorname{erfc} \left[\frac{\left(\frac{V_r(t)}{V_i} - 1 \right)}{\sqrt{\frac{16\,\alpha}{3\,r_m} \left(2 - \left(1 - \frac{V_r(t)}{V_i} \right) \left(1 - \frac{V_r(t)}{V_i} \right) \right)}} \right] \qquad (4.11)$$

α is the only fitting parameter. The root mean square error (RMSE) would be used to quantify the difference between observed and simulated f (t).

Dispersivity parameters

Longitudinal dispersivity α estimated as a fitting parameter in equation (4.11) at I =0.5 and relative dispersivity α_{rd} as estimated from equation (4.9 & 4.10) are given in Table 4.2 for different BSV and $\bar{t}$. It showed a good matching of experimental with predicted f (t) points up to I = 0.6 (Figure 4.6).

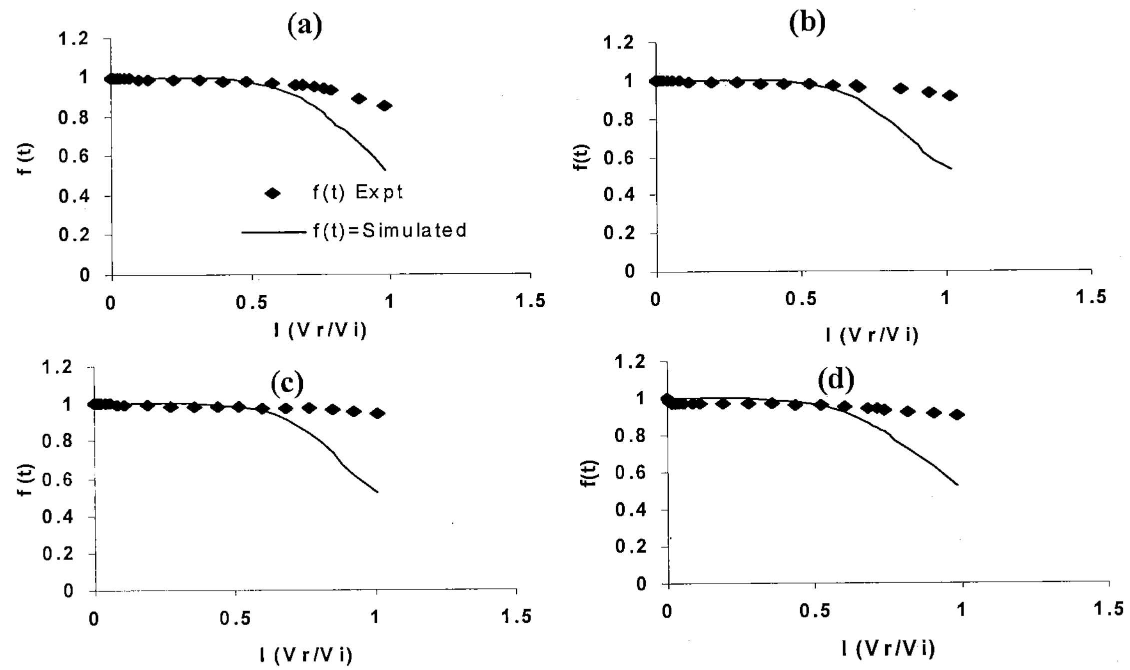

Figure 4.6: Fraction of injectant present in the recovered water f(t) versus recovery percentage I at (a) BSV-6000m^3 & $\bar{t}$ -7.2d (b) BSV-10000m^3 & $\bar{t}$ -6.5d (c) BSV-14000m^3 & $\bar{t}$ -13.5d (d) BSV-14000m^3 & $\bar{t}$ -70d

Nevertheless the RMSE values (0.11-0.12) for the whole range I up to 1 in each cycle as given in Table 4.2 was also satisfactory. Lower matching of experimental and predicted f (t) at I > 0.6, however, indicated that there was some deviation from the principle assumption of the model. The major limitations are that the regional hydraulic gradient and t_s have been neglected and aquifer homogeneity is assumed. The data given in Table 3.1 also says that the regional hydraulic gradient (0.0007 in the east direction away from the ASR well) was not negligible. Pavelic *et al.,* (2002a) observed that analytical model fits good in 6 and poor in 3 of total 9 sites in Australia and USA. The α & α_{rd} for different BSV and $\bar{t}$ values (Table 4.2) were in the same order of magnitude as reported by (Pavelic *et al.,* 2002a).

It may be seen in Figure 4.7 that the longitudinal dispersivity α decreased linearly with BSV.

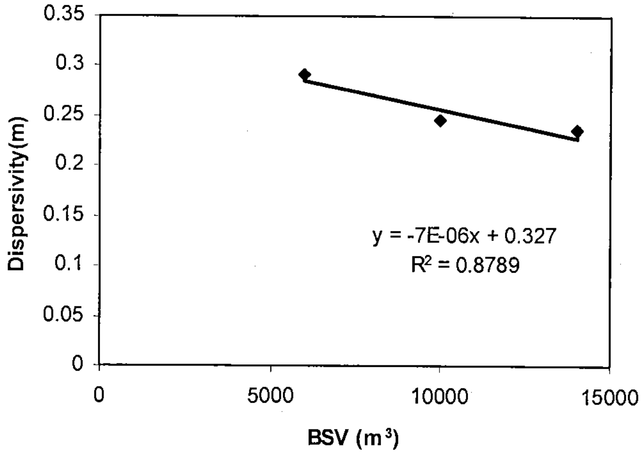

Figure 4.7: Dispersivity (α) as a function of buffer storage volume BSV

Relative dispersivity α_{rd} also decreased with BSV and increased with residence time $\bar{t}$ (Table 4.2). It showed that α and α_{rd} were the main factors to affect RE. The decrease in dispersivity parameters (α, α_{rd}) with BSV and their increase with $\bar{t}$ may explain the above increasing and decreasing RE with BSV and $\bar{t}$ (Table 4.2). Pyne (1995, 2002) and Pavelic *et al.,* (2002a) also reported that dispersivity was the main process to affect RE. The study has the practical implication for economic development of aquifer storage and recovery operations where native water are of poor quality and the conjunctive use of ground water and canal water is prevalent for irrigation purposes. Canal, river and storm water is a vast and under-valued resource with potential to provide large volume of irrigation supplies if it can be stored inter-seasonally in ASR in general and by improving the quality of ground water in particular.

4.2 GEO-PHYSICOCHEMICAL INTERACTIONS

4.2.1 Extent of mixing and physical and chemical reactions

The integrated native water percentage in cumulative recovered water volume in time t, M (t), for any of the quality parameter, was defined in line with (Ragone and Vecchioli, 1975; Pavelic *et al.*, 2002a) as:

$$M(t) = \frac{C_{rw}(t) - C_i}{C_n - C_i} \times 100 \tag{4.12}$$

C_{rw} (t) is the integrated (weighted average) concentration of a given parameters as function of time t in the cumulative recovered volume of recovered water V_r. This concentration is indicative of the quality improvement in recovered water stored in the tank before use .C_i, and C_n are concentrations of given parameters in injected and native water.

The C_{rw} (t) can be estimated as:

$$C_{rw}(t) = \left[\frac{\int_{tr1}^{tr2} C_r(t) qr(t) dt}{\int_{ti1}^{ti2} qr(t) dt} \right] = \frac{\sum C_r(t) \Delta V_r}{\sum \Delta V_r} \tag{4.13}$$

Where C_r is the instantaneous concentration of a given parameter as a function of time t in the instantaneous recovered water sample Δ Vr.

Chloride was taken as an indicator ion for quantifying the simple mixing process between native and injected water because chloride is supposed not to undergo any precipitation, dissolution, adsorption and ion exchange in the soil water system. The integrated native water percentage in the cumulative recovered water (M) explained in previous section can also be used to quantify the physical and chemical processes. Let M for chloride at 100 % recovery is $M^*(Cl^-)$ and let the M value for any other quality parameter X at 100 % recovery is $M^*(X)$. Any water quality parameter that show the $M^*(X)$ value close to $M^*(Cl^-)$ value [in this study the critical limit assumed is with in ±10 % of $M^*(Cl^-)$ value] then the parameter is considered to have gone through the process of mixing only (no physical and chemical reaction). However, $M^*(X)$ value beyond the range $M^*(Cl^-) \pm 0.1^* M^*(Cl^-)$ means that some other interactions have taken place in addition to simple mixing. Depending on whether the $M^*(X)$ is more than 1.10 $M^*(Cl^-)$ or less than 0.9 $M^*(Cl)$ and the concentration of particular parameter in native groundwater C_n (X) and injected water C_i (X), different physical and chemical processes are identified according to Table 4.3.

Total amount of salt / parameter (TA) present in the recovered volume of water (V_r) can be estimated as:

$$TA(t) = \int_{tr1}^{tr2} Cr(t)qr(t)dt = V_r \times C_{rw}(t) \tag{4.14}$$

Amount of salt / parameter due to mixing (MA) is estimated as:

$$MA(t) = C_n\left[V_r \frac{M\ (Cl^-)}{100}\right] + C_i\left[V_r - V_r \frac{M(Cl^-)}{100}\right]_i \tag{4.15}$$

Amount of salt / parameter produced/consumed (IA) due to geo-physical and chemical interaction is found from the difference of TA and MA.

Table 4.3: Possibility of different physicochemical processes between native groundwater and injected water (see text for the definition of different symbols).

Mixing percentage	Parameter concentration	Physicochemical process
$0.9[M_2^*(Cl^-)] \leq M_2^*(X) \leq 1.1[M_2^*(Cl^-)]$	-	Simple mixing, no physicochemical reaction
$M_2^*(X) > 1.10\ [M_2^*(Cl^-)]$	$C_n(X) > C_i(X)$	Production/release/dissolution
$M_2^*(X) > 1.10\ [M_2^*(Cl^-)]$	$C_n(X) < C_i(X)$	Consumption/precipitation /dissipation
$M_2^*(X) < 0.9\ [M_2^*(Cl^-)]$	$C_n(X) > C_i(X)$	Consumption/precipitation /settling
$M_2^*(X) < 0.9\ [M_2^*(Cl^-)]$	$C_n(X) < C_i(X)$	Production/release/dissipation

4.2.2 Mixing behaviour:

Chloride was taken as an indicator ion for quantifying the mixing process between native and injected water. Integrated native water percentage of chloride $M\ (Cl^-)$ at any recovery percentage I quantifies the simple mixing process as the fraction of native water mixed in the recovered water, as Cl^- does not participate in geo-physicochemical interactions. Simple mixing as represented by chloride integrated native water percentage in the recovered water at 100 % recovery $M^*(Cl^-)$ decreased linearly with BSV (Figure 4.8) as:

$$M^*(Cl^-) = -0.0015\ BSV + 23.984 \qquad r^2 = 0.97 \qquad (4.16)$$

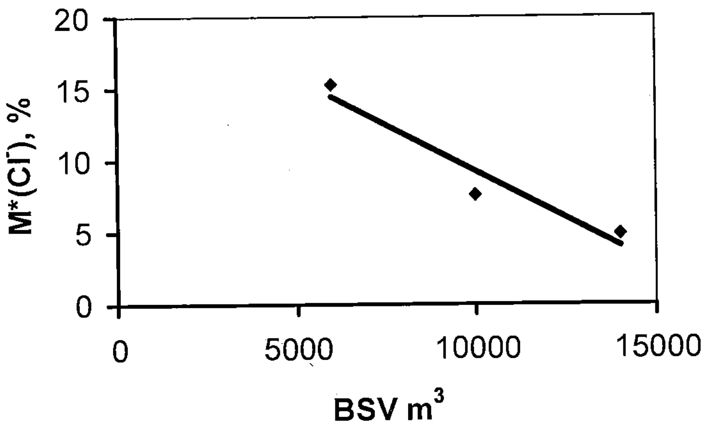

Figure 4.8: Mixing percentage M*(Cl$^-$) as a function of buffer storage volume

It was because buffer zone restricts the direct mixing of injected water with the native water and this leads to successive decrease in the proportion of native water in the recovered water with increasing BSV. It increased from 4.93 to 8.75 with residence time $\bar{t}$ of 70.8 days at BSV of 14000 m^3 because more operation time available for dispersion and regional movement of injected water bubble. The M*(Cl$^-$) of 15.30 % at BSV of 6000 m^3 means that 15.30 % of native water is mixed with 84.7 % of injected water to reach at 100 % recovery.

The integrated native water percentage in the recovered water at 100 % recovery (M*) for different parameter (Table 4.4) as compared to that of chloride showed that Calcium, Bicarbonate, Borate, Potassium and Temperature of the recharge water have been affected most by geo-chemical reactions between the native groundwater and injected water.

Other parameters in the recovery water were mainly affected by simple mixing between native groundwater and injected water.

The integrated native water percentage in the recovered water M was plotted as a function of recovery percentage I for all quality parameters for all ASR cycles of different BSV and $\bar{t}$ in figure 4.9.

Table 4.4: Concentration (mmolL^{-1}) of native (C_n) and injected (C_i) water and integrated concentration of recovered water C_{rw}* at 100 % recovery of different quality parameters

Parameter	C_n	C_i	C_{rw}*			
			BSV (m^3) & t (d)			
			6000 & 7.2	10000 & 6.0	14000 & 13.5	14000 & 70.83
EC (dSm^{-1})	28.40	0.27	4.46(14.87)	2.54(8.07)	1.72(5.46)	2.88(9.26)
Cl^- (mmolL^{-1})	261.00	1.20	40.95(15.30)	20.92(7.59)	14.01(4.93)	23.94(8.75)
SO_4^{2-} (mmolL^{-1})	3.60	0.16	0.73(16.7)	0.48(8.70)	0.39(6.33)	0.48(9.36)
HCO_3^- (mmolL^{-1})	24.00	0.80	6.80(25.88)	4.65(15.13)	3.55(11.85)	5.23(19.10)
CO_3^{-2} (mmolL^{-1})	0.00	0.00	0.00	0.00	0.00	0.00
BO_3^- (mmolL^{-1})	0.30	0.005	0.07(22.15)	0.07(20.76)	0.02(6.15)	0.05(13.91)
Na^+ (mmolL^{-1})	159.10	0.49	23.09(14.25)	13.06(7.93)	9.03(5.39)	16.94(10.36)
K^+(mmolL^{-1})	2.11	0.06	0.61(26.87)	0.49(20.96)	0.21(7.15)	0.45(19.13)
Ca^{+2} (mmolL^{-1})	19.50	0.60	5.19 (24.28)	2.89 (12.15)	2.11 (7.97)	3.15 (13.48)
Mg^{+2} (mmolL^{-1})	43.00	0.40	6.73 (14.86)	3.17 (6.50)	2.26 (4.36)	3.20 (6.58)
Em (%)$^{\#}$	9.70	8.70	-6.20	-9.60	-4.50	-10.00
pH	8.45	7.65	8.10	8.07	8.09	8.29
Temperature (°C)	30.50	27.50	29.05(50.12)	NO	NO	NO

Figures in parentheses indicates the mixing percentage M at 100 % recovery* *NO - Not observed*

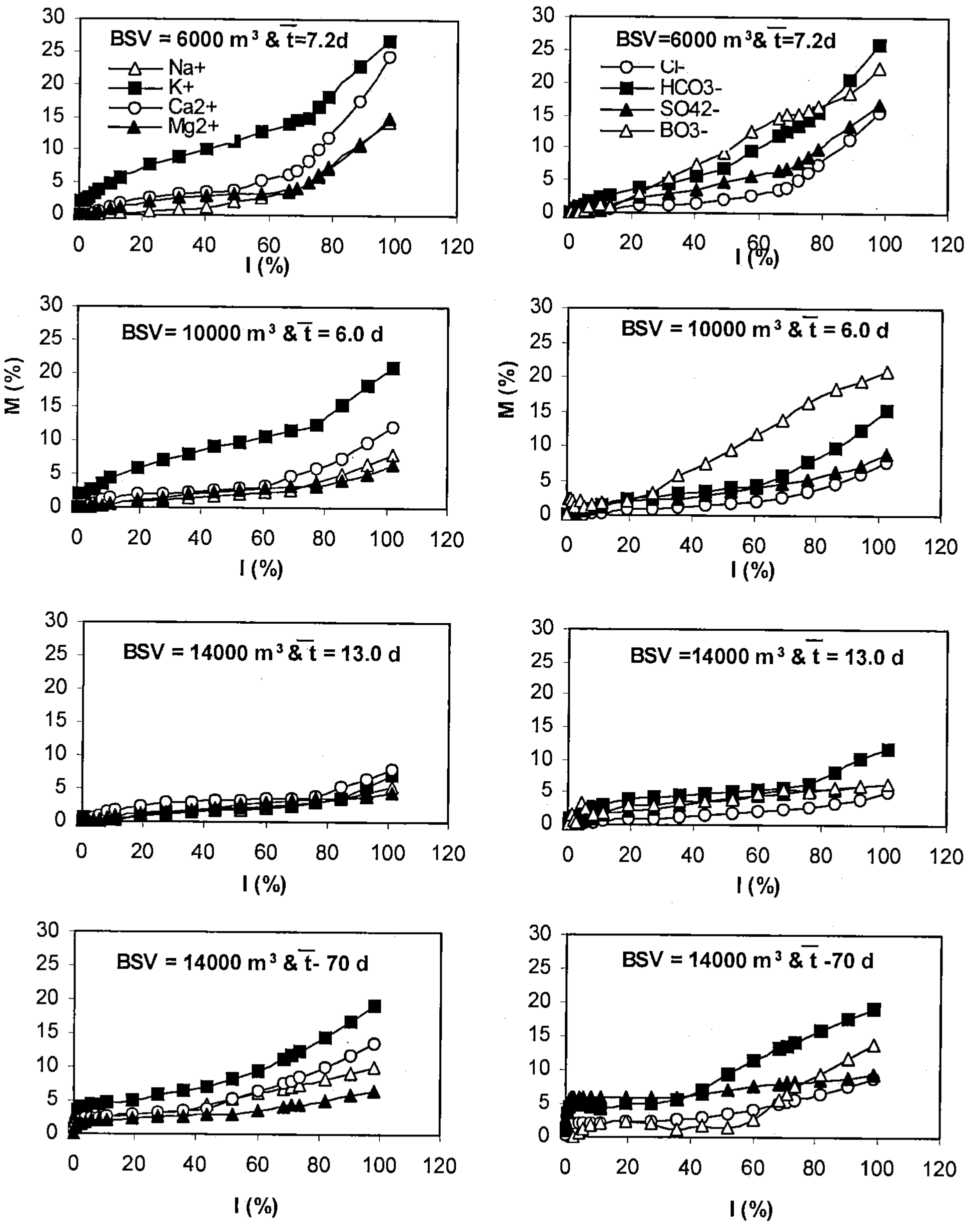

Figure 4.9: Mixing M of quality parameters versus recovery percentage I at indicated buffer storage volume BSV and residence time $\bar{t}$

It showed an increase in mixing M with recovery percentage I for all the quality parameters. It means that the water recovered was a mixture of injected water and native groundwater and the proportion of native groundwater increased with recovery percentage showing increasing mixing M as the recovered water is withdrawn radially away from the ASR well. Mixing curves of M versus I showed that M increased linearly with I from 0-60 % for all parameters; M increased more sharply at I > 60 %. It was because the role of dispersion and regional movement of the injected water bubble may have increased more sharply with increasing I > 60 %. The dependence of M on these factors was also emphasized by Pavelic *et al.*, (2002a).

4.2.3 Physical and chemical interactions

The natural groundwater chemistry is dominated by sodium and chloride (Figure 13).

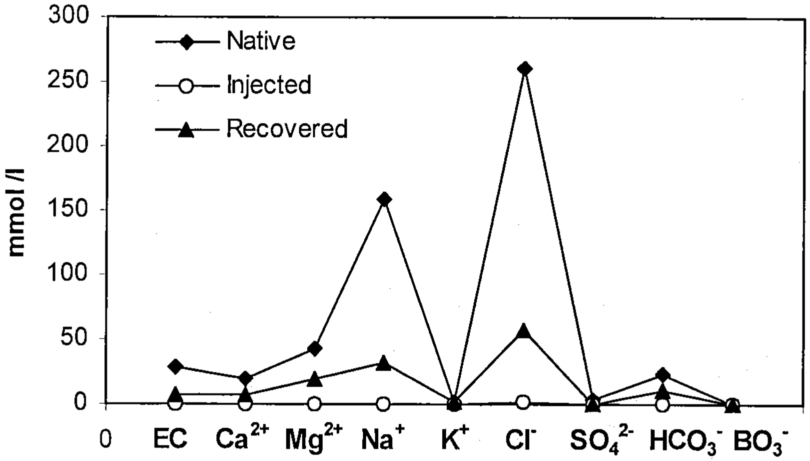

Figure 4.10: Comparison of average major ion chemistry in native, injected and recovery water (BSV - 6000 m^3) in ASR cycle

Native groundwater salinity is approximately 18176 mg L^{-1} (EC - 28.4 dS/m) and is therefore, unsuitable for irrigation use. Equilibrium with the limestone aquifer leads to significant concentrations of calcium and bicarbonate.

Calcite dissolution

The integrated native water percentage value in the recovered water M* at recovery percentage I of 100 for Ca^{2+} and HCO_3^- (Table 4.4) were much higher than that of simple mixing M* (Cl^-) value at all BSV and residence time $\bar{t}$. This means that if only simple mixing had occurred, the concentration of Ca^{2+} and HCO_3^- in recovered water would have been within ± 10 % of M* (Cl^-). Therefore, it was a case where M* (Ca^{2+} and HCO_3^-) > 1.10 M* (Cl^-) and C_n (Ca^{2+} and HCO_3^-) > C_i (Ca^{2+} and HCO_3^-) allowing calcium bearing mineral calcite $CaCO_3$ to dissolve from the aquifer (Table 4.3). The low pH value of injected water (pH = 7.65) as compared to that of native groundwater water (pH = 8.45) may have caused dissolution of calcite ($CaCO_3$) present in the aquifer material (Table 3.3) to form Ca^{2+} and HCO_3^- following equation (4.17) as:

$$CaCO_3 + H_2CO_3 \rightarrow Ca(HCO_3)_2 \rightarrow Ca^{2+} + 2\,HCO_3^- \qquad (4.17)$$

It means that one mole of calcite mineral-weighing equals to 100 gm would produce one mole of Ca^{2+} and two moles HCO_3^-. Similar results of calcite dissolution from the aquifer by injecting low pH water were reported by Malik *et al.,* (2002b). On comparing HCO_3^- production (12166 mol_a) with Ca^{2+} production (5838 mol_c) from 2000 m^3 of recovered water at BSV of 6000 m^3 from Table 4.5, it was found that HCO_3^- were overproduced by 3.1 % of Ca^{2+} production. Such overproduction of HCO_3^- as compared to Ca^{2+} was 22.0, 26.9 and 12.5 % at BSV of 10000, 14000 m^3 and 14000 m^3 BSV with 70.8 days residence time. This overproduction < 30 % may be considered within acceptable limit under uncontrolled field conditions where contribution of some bicarbonate producing reactions such as dissolution from $MgCO_3$ present as impurities in the calcite mineral might have been got ignored as M*(Mg^{2+}) was within ±10 % of M*(Cl^-) (Table 4.4). Slight overproduction of HCO_3^- as compared to Ca^{2+} was also reported by Vanderzalm *et al.,* (2002) and was attributed to high CO_2 production linked to organic matter oxidation.

calcite in equivalent amounts of Ca^{2+} and HCO_3^- was verified quantitatively in all ASR cycle of different BSV and $\bar{t}$.

It may be further seen from Table 4.5 that calcite dissolution and interaction amount IA of Ca^{2+} and HCO_3^- at 100 % recovery decreased with BSV because of the decreasing integrated native water percentage in the recovered water M* (Ca^{2+} and HCO_3^-) with increasing BSV (Table 4.4). Nevertheless their production proportion to their integrated M* did not follow the decreasing pattern with BSV. For example: Production proportion for HCO_3^- i.e. $[M^*(HCO_3^-) - M^*(Ca^{2+})] / [M^*(HCO_3^-)]$ of 40.8, 49.8 and 58.3 % at BSV of 6000, 10000 and 14000 m^3 did not follow the decreasing pattern with increasing BSV.

It may be further seen from Table 4.5 that calcite dissolution increased with residence time by 55 %. It may be because of more operation time available for reactions.

Potassium release

The integrated native water percentage in the recovered water M* at 100 % water recovery for K^+ was also much higher than that of $M^*(Cl^-)$ and concentration of potassium in native water was much higher than injected water (Table 4.4). It shows that potassium was released (Table 4.3) from the aquifer clay minerals possibly due to freshening of brackish groundwater. It is likely that potassium was released from the potassium bearing clay minerals from its adsorbed/non-exchangeable state to the solution form due to increased hydraulic pressure during injection process. The dominant clay mineral of the region is illite (Goyal *et al.*, 1990).

For potassium it may be seen from Table 4.5 that 473 mol_c (9 kg) of potassium at a BSV of 6000 m^3 has been released in 2000 m^3 of recovered water. Potassium release decreased with increasing BSV, as was a case for calcite dissolution. Potassium release increased from 98 to 421 mol_c with increased residence time $\bar{t}$ of 70.8 days. Malik *et al.*, (2002b) also reported K release in ASR of such an area of semi-arid region.

Table 4.5: Effect of buffer storage volume BSV and residence time $\bar{t}$ on total amount TA, mixing amount MA and interaction amount IA of different constituent present in 2000 m^3 of recovered water in ASR cycles

BSV = 6000 m^3 & $\bar{t}$ = 7.2 d			
Parameter (mol)	**TA**	**MA**	**IA**
Calcium (mol$_c$)	9360	6983	2377
Bicarbonate (mol$_a$)	13600	8699	4901
Potassium (mol$_c$)	1220	747	473
Borate (mol$_a$)	140	100	40
Heat (KJ)	239146	230138	9008
BSV = 10000 m^3 & $\bar{t}$ = 6.0 d			
Calcium (mol$_c$)	5780	4069	1711
Bicarbonate (mol$_a$)	9300	5122	4178
Potassium (mol$_c$)	980	431	549
Borate (mol$_a$)	140	55	85
BSV = 14000 m^3 & $\bar{t}$ = 13.5 d			
Calcium (mol$_c$)	4330	3064	1266
Bicarbonate (mol$_a$)	7100	3888	3212
Potassium (mol$_c$)	420	322	98
Borate (mol$_a$)	46	39	7
BSV = 14000 m^3 & $\bar{t}$ = 70.8 d			
Calcium (mol$_c$)	6640	4508	2132
Bicarbonate (mol$_a$)	10460	5660	4800
Potassium (mol$_c$)	900	479	421
Borate (mol$_a$)	100	62	38

Borate release

The integrated native water percentage in the recovered water M* at recovery percentage I of 100 for BO_3^- was also much higher than that for chloride and concentration of BO_3^- in native water was much high than in injected water. This means that if only simple mixing had occurred the concentration of BO_3^- in the recovered water would have been within ± 10 % of M* (Cl-). Therefore, it was a case where M* (BO_3^-) > 1.10 M* (Cl^-) and Cn (BO_3^-) > Ci (BO_3^-) allowing borate bearing mineral (Tourmaline) to dissolve from the aquifer (Table 4.3). The low injected water pH (7.65) as compared to that of native groundwater pH (8.45) may have caused the dissolution of tourmaline, generally present in the aquifer material in semi arid region to form borate (BO_3^-) following Equation (4.18).

$$H_3BO_3 \leftrightarrow H_2BO_3^- + H^+ \qquad (4.18)$$

Nevertheless, sodium was not found produce (Table 4.5) because sodium might have been consumed in exchanging K during its release from the illite clay mineral.

The interaction amount for borate at 100 % recovery decreased with BSV except at BSV of 10000 m^3 where it showed a slight increase as compared to BSV of 6000 m^3 (Table 4.5).

Heat transport

Temperature of the native, injected and recovered water was monitored in 1st ASR cycle of BSV 6000 m^3 (Table 4.4). The integrated native water percentage in the recovered water at 100 % water recovery M* for temperature was also much higher than that of M* (Cl^-). The temperature of the native water (30.5 °C) was more than that of injected water (27.5°C) (Table 4.4). It means that some additional heat was produced during mixing of injected with native water. It may be seen from Table 4.5 that 239146 KJ of heat was present in 2000 m^3 of recovered water at 100 % recovery. Out of which 230138 KJ was due to simple mixing and 9008 KJ was produced from dissolution and precipitation reactions Viz.

1) Inter aquifer heat conduction with the layers below and above will take a relatively large effect especially if the aquifer is thin,
2) heat of calcite dissolution and
3) heat exchange between water and grains in the aquifer during injection and recovery cycles.

4.2.4 Quantification of quality parameters for irrigation

1) **Electrical Conductivity**

Groundwater quality of the recovered water in terms of electrical conductivity EC was better than that of native water (Figure 4.10). Integrated mixing M increased with recovery percentage I (Figure 4.11) as the proportion of native groundwater in recovered water increased with recovery percentage I.

It implied that the first water has a much better quality than the water at the end of the season. This would be beneficial for the crops as the crops are more sensitive at the earlier stages of growth.

Integrated recovery efficiency CRE is defined as the recovery percentage I at target time to meet the target integrated EC_{rw} of the recovered water (2 dS/m). Recovery efficiency RE increased linearly from 77 to 108 % with increase in BSV from 6000 m^3 to 14000 m^3 as:

$$RE = 3.3275\ BSV + 60.205 \qquad r^2 = 0.98 \qquad (4.18)$$

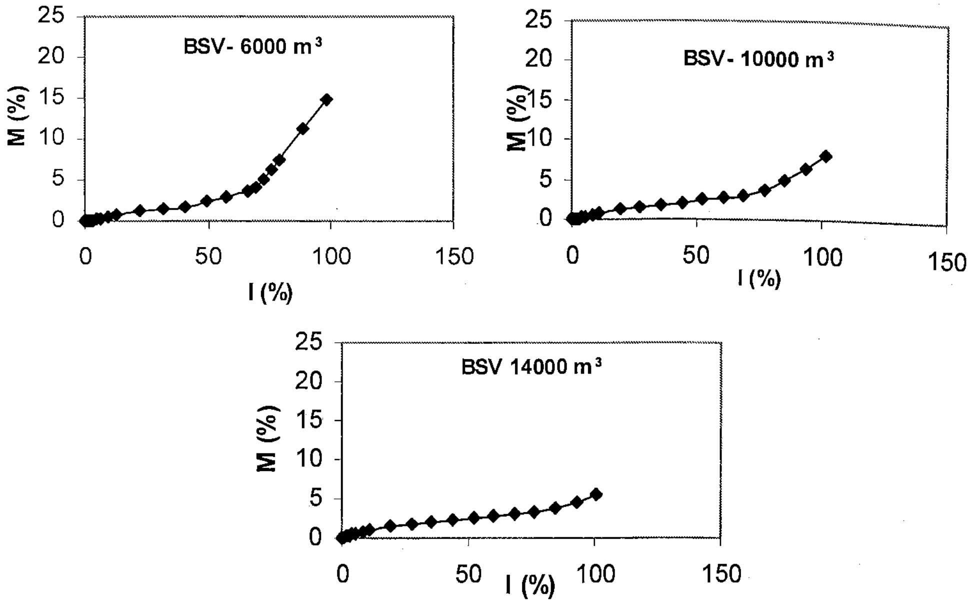

Figure 4.11: Integrated mixing M of electrical conductivity EC_{rw} versus recovery percentage I at indicated buffer storage volume

Increased RE with BSV was due to decreased mixing with increasing BSV. Recovery efficiency decreased from 108 to 74.2 % with increasing residence time $\bar{t}$ from 13 to 70 days in 4th ASR cycle. It may be because of more operation time available for quality parameter to disperse. Pavelic *et al.,* (2002a) and Pyne, (1998) had also reported the decrease in RE with increasing residence time in brackish aquifer depending upon aquifer characteristic and BSV. Seventy days of residence time is sufficient time to provide some supplementing irrigation to the crops from water stored economically and safely in aquifer.

2) **Energy / heat**

Temperature of the recovered water increased with recovery percentage because the proportion of native groundwater in the recovered water increased with I. Therefore, it will have cold recovery early in the growing season and get warmer, as the recovery continues as mixing increases. This would be more beneficial for the crops as the crops are more sensitive to frost at the early stage of growth. Increased water temperature of the recovered water is a desirable feature during winter season and may be helpful in preventing frost damage to crops. In terms of energy gain, raising the temperature of recovered water by 1.55 ^{0}C as compared to injected water (Table 4.4) was 6.5 KJ/L.

3) **Nutritional value**

Potassium of recovered water increased with recovery percentage because the proportion of native groundwater in the recovered water increased with I (Figure 4.9). It implied that first recovered water has lower potassium than water at the end of the season. This would be beneficial to crops as the nutritional requirement increases with stage of growth. The integrated concentration C_{rw} as estimated from Equation 4.13 at target water quality was 0.40, 0.43 and 0.21 mmol L^{-1} at BSV of 6000, 10000, 14000 m^3 and it increased from 0.21 to 0.31 mmol L^{-1} with residence time t of 70.8 days. This would add 9, 10, and 5 kg potassium/irrigation of 0.06 m at BSV of 6000 10000, 14000 m^3 and it increased from 5 to 7 kg with residence time $\bar{t}$ of 70.8 days. This would save 1.8, 2.0, 1.0 $ / irrigation of 0.06 m at BSV of 6000, 10000, 14000 m^3.

The study would, therefore, serve the interest of researchers, industrialist, managers, farmers and other water utilities services of semi-arid regions where presence of calcite, highly saline groundwater and its high potassium content; and wide temperature variation is a general feature.

4.3 MODELLING OF GROUNDWATER RECHARGE

4.3.1 Calibration

High regression coefficient R^2 (0.96), low value of objective function SSQ (1.12) and low mean RMSE 0.81 for piezometeric pressure head (Table 4.6) and 1.59 for observation well pressure head (Table 4.7) calibrated the model for 1st ASR cycle.

Table 4.6: Calibration and validation statistical tests of draw up and draw down in pressure heads in piezometer during recharge and recovery

Cycle No.	BSV (m^3)	$\bar{t}$ (d)	n		*RMSE*		ME (%)
			Recharge	Recovery	Recharge	Recovery	
Calibration							
1	6000	7.20	142	226	0.32	1.29	99.82
Validation							
2	10000	6.05	79	127	0.45	1.21	99.84
3	14000	13.55	161	209	0.67	0.89	99.91
4	14000	70.83	77	128	0.26	0.90	99.90
5	14000	118.35	70	120	0.32	1.00	99.88
6	14000	113.20	72	120	0.29	1.29	99.80
Mean					0.39	1.10	99.86

Table 4.7: Calibration and validation statistical tests of draw up and draw down in pressure heads in observation well

Cycle No.	BSV (m^3)	$\bar{t}$ (d)	n		*RMSE*		ME (%)
			Recharge	Recovery	Recharge	Recovery	
Calibration							
1	6000	7.20	30	51	1.25	1.93	91.52
Validation							
2	10000	6.05	45	64	1.16	1.56	94.58
3	14000	13.55	75	105	0.83	0.91	97.81
Mean					1.08	1.47	94.57

Drawup increased with time and decreased with radial distance during recharge. Similarly drawdown also decreased with time and with radial distance during recovery (Figure 4.12).

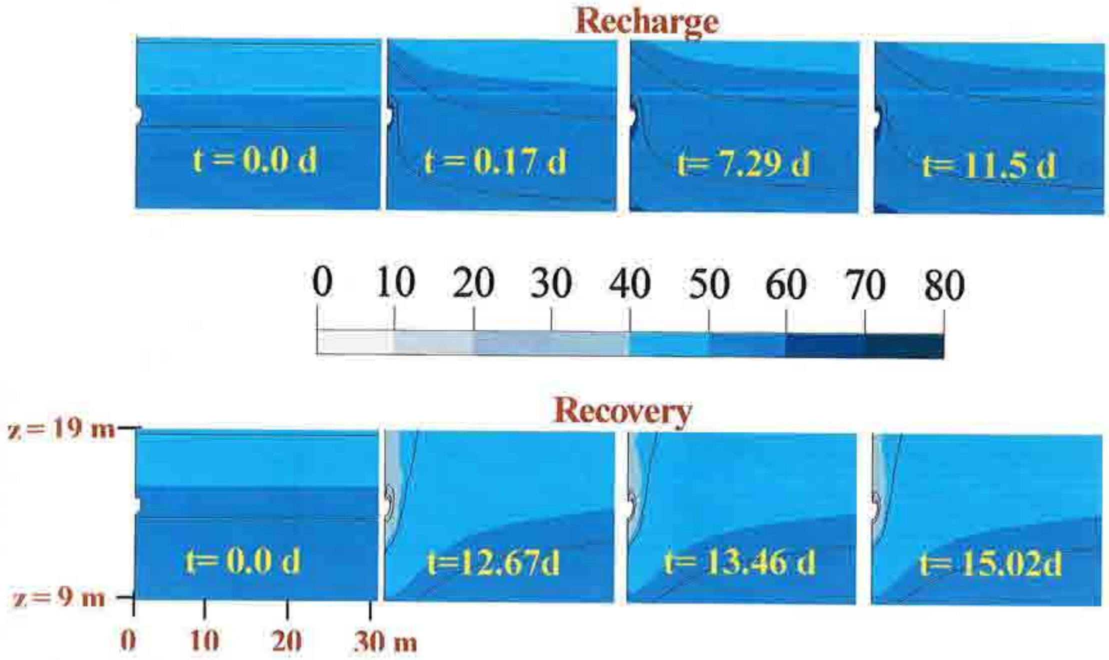

Figure 4.12: Development of pressure isolines at increasing time of recharge and recovery in first ASR cycle as a function of time

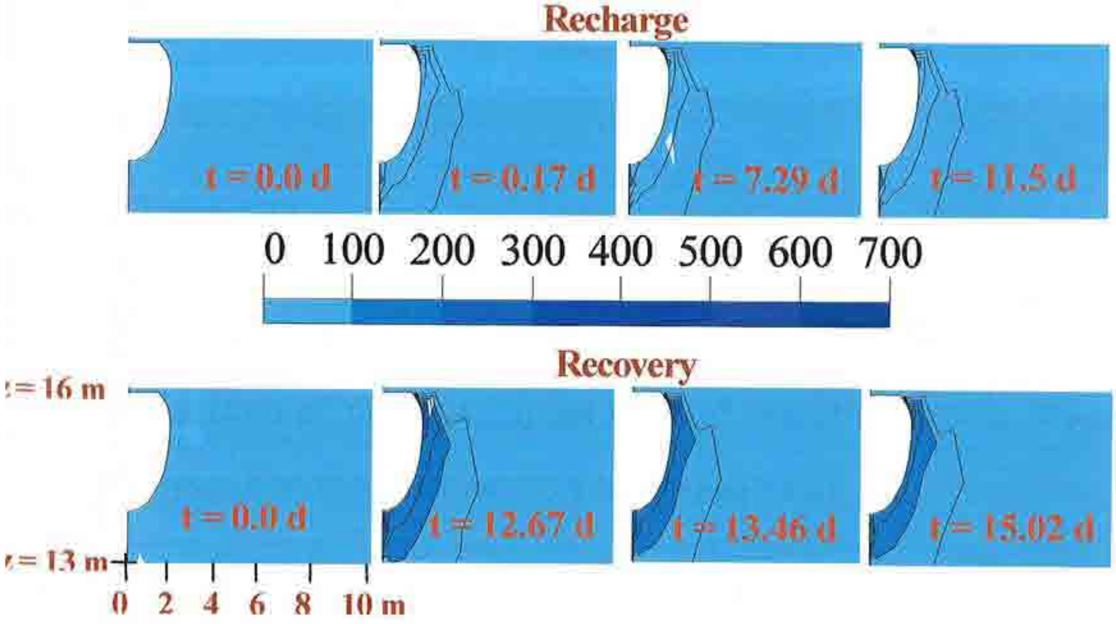

Figure 4.13: Development of velocity isolines at increasing time of recharge and recovery in 1st ASR cycle as a function of time

Velocity isolines at different times decrease with increasing radial distances (r) and increased with time during recharge and recovery (Figure 4.13).

Velocity vectors intensity and directions were away from the cavity during recharge (Figure 4.14a) and towards the cavity during recovery (Figure 4.14b).

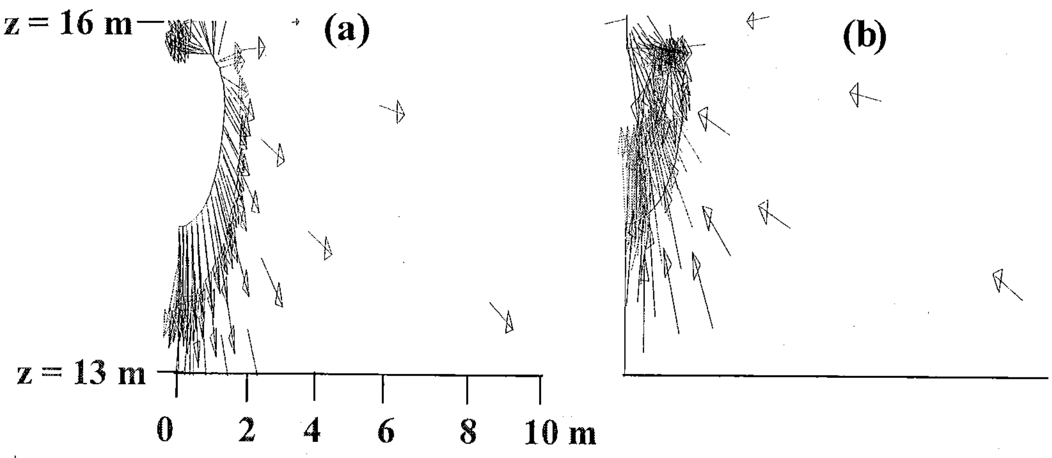

Figure 4.14: Velocity vectors showing intensity and direction during (a) recharge and (b) recovery

4.3.2 Validation

There was good matching between experimental and simulated drawup & drawdown in piezometric pressure heads in 1st, 2nd and 3rd ASR cycles of increasing BSV of 6000, 10000 and 14000 m^3 (Figure 4.15a) and in 4th, 5th and 6th ASR cycles of increasing residence time $\bar{t}$ of 70.8, 118.4 and 113.2 days (Figure 4.15b).

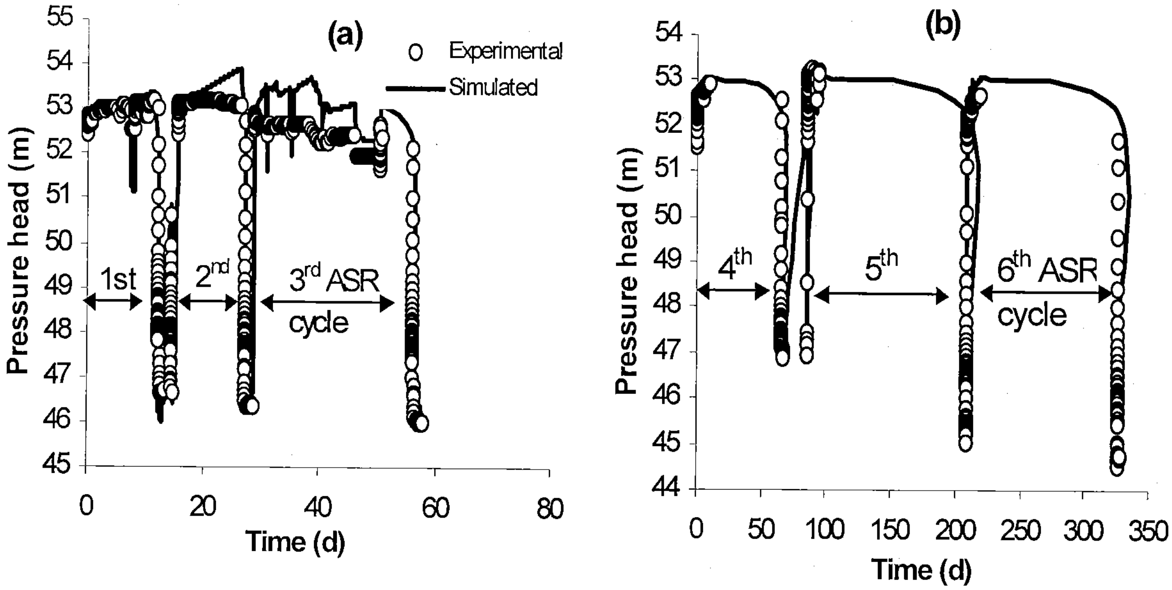

Figure 4.15: Simulated versus experimental drawup and drawdown of piezometric head at (a) 1st, 2nd and 3rd ASR cycles of BSV = 6000, 10000 & 14000 m^3 and (b) 4th, 5th and 6th ASR cycles of $\bar{t}$ = 70.8, 118.6 & 113.2 d

The under prediction of piezometric pressure heads (Figure 4.16 a&b) observed during the initial 0.01042 d (15 min and 15 – 30 min) near the cavity centre during recovery might have been due to the facts: (1) that HYDRUS-2D model does not take into account the storage coefficient in the aquifer and / or (2) the entry points resistances of piezometers might have delayed their response to drawdown pressure heads under actual field conditions. However, simulated drawup pressure heads had a good matching at all the times (Figure 4.16 c&d)

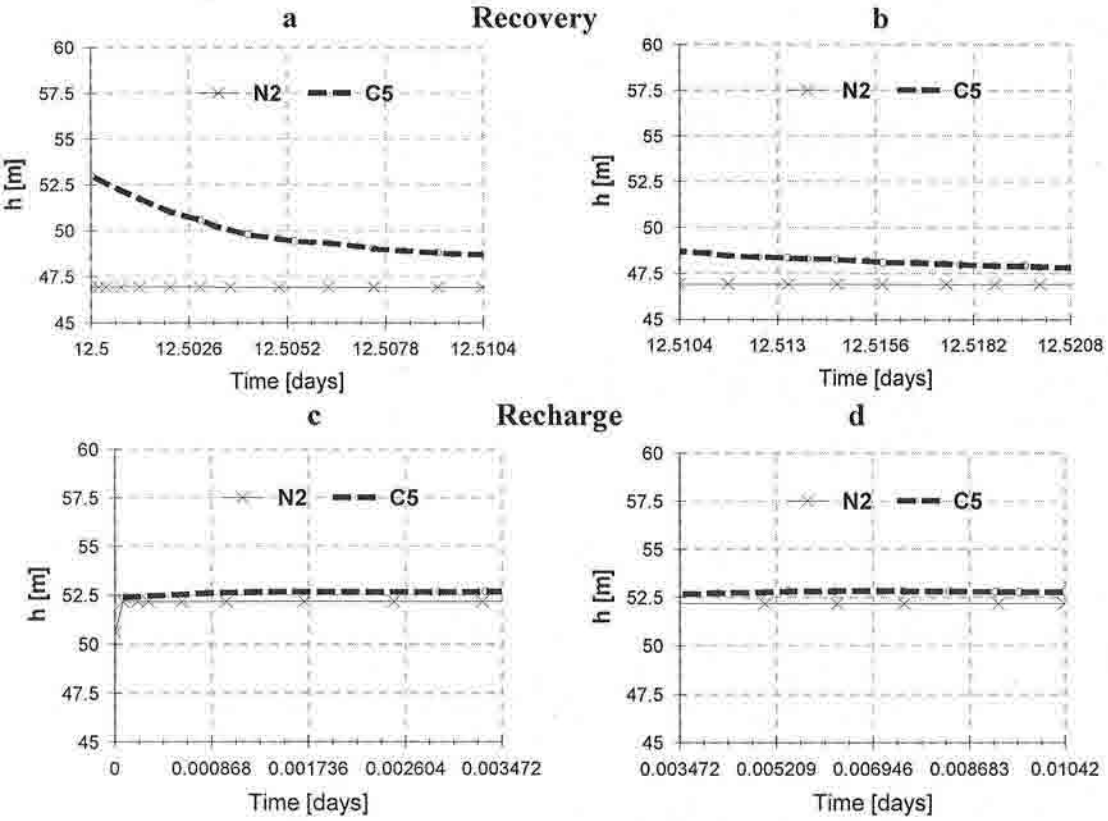

Figure 4.16: Simulated (N2) versus experimental (C5) piezometric pressure heads of (a) Initial 0.0104 d (15 min) during drawdown, (b) 0.0104 – 0.02.8 d (15 - 30 min) during drawdown, (c) Initial 0.0104 d (5 min) during drawup and (d) 0.0104 – 0.02.8 d (5 - 15 min) during drawup in first ASR cycle.

The matching of experimental and simulated observation well pressure heads data points was not as satisfactory as that in piezometer during first 2 cycles of BSV- 6000 and 10000 m^3 (Figure 4.17). The under prediction of observation well pressure head observed in 1st and 2nd ASR cycle was due to effect of seepage from canal and water courses flowing nearby experimental area. During the 3rd ASR cycle of BSV 14000 m^3 the matching of experimental and simulated data points was satisfactory as the experiment was conducted during the canal dry period.

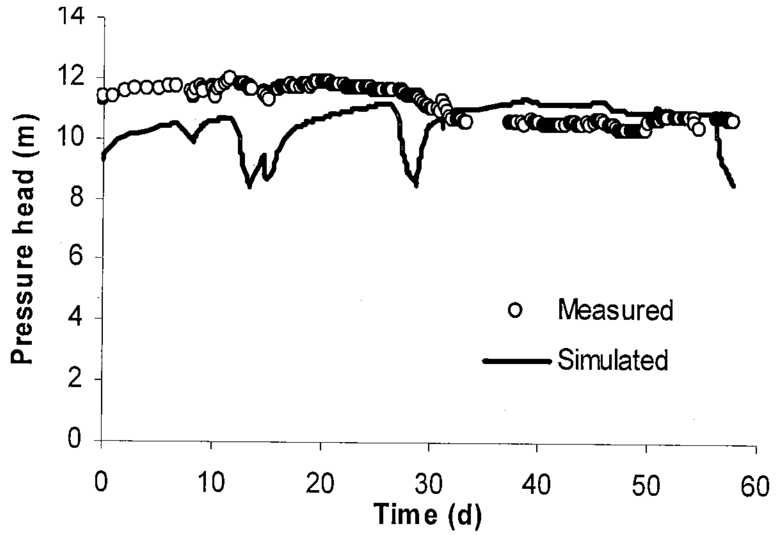

Figure 4.17: Simulated versus experimental rise and fall in pressure head (m) in observation well at (a) BSV = 6000, 10000 & 14000 m^3

High mean modelling efficiency ME (99.86% in piezometer & 94.57 % in observation well) and low RMSE (0.26 to 0.67 of piezometer & 0.83 to 1.25 m of observation well in drawup and 0.89 to1.29 of piezometer & 0.91 to1.93 m of observation well in drawdown) of predicted and experimental pressure head value for 2 to 6th ASR cycle validate Hydrus 2D model for groundwater recharge in ASR well. The RMSE and ME did not vary with ASR cycle, BSV and $\bar{t}$, further confirmed the validity of the model over long period of time. The higher RMSE values for observation well (Table 4.7) as compared to that of piezometer might have been due to seepage of water through canal and watercourses near the experimental area, which accounts for higher observed water pressure in observation well. Therefore, Hydrus 2D may safely be used for projecting and optimizing the operational factors as BSV and residence time $\bar{t}$ of the recharge water for the success of ASR technology. The model is quite fast and user friendly. So far, the model has been used for predicting water, salt and heat balance studies, moisture, salt, heat and pressure distributions in soil profiles mostly in unconsolidated zone (Bristow *et al.*, 2002; Schmalz *et al.*, 2003; Manglik *et al.*, 2004). So far it's only few application to simulate groundwater recharge have been reported (Malik *et al.*, 2004). Most commonly used model for 2D and 3D groundwater simulation are Modflow and Feflow.

4.3.3 Radial Influencing zone

Radial influencing zone r_{iz} is taken as that radial distance z up to which there is 5% of maximum drawup and drawdown during recharge and recovery of each cycle. It means that r_{iz} would vary with recharge, recovery, BSV and $\bar{t}$ of ASR cycle. It increased with BSV with a mean value of 122 during recharge. It may be due to buffer zone that restricts the direct mixing of the injected water with the native water. It is more for recharge than for recovery (Table 4.8) because of the more time available (Table 3.2) for spatial movement of the recharged water during recharge. Mean radial influencing zone of 122 m (Table 4.8) at experimental ASR site suggested that next tubewell should be installed atleast 122 m away from the existing ASR well. Differing r_{iz} values have been reported by Pyne (1995) in Florida, USA and Malik *et al.,* (2004) in Badyan, India.

Table 4.8: Radial influence zone r_{iz} (m) at different BSV and $\bar{t}$ for recharge and discharge in ASR well

Cycle number	BSV (m^3)	$\bar{t}$ (d)	r_{iz} (m) Recharge	r_{iz} (m) Recovery
1	6000	7.20	111	57
2	10000	6.05	127	46
3	14000	13.55	129	25
4	14000	70.83	16	16
5	14000	118.35	15	15
6	14000	113.20	24	24

4.3.4 Numerical versus anlytical solutions

It may be seen from figure 4.18 that the Forchheimer model under predicted the piezometric drawup and drawdown at all radial distances. The difference of the mean was also significant (Table 4.9). The radial influencing zone were also not identical i.e. 111 and 87 m from the Hydrus 2D model and Forchheimer model.

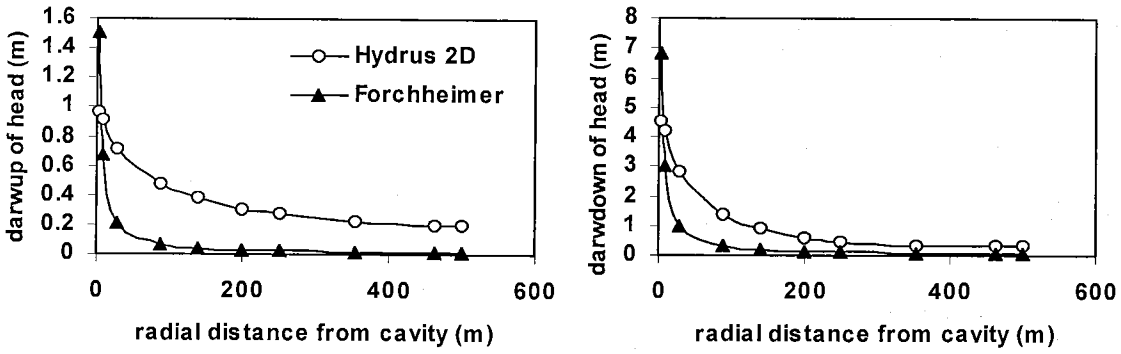

Figure 4.18: Drawdown and drawup in pressure head as a function of radial distance from cavity (m) as given numerically by Hydrus 2D model and analytically by Forchheimer

Table 4.9: Paired t- test for drawup and drawdown as given by Hydrus 2D and Forchheimer model (n=10)

	Drawup	**Drawdown**
	(m/d)	
Standard Deviation	0.42	2.05
Difference of mean (d)	0.21	0.40
t_{cal}	2.33*	1.18

* Significant at 5 % level

4.3.5 Model projection

The model is used to project the effects of geo-hydrological parameters: aquifer anisotropy, length of sand patch on confining silty clay layer at r = 100 m and aquifer saturated hydraulic conductivity (K_s), in an ASR well. The optimum radial influence zone r_{iz} should not exceed 100 m so as to avoid interference of influencing zone with that of adjoining farmer's tubewell, as the average land holding in India is 2.2 acre.

(i) Aquifer anisotropy

Anisotropy had the largest impact on the r_{iz} (Figure 4.19 a, b & c). The r_{iz} decreased sharply with increase in anisotropy from 1 to 10 and decreased slowly with 10 to 15 (Figure 4.19a). The targeted r_{iz} was reached at anisotropy of 1.

(ii) Aquifer saturated length of sand patches in confining silty loam layer

The r_{iz} decreased sharply with the increase in length of sand patch from 0 to 20 m and decreased slowly with increase in length of sand patch from 20 - 40 m in the confining layer (Figure 4.19b). The targeted r_{iz} was reached up to 10 m of sand patch in confining layer.

(iii) Aquifer saturated hydraulic conductivity

The r_{iz} decreased with increase in hydraulic conductivity of aquifer from 8.2 – 10.2 m/d and increased slowly from 10.2 – 11.2 m/d (Figure 4.19c). The r_{iz} remained more than the targeted zone of 100 m at K_s of 9.2 m/d. So it is always risky to install ASR well where the aquifer saturated hydraulic conductivities are more than 9.2 m/d under the given other geo-hydrological parameters

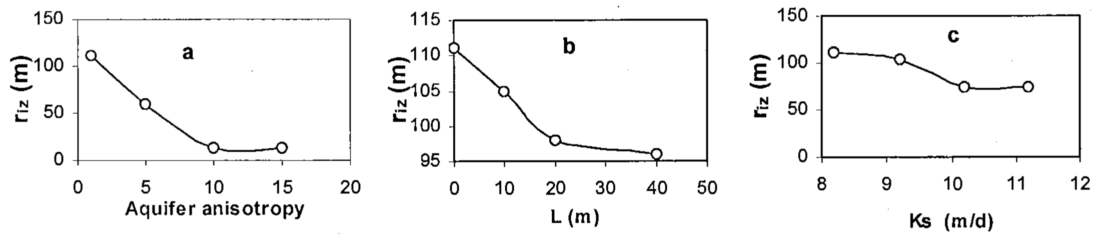

Figure 4.19: Model projection of influencing zone as a function of (a) Aquifer Anisotropy (b) Length of sand patches in confining layer, L (c) Aquifer hydraulic conductivity, K_s

Chapter V

SUMMARY

The aquifer storage recovery ASR site of highly brackish native water was selected at Soil Research Farm, Hisar, Haryana, India (28°59' to 29°49' N latitude and 75°11' to 76°18' longitude at an elevation of 215 m above mean sea level) where an irrigation cavity type well was installed with the injection facility through a submersible pump by removing the check valve permanently while installing the pump under Indo-German collaborative project on "Artificial recharge of ground water through integrated sand filter – injection well technique" between Chaudhary Charan Singh Haryana Agricultural University, Hisar-125004, India and University of Hohenheim, Institute for Soil Science and Land Evaluation (Biogeophysics Section), 70593 Stuttgart, Germany. Soil samples from different layers taken during the installation of piezometers, were oven dried and ground gently with the pestle-mortar. The fraction remaining above a 2 mm sieve was identified as calcite concretions. The soil passed through the sieve was analyzed for different physico-chemical properties. Soil analysis was done with the standard methods. Water samples of recovery water as a function of recovery time and that of injected and native water were analyzed for EC using potable conductivity meter, temperature, organic carbon OC, cations (Na^+, K^+, Ca^{2+}, Mg^{2+}, NH_4^+, Zn^{2+}) and anions (CO_3^{2-}, HCO_3^-, Cl^-, SO_4^{2-}, BO_3^-) by standard methods. Injection and recovery rates were measured with mechanical water meters.

Canal water was gravity injected to create buffer storage volume BSV of 6000, 10000 and 14000 m^3 in 1, 2 and 3 ASR cycle employing pump column siphon system under shallow water table depth (0.54 - 2.08 m) during July-August 2002. Residence time of

70.8, 118.35 and 113.20 days were allowed at a BSV of 14000 m^3 in 4th, 5th and 6th ASR cycles. In each cycle the volume injected to be recovered V_i was kept as 2000 m^3.

Injection rates decreased from 23.23 to 13.29 $m^3 h^{-1}$ while recovery rates remained constant in each cycle at average value of 60.21 $m^3 h^{-1}$. The instantaneous recovery efficiency IRE and integrated recovery efficiency CRE increased with BSV linearly as IRE = 54.708 + 3.8125 BSV and CRE = 46.233 + 2.465 BSV. The observed IRE and CRE at target EC* (2 dS m^{-1}) of recovered water was 80.2 % and 108 % at BSV of 14000 m^3. Recovery efficiency also increased with increasing target EC* of the recovered water linearly as IRE = 55.833 + 3 EC* and CRE = 62.33 +8.375 EC*. Recovery efficiency decreased with increasing storage time. Longitudinal dispersivity decreased with buffer storage volume.

Chloride was taken as an indicator ion for quantifying the mixing process between native and injected water. Integrated native water percentage of chloride M (Cl^-) at any recovery percentage I quantifies the simple mixing process as the fraction of native water mixed in the recovered water, as Cl^- does not participate in geo-physicochemical interactions. Simple mixing decreased linearly with BSV [M*(Cl-) = -0.0015 BSV + 23.984; r^2 = 0.97] and increased with residence time. The integrated native water percentage in the recovered water at 100 % recovery (M*) for different parameter as compared to that of chloride showed that Calcium, Bicarbonate, Borate, Potassium and Temperature of the recharge water have been affected most by geo-chemical reactions between the native groundwater and injected water. Other parameters in the recovery water were mainly affected by simple mixing between native groundwater and injected water. Calcite dissolution decreased with BSV and increased with residence time of 70.8 days. Groundwater quality of the recovered water was better than that of native water. Potassium concentration and temperature of the recovered water were more than that of injected water at all BSV. Energy of 6.5 KJ was gained in one litre of the recovered water by raising the temperature of injected water from 27.5 to 29.05 °C. Potassium and borate released from Illite and Tourmaline mineral, respectively were 473 and 40 moles in 2000 m^3 of recovered water at BSV of 6000 m^3.

A finite element flow model, HYDRUS-2D was used to simulate the drawup and drawdown in piezometric pressure heads during recharge and recovery in aquifer storage and recovery ASR cycles of varying buffer storage volume BSV and residence time $\bar{t}$ in a highly brackish semi-confined aquifer under shallow water table condition (2.54 m). The physical flow region involved a soil profile 500 m wide and 69 m deep with an exocentric elliptical cavity of 1 m horizontal radius and 1 m vertical radius at 54 m depth. No flux boundary condition was given at soil surface, bottom and lateral sides of the flow region. Saturated hydraulic conductivity was estimated through inverse modelling technique using the experimental pressure heads h time pairs during the first ASR cycle from a piezometer ($z = 54$ m, $r_{iz} = 10$ m); and observation well ($z = 12.4$ m, $r_{iz} = 10$ m).

High regression coefficient R^2 (0.96), low value of objective function SSQ (1.12) and low mean RMSE 0.81 for piezometeric pressure head and 1.59 for observation well pressure head calibrated the model for 1st ASR cycle. High mean modelling efficiency ME (99.86% in piezometer & 94.57 % in observation well) and low RMSE of predicted and experimental pressure head value for 2 to 6th ASR cycle validated Hydrus 2D model for groundwater recharge in ASR well. Radial influencing zone increased with BSV with a mean value of 122 m during recharge. The model projected the decrease in radial influencing zone with decrease in –ve radial hydraulic gradient, increase in aquifer anisotropy and increasing length of sand patch in the confining layer.

Chapter VI

CONCLUSION AND PERSPECTIVE

Conclusion of the study under taken are presented as:

- Injection rates were lower than recovery rates due to shallow groundwater level
- The injection in ASR well was possible even under shallow water table condition (dwo < 1 m)
- Integrated recovery efficiency was always greater than instantaneous recovery efficiency
- Recovery efficiency increased with buffer storage volume linearly
- Integrated recovery efficiency of 108 % was achieved at buffer storage volume of 14000 m^3 in residence time of 13.5 days
- Recovery efficiency increased with increasing target EC* of the recovered water.
- Recovery efficiency decreased with increasing storage time
- An analytical model described the f(t) versus I value successfully up to I=0.6.
- Longitudinal dispersivity decreased with increasing buffer storage volume
- The integrated native water percentage in the recovered water M increased with recovery percentage I for all the quality parameters for all ASR cycles
- Simple mixing at 100 % recovery $M^*(Cl^-)$ was 15.30, 7.59 and 4.93 for BSV of 6000, 10000, 14000 $m^3$and it increased from 4.93 to 8.75% with residence time of 70.8 days

- Dissolution of calcite in equivalent amounts of Ca^{2+} and HCO_3^- was verified quantitatively in all ASR cycle and it decreased with BSV and it increased from 126.6 to 213.2 with residence time of 70.8 days
- Release of Ca^{2+} and HCO_3^- from dissolution of Calcite and of K^+ from Illite and of borate from Tourmaline decreased with BSV and increased with residence time
- Recovery efficiency at target integrated EC_{rw} of 2 dS/m increased linearly from 77 to 108 % with increase in BSV from 6000 to 14000 m^3 and it decreased from 108 to 74.2 % with residence time $\bar{t}$ of 70 days
- Energy gain in raising the temperature of recovered water was 6.5 KJ/L.
- One irrigation of 0.06 m would add 9, 10, and 5 and 7 kg potassium at BSV of 6000, 10000, 14000 m^3 and would save 2 $ / irrigation of 0.06m at BSV of 2000 m^3
- Hydrus-2D simulated the drawup and drawdown of pressure head quite well during the whole period of time of recharge and recovery in 6 ASR cycles
- The radial influencing zone of the ASR well increased with increasing BSV from 6000 to 14000 m^3 with mean value of 122 m
- The radial influencing zone decreased with decrease in –ve radial hydraulic gradient, increase in aquifer anisotropy and increase in length of sand patch in the confining layer
- Hydrus 2D can be used for groundwater studies

Perspective / Practical implication

The study has the practical implication for economic development of aquifer storage and recovery operations where native water are of poor quality and the conjunctive use of ground water and canal water is prevalent for irrigation purposes. Canal, river and storm water is a vast and under-valued resource with potential to provide large volume of irrigation supplies if it can be stored inter-seasonally in ASR in general and by improving the quality of ground water in particular. It not only improves the productivity and total food production but also helps in maintaining the water table at desire depth especially in the brackish groundwater zones. The study would, therefore, serve the interest of researchers, industrialist, managers, farmers and other water utilities services of semi-arid regions where presence of calcite, highly saline groundwater and its high potassium content; and wide temperature variation is a general feature. Modelling of water pressure heads of ASR technology would be helpful in quantifying the temporal and spatial drawup and drawdown in water levels, assessing the environmental impacts on long-term basis for the planners and researchers and also in projecting the radial influencing zone at varying hydraulic properties of the aquifer.

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Appendix-I

The practical detail of determing different water quality parameters are given as:

Cations

Sodium Na^+

Instrument used - Flamephotometer.

Dissolve 2.543 g sodium chloride NaCl (AR grade) in distilled water and make to 1 L to prepare 1000 ppm stock solution of Na. Then prepare 60, 40, 30, 20, 10 and 5 ppm standard solution from the stock solution by dilution. A curve is drawn by plotting flame photometer readings against Na concentration. Than the reading of water samples were converted into their concentration using the standard curve. Instrument must be checked after 10/15 samples with standards for accuracy.

Potassium K^+

Instrument used - Flamephotometer.

Dissolve 1.903 gm of potassium chloride (AR grade) in distilled water per litre to prepare a stock solution of 1000 ppm K. Than prepared 25, 15, 10, 5 and 2 ppm standard solution from stock solution by dilution. Standard curve is prepared by plotting flame photometer readings against concentration of K. Then the readings of water samples were converted into their concentration using the standard curve. Instrument must be checked after 10/15 samples with standards for accuracy.

Calcium + Magnesium (Ca^{+2} +Mg^{+2})

Method used: Versenate method (EDTA)

One ml of water sample was taken in china dish and diluted. One ml of ammonium chloride-hydroxide buffer solution was added to maintain the pH of the sample at 10. Two to three drops of Eriochrome black .T. indicator was added and titrated it with N/100 ethylene diamine tetra-acetic acid EDTA (Versenate solution). The end point was blue or bluish green color.

Calcium Ca^{2+}

Method used: Versenate (EDTA) method

One ml of water sample was taken in china dish and add 5 ml of 16 % NaOH to maintain the pH of the aliquot at 12. Add 40 – 50 mg of Murexide indicator and titrate it with N/100 EDTA till the colour changes from orange red to reddish violet.

Calcium is calculated as:

$$\text{Ca (meL}^{-1}) = \frac{\text{Volume of EDTA used (ml) X N X 1000}}{\text{ml of aliquot used}}$$

Anions

Carbonate CO_3^{2-}

Method used: Acidimetric titration

Five ml water sample was taken in 100 ml conical flask. Phenolphthalein was used as an indicator appearance of pink color shows the presence of CO_3^{2-}. If present then titrate with H_2SO_4 (N/50).

Bicarbonate HCO_3^-

Method used: Acidimetric titration

Five ml water sample was taken in 100 ml conical flask. Methyl red was used as an indicator, which gave orange color to the water samples in the presence of HCO_3^-. Titrate it with N/50 standard H_2SO_4 until the orange color changes to rose red. Judgement of end point must be carefully done to achieve accuracy.

$$\text{HCO}_3^-\ \text{(meL}^{-1}) = \frac{\text{Volume of H}_2\text{SO}_4\ \text{used (ml) X N 1000}}{\text{ml of aliquot used}}$$

Preparation of N/50 H_2SO_4 – to calculate the volume V_1 of concentrated H_2SO_4 ($N_1 = 36$) to make a volume one litre (V_2) by the formula:

$$N_1V_1 = N_2V_2$$

Where, N_1 = Normality of acid, V_1 = Volume required, N_2 = Normality to be made and V_2 = Volume to be made

Chloride Cl^-

One to five ml of water sample was taken in 100 ml conical flask and dilute it accordingly. Five to six drops of potassium chromate K_2CrO_4 was added as indicator, which gives orange color to water samples in the presence of chloride. Standard silver nitrate $AgNO_3$ (N/50) was used for titration until the orange color change to brick red.

$$Cl^- \ (meL^{-1}) = \frac{\text{Volume of } AgNO_3 \text{ used (ml) X N X 1000}}{\text{ml of aliquot used}}$$

Sulfate SO_4^{2-} (Calorimetric method)

Prepare 1000 ppm of sulfate stock solution by dissolving 1.347 gm of $(NH_4)_2SO_4$ (AR grade) in distilled water and make the volume to 1000 ml. Then prepare 2, 4, 6, 8, 10, 20, 30 and 40 ppm standard solution of SO_4^{2-} from stock solution by dilution and read the absorbance on spectronic- 20 to make standard curve. To a water sample add a pinch of $BaCl_2$ and 1 ml of 0.25 % gum acacia and make the volume to 25 ml and absorbance is noted immediately on Spectronic – 20.

Boron $H_2BO_3^-$: Colorimetric (Richard, 1968)

Prepare 100 ppm borate stock solution by dissolving 0.572 gm boric acid (AR grade) in distilled water to make 1000 ml volume of 100 ppm stock solution of boron. Then prepare 0.05, 0.1, 0.2, 0.4, 0.8 and 1.0 ppm standard solution from the stock solution by dilution. The values of these standards were observed on spectronic-20 at wavelength 420 nm and were plotted on a graph to make a standard curve. One or two ml of water sample was taken in 25 ml volumetric flask. Then add 4 ml of buffer solution (250 g ammonium acetate and 15 g EDTA and 125 ml of glacial acetic acid to make 500 ml solution with distilled water) and 4 ml of azomethine – H reagent (0.45 g azomethine – H in 100 ml of 1 % L- ascorbic acid). The color is allowed to develop for 1 h and the volume is made up to mark. The absorbance is measured on Spectronic – 20 at 420 nm.

Electrical Conductivity EC

Instrument used – Digital electrical conductivity meter (ELICO) and potable digital instrument (Eijelkelkemp).

Dissolve 0.7456 g KCl (AR grade) in distill water to 1000 ml volume to make 0.02 M KCl standard solution. This will give 1.413 dS m^{-1} of electrical conductivity. Cell constant was calculated as:

$$\text{Cell Cons tan t} = \frac{\text{Theoretical value}}{\text{Observed value}}$$

Temperature correction was automatically made for 25 °C in the meter.

pH

Instrument used –Digital μ meter (ELICO) and potable digital instrument (Eijelkelkemp).
Principle: A glass surface in contact with hydrogen ions of the solution under test, acquires an electrical potential, which depends on the concentration of H^+ ions. A measure of the electrical potential is, therefore , gives the H^+ concentration or pH of the solution.

Standard solution used were: Buffer solutions of pH 4, 7.2 and 9 were made from the standard buffer tablets available for the purpose by dissolving in 100 ml of distilled water.

Organic carbon (Walkley and Black method, 1934)

Ten ml of water sample was taken in 500 ml conical flask and add 10 ml potassium dichromate, 20 ml of concentrated H_2SO_4, 200 ml distilled water and 0.5 g sodium fluoride. Add 1 ml of diphenylamine indicator and titrate it with N/2 ferrous ammonium sulfate. The end point was green. Similar readings were taken for blank.

Calcium carbonate $CaCO_3$ (Puri's method)

Calcium carbonate $CaCO_3$ can be determined by titrating the suspension with 0.5 N H_2SO_4 in presence of indicators. Place 10 g of soil in beakers and add 100 ml of distill water. Add 0.2 – 0.5 g of calcium sulphate $CaSO_4$ to make the appearance of the color very distinct and bring it to boiling and then add 0.1 N of $AlCl_3.6H_2O$ solution. The content was shaked for few minutes. Then add 10 drops each of bromothymol blue and bromocresol green indicators. Green color shows the presence of $CaCO_3$ while golden yellow color is the indicative of its absence.

Calcium sulfate $CaSO_4$ (precipitation with acetone)

Add to 20 ml of aliquot 20 ml of acetone and mix. Allow it to stand for few minutes until precipitates flocculates. Centrifuge it for 3 min at 1000 rpm, decant off the supernatant liquid and drain it on filter paper for 5 min. Rinse of the tube with 10 ml of acetone and again centrifuge it for 3 min. Decant off the supernatant liquid and invert the tube and drain on filter paper. Add exactly 40ml of distill water to the tube and shake it till precipitates dissolves. Measure the EC of the solution and determine the concentration of gypsum $CaSO_4$ by reference to the following graph

$CaSO_4$ concentration (me L^{-1})	EC at 25 ^{0}C (dS m^{-1})
1.0	0.121
2.0	0.226
5.0	0.500
10.0	0.900
20.0	1.584
30.5	2.205

Milliequivalent of $CaSO_4$ in aliquot = (me L^{-1} of CaSO4 from conductivity meter reading) X (ml of water used to dissolve precipitates) / 100

Appendix - II

Table A II: Electrical Conductivity EC. pH and f(t) of the recovered water in different ASR cycles

ASR cycle 1

BSV = 6000 m^3 **EC_n = 28.4 dS m^{-1}**

V_i = 2000 m^3 **EC_i = 0.265 dS m^{-1}**

Time (h)	qr (L h^{-1})	Vr (L)	del Vr (L)	I (%)	EC (dS m^{-1})		pH		f (t)		RMSE
					Cr	Crw	Cr	Crw	Expt	Simulated	
1	2	3	4	5	6	7	8	9	10	11	12
0.02	64800	1080	1080	0.05	0.274	0.274	7.85	7.85	1.00	0.9995	0.0001
0.25	64800	16200	16200	0.81	0.274	0.274	7.85	7.85	1.00	0.9995	0.0002
0.50	64800	32400	16200	1.62	0.29	0.282	7.91	7.88	1.00	0.9995	0.0002
0.75	64800	48600	16200	2.43	0.285	0.283	7.91	7.89	1.00	0.9995	0.0002
1.00	64800	64800	16200	3.24	0.305	0.289	7.91	7.90	1.00	0.9995	0.0002
1.50	64800	97200	32400	4.86	0.417	0.331	7.95	7.91	1.00	0.9995	0.0003
2.00	64800	129600	32400	6.48	0.465	0.365	7.96	7.93	1.00	0.9995	0.0003
3.00	64800	194400	64800	9.72	0.585	0.438	7.96	7.94	0.99	0.9995	0.0021
4.00	64800	259200	64800	12.96	0.651	0.491	8.00	7.95	0.99	0.9995	0.0029
7.00	63000	448200	189000	22.41	0.798	0.621	8.01	7.98	0.99	0.9995	0.0036
10.00	63000	637200	189000	31.86	0.85	0.689	8.01	7.99	0.99	0.9950	0.0038

VII

13.00	57600	810000	172800	40.50	0.995	0.754	8.05	8.00	0.98	0.9940	0.0048
16.00	57600	982800	172800	49.14	1.672	0.915	8.03	8.01	0.98	0.9820	0.0049
19.00	57600	1155600	172800	57.78	1.975	1.074	8.05	8.01	0.97	0.9525	0.0062
22.00	57600	1328400	172800	66.42	2.675	1.282	8.10	8.02	0.96	0.9080	0.0129
23.00	57600	1386000	57600	69.30	4.092	1.399	8.15	8.03	0.96	0.8855	0.0208
23-51	0	1386000	0	69.30							
51.00	0	1386000	0	69.30							
52.00	64800	1450800	64800	72.54	8.02	1.695	8.21	8.04	0.95	0.8490	0.0303
53.00	64800	1515600	64800	75.78	8.96	2.005	8.23	8.05	0.94	0.8200	0.0400
54.00	64800	1580400	64800	79.02	9.55	2.315	8.25	8.05	0.93	0.7855	0.0510
57.00	64800	1774800	194400	88.74	12.25	3.403	8.25	8.08	0.89	0.6645	0.0708
60.00	64800	1969200	194400	98.46	14.065	4.455	8.28	8.10	0.85	0.5280	0.0998

qr - recovery rate; **Vr** - volume recovered at time (t); **I** - recovery percentage; **f (t)** - fraction of the injectant in the recovered water; RMSE-root Mean square error, **V_i** - volume injected to be recovered, **BSV** - buffer storage volume,**ECn & ECi** - Electrical conductivity of native and injected water

ASR cycle 2

BSV = 10000000 l EC_n = 28.4 dS m^{-1}

V_i = 20000000 EC_i = 0.265 dS m^{-1}

Time (h)	qr (L h^{-1})	Vr (L)	del Vr (L)	I (%)	EC (dS m^{-1})		pH		f (t)		RMSE
					Cr	Crw	Cr	Crw	Expt	Simulated	
1	2	3	4	5	6	7	8	9	10	11	12
0.02	55800	930	930	0.05	0.272	0.272	7.80	7.80	0.999	0.9998	5.06E-05
0.25	55800	13950	13950	0.70	0.272	0.280	7.82	7.82	0.999	0.9998	5.07E-05
0.50	55384	27796	13846	1.39	0.272	0.285	7.83	7.83	0.999	0.9995	5.59E-05
0.75	55384	41642	13846	2.08	0.274	0.272	7.85	7.83	1.000	0.9995	1.35E-04
1.00	55384	55488	13846	2.77	0.305	0.28	7.85	7.84	0.999	0.9995	1.47E-04
1.50	55384	83180	27692	4.16	0.41	0.323	7.85	7.84	0.998	0.9995	3.20E-04
2.00	55384	110872	27692	5.54	0.46	0.357	7.90	7.86	0.997	0.9995	6.40E-04
3.00	55384	166256	55384	8.31	0.556	0.432	7.90	7.87	0.994	0.9995	1.25E-03
4.00	55384	221640	55384	11.08	0.648	0.479	7.85	7.87	0.992	0.9995	1.97E-03
7.00	55384	387792	166152	19.39	0.79	0.612	7.91	7.88	0.988	0.9990	3.16E-03
10.00	55384	553944	166152	27.70	0.845	0.682	7.95	7.90	0.985	0.9975	4.15E-03
13.00	55384	720096	166152	36.00	0.99	0.753	7.96	7.92	0.982	0.9975	5.27E-03
16.00	55384	886248	166152	44.31	1.153	0.827	7.99	7.93	0.980	0.9945	6.15E-03

19.00	55384	1052400	166152	52.62	1.469	0.928	8.05	7.95	0.977	0.9810	6.23E-03
22.00	54540	1216020	163620	60.80	1.487	1.004	8.10	7.97	0.974	0.9540	7.67E-03
25.00	54540	1379640	163620	68.98	1.965	1.118	8.15	7.99	0.970	0.9060	1.62E-02
28.00	54540	1543260	163620	77.16	3.205	1.339	8.20	8.01	0.962	0.8960	2.20E-02
31.00	54540	1706880	163620	85.34	4.256	1.618	8.22	8.03	0.952	0.7285	5.46E-02
34.00	54540	1870500	163620	93.53	6.741	2.066	8.22	8.05	0.936	0.5950	9.38E-02
37.00	54540	2034120	163620	101.71	7.963	2.541	8.25	8.07	0.919	0.5340	1.27E-01

ASR cycle 3

BSV = 14000000 l EC_n = 28.4 dS m^{-1}

V_i = 2000000 l EC_i = 0.265 dS m^{-1}

Time (h)	qr ($L\ h^{-1}$)	Vr (L)	del Vr (L)	I (%)	EC (dS/m)		pH		f (t)		RMSE
					Cr	Crw	Cr	Crw	Expt	Simulated	
1	2	3	4	5	6	7	8	9	10	11	12
0.02	55800	930	930	0.05	0.19	0.19	7.80	7.80	1.000	1.000	0.0005
0.25	55800	13950	13950	0.70	0.19	0.19	7.80	7.80	1.000	1.000	0.0007
0.50	55800	27900	13950	1.40	0.27	0.23	7.85	7.83	1.000	1.000	0.0007
0.75	55384	41746	13846	2.09	0.27	0.24	7.83	7.83	1.000	1.000	0.0007
1.00	55384	55592	13846	2.78	0.30	0.26	7.85	7.83	1.000	1.000	0.0008
1.50	55384	83284	27692	4.16	0.41	0.31	7.91	7.86	0.998	1.000	0.0008
2.00	55384	110976	27692	5.55	0.45	0.34	7.90	7.87	0.997	1.000	0.0009
3.00	55384	166360	55384	8.32	0.53	0.41	7.99	7.91	0.995	0.999	0.0010
4.00	55384	221744	55384	11.09	0.64	0.46	7.99	7.93	0.993	0.999	0.0020
7.00	54540	385364	163620	19.27	0.79	0.60	7.99	7.96	0.988	0.999	0.0030
10.00	54540	548984	163620	27.45	0.88	0.69	8.02	7.97	0.985	0.999	0.0040
13.00	54540	712604	163620	35.63	0.99	0.76	8.04	7.99	0.983	0.997	0.0050
16.00	54540	876224	163620	43.81	1.10	0.82	8.05	8.00	0.981	0.996	0.0060

											XI
19.00	54540	1039844	163620	51.99	1.25	0.89	8.05	8.01	0.978	0.986	0.0070
22.00	54540	1203464	163620	60.17	1.39	0.96	8.08	8.02	0.976	0.962	0.0070
25.00	54540	1367084	163620	68.35	1.58	1.03	8.12	8.03	0.973	0.917	0.0150
28.00	54540	1530704	163620	76.54	1.76	1.11	8.18	8.05	0.970	0.843	0.0320
31.00	54540	1694324	163620	84.72	2.70	1.26	8.18	8.06	0.965	0.738	0.0600
34.00	54540	1857944	163620	92.90	3.50	1.46	8.20	8.07	0.958	0.617	0.0971
37.00	54540	2021564	163620	101.08	4.70	1.72	8.24	8.09	0.948	0.517	0.1370

ASR cycle 4

BSV = 14000000 l & ts = 70 d EC_n = 28.4 dS m^{-1}

V_i = 2000000 l EC_i = 0.265 dS m^{-1}

Time (h)	qr (L h^{-1})	Vr (L)	del Vr (L)	I (%)	EC (dS m^{-1})		pH		f (t)		RMSE
					Cr	Crw	Cr	Crw	Expt	Simulated	
1	2	3	4	5	6	7	8	9	10	11	12
0.02	55800	930	930	0.05	0.272	0.315	7.82	7.82	0.9984	1.000	0.000
0.25	55800	13950	13950	0.74	0.880	0.844	7.92	7.92	0.9796	1.000	0.004
0.50	55800	27900	13950	1.44	1.110	0.973	7.95	7.94	0.9751	1.000	0.007
0.75	55384	41746	13846	2.13	1.060	1.001	8.02	7.96	0.9741	1.000	0.009
1.00	55384	55592	13846	2.83	1.040	1.010	8.02	7.98	0.9737	1.000	0.010
1.50	55384	83284	27692	4.21	1.020	1.013	8.05	8.00	0.9736	1.000	0.012
2.00	55384	110976	27692	5.60	1.010	1.012	8.09	8.02	0.9737	1.000	0.013
3.00	55384	166360	55384	8.36	1.010	1.011	8.15	8.07	0.9737	0.999	0.014
4.00	55384	221744	55384	11.13	1.010	1.011	8.16	8.09	0.9737	0.999	0.015
7.00	54540	385364	163620	19.31	1.140	1.065	8.25	8.16	0.9718	0.999	0.016
10.00	54540	548984	163620	27.50	1.200	1.105	8.25	8.19	0.9704	0.998	0.017
13.00	54540	712604	163620	35.68	1.370	1.166	8.27	8.20	0.9682	0.994	0.018
16.00	54540	876224	163620	43.86	1.660	1.258	8.28	8.22	0.9649	0.983	0.019

19.00	54540	1039844	163620	52.04	2.160	1.400	8.25	8.22	0.9599	0.961	0.019
22.00	54540	1203464	163620	60.22	2.880	1.601	8.31	8.24	0.9527	0.922	0.020
25.00	54540	1367084	163620	68.40	3.930	1.879	8.31	8.24	0.9428	0.865	0.026
25-455	0	1367084	0	68.40							
455.00	54540	1367084	163620	68.40	2.760	0.000	8.32	0.00	0.0000	0.000	0.000
456.00	54540	1421624	54540	71.13	4.190	1.968	8.35	8.25	0.9397	0.843	0.034
457.00	54540	1476164	54540	73.85	4.220	2.051	8.35	8.25	0.9367	0.818	0.043
460.00	54540	1639784	163620	82.04	4.450	2.290	8.38	8.26	0.9282	0.729	0.061
463.00	54540	1803404	163620	90.22	5.360	2.569	8.4	8.28	0.9183	0.628	0.088
466.00	54540	1967024	163620	98.40	6.260	2.875	8.41	8.29	0.9074	0.523	0.122

Appendix - III

Table A III: Water quality parameter of native, injeted and recovered water at Hisar site as a function of recovery percentage (I) in different cycles

ASR cycle 1

BSV = 6000 m^3 & $\overline{t}$ = 7.2 d V$_i$ = 2000 m^3

I	Na^+		K^+		Ca^{+2}		Mg^{+2}		HCO_3^-		Cl^-		SO_4^{2-}		BO_3^-		NO_3^-		EM	RSC	SAR
(%)	(me/L)																		(%)		
	Cr	Crw	Cr	Crw	Cr	Crw	Cr	Crw	Cr	Crw	Cr	Crw	Cr	Crw	Cr	Crw	Cr	Crw			
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
0.05	0.5	0.5	0.1	0.1	1.2	1.2	0.8	0.8	0.8	0.8	1.2	1.2	0.32	0.32	0.01	0.01	0.15	0.15	3.0	-1.2	0.49
0.81	0.5	0.5	0.1	0.1	1.2	1.2	0.8	0.8	0.8	0.8	1.2	1.2	0.32	0.32	0.01	0.01	0.15	0.15	4.5	-1.2	-0.08
1.62	0.5	0.5	0.1	0.1	1.2	1.2	0.8	0.8	1.0	0.9	1.2	1.2	0.32	0.32	0.00	0.01	0.15	0.15	-2.4	-1.0	-0.10
2.43	0.5	0.5	0.1	0.1	1.2	1.2	0.9	0.8	1.0	0.9	1.4	1.3	0.32	0.32	0.00	0.01	0.16	0.15	-5.3	-1.1	-0.10
3.24	0.7	0.5	0.1	0.1	1.4	1.3	1.2	0.9	1.2	1.0	1.4	1.3	0.36	0.33	0.01	0.01	0.2	0.17	6.5	-1.4	-0.08
4.86	0.7	0.6	0.2	0.1	1.4	1.3	1.4	1.1	1.2	1.1	2.0	1.5	0.30	0.32	0.01	0.01	0.22	0.18	-2.1	-1.6	-0.08
6.48	0.8	0.6	0.2	0.1	1.8	1.4	1.7	1.2	1.6	1.2	2.4	1.8	0.36	0.33	0.01	0.01	0.22	0.19	-3.9	-1.9	-0.07
9.72	1.1	0.8	0.2	0.2	2.2	1.7	2.0	1.5	1.6	1.3	3.6	2.4	0.39	0.35	0.01	0.01	0.22	0.20	-6.5	-2.6	-0.06
12.96	1.5	1.0	0.2	0.2	2.5	1.9	2.3	1.7	1.8	1.5	4.2	2.8	0.59	0.41	0.01	0.01	0.22	0.21	-4.1	-3.0	-0.06
22.41	2.5	1.6	0.3	0.2	2.7	2.2	3.9	2.6	2.0	1.7	5.4	3.9	0.77	0.56	0.02	0.01	0.22	0.21	10.7	-4.6	-0.05
31.86	3.1	2.0	0.3	0.2	2.9	2.4	4.2	3.1	2.2	1.8	6.4	4.6	0.77	0.62	0.04	0.02	0.22	0.21	8.7	-4.9	-0.05
40.50	4.3	2.5	0.4	0.3	3.0	2.6	4.5	3.4	3.2	2.1	7.8	5.3	0.77	0.65	0.05	0.03	0.23	0.22	0.9	-4.3	-0.06

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
49.14	11.5	4.1	0.4	0.3	3.1	2.6	4.8	3.6	3.6	2.4	13.2	6.7	1.2	0.7	0.06	0.03	0.22	0.22	7.9	-4.3	-0.07
57.78	12.2	5.3	0.5	0.3	6.8	3.3	4.0	3.7	6.5	3.0	17.2	8.3	1.2	0.8	0.09	0.04	0.20	0.22	-7.4	-4.3	-0.08
66.42	15.9	6.7	0.5	0.3	5.4	3.5	7.2	4.2	7.5	3.6	22.2	10.1	1.7	0.9	0.09	0.05	0.30	0.23	-9.0	-5.1	-0.07
69.30	29.4	7.6	0.6	0.4	8.4	3.7	9.5	4.4	7.0	3.7	40.3	11.3	2.3	1.0	0.08	0.05	0.40	0.23	-4.5	-10.9	-0.03
72.54	44.6	9.3	0.6	0.4	17.2	4.3	21.7	5.1	8.0	3.9	79.6	14.4	3.8	1.1	0.05	0.05	0.52	0.25	-8.9	-30.9	-0.01
75.78	50.9	11.1	1.1	0.4	18.8	5.0	24.7	6.0	8.0	4.1	83.6	17.4	4.2	1.2	0.09	0.05	0.50	0.26	-0.9	-35.5	-0.01
79.02	52.6	12.8	1.3	0.4	21.6	5.6	26.7	6.8	12.0	4.4	89.2	20.3	5.0	1.4	0.09	0.05	0.55	0.27	-4.6	-36.3	-0.01
88.74	65.4	18.5	1.3	0.5	26.0	7.9	34.9	9.9	15.0	5.6	116.2	30.8	5.3	1.8	0.11	0.06	0.55	0.30	-7.2	-45.9	-0.01
98.46	68.2	23.4	1.4	0.6	33.2	10.4	45.9	13.5	18.0	6.8	133.6	40.9	6.5	2.3	0.17	0.07	0.60	0.33	-6.7	-61.1	-0.01
C_i	0.5		0.06		1.2		0.8		0.8		1.2		0.32		0.005						
C_n	159.1		2.1		39.0		86.0		24.0		261		7.19		0.300						

C_i & C_n - concentration of salts in injected water and native water respectively, BSV - buffer storage volume, t_s - storage time

Vi - volume injected to be recovered, EM - error mean (%), RSC - residual sodium concentration, SAR- sodium adsorption ratio

ASR cycle 2

BSV = 10000 m^3 & $\overline{t}$ = 6.05 d

V$_i$ = 2000 m^3

I	Na^+		K^+		Ca^{+2}		Mg^{+2}		HCO_3^-		Cl^-		SO_4^{2-}		BO_3^-		NO_3^-		EM	RSC	SAR
(%)	(me/l)																		(%)		
	Cr	Crw	Cr	Crw	Cr	Crw	Cr	Crw	Cr	Crw	Cr	Crw	Cr	Crw	Cr	Crw	Cr	Crw			
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
0.05	0.5	0.5	0.1	0.1	1.2	1.2	0.8	0.8	1.2	1.2	1.2	1.2	0.32	0.32	0.01	0.01	0.15	0.15	-5.36	-0.80	0.48
0.69	0.5	0.5	0.1	0.1	1.2	1.2	0.8	0.8	1.2	1.2	1.2	1.2	0.32	0.32	0.01	0.01	0.15	0.15	-3.88	-0.80	-0.6
1.38	0.5	0.5	0.1	0.1	1.2	1.2	0.8	0.8	1.2	1.2	1.2	1.2	0.36	0.34	0.01	0.01	0.15	0.15	-5.36	-0.80	-0.6
2.08	0.5	0.5	0.1	0.1	1.3	1.2	0.9	0.8	1.2	1.2	1.2	1.2	0.36	0.35	0.01	0.01	0.15	0.15	-4.52	-1.00	-0.483
2.77	0.8	0.6	0.1	0.1	1.3	1.3	0.9	0.9	1.4	1.3	1.4	1.3	0.36	0.35	0.00	0.01	0.15	0.15	-7.91	-0.80	-0.688
4.15	0.9	0.7	0.1	0.1	1.5	1.3	1.1	0.9	1.4	1.3	1.6	1.4	0.36	0.35	0.02	0.01	0.15	0.15	2.383	-1.20	-0.55
5.54	1.1	0.8	0.1	0.1	1.7	1.4	1.2	1.0	1.4	1.3	1.8	1.5	0.39	0.36	0.00	0.01	0.15	0.15	9.884	-1.50	-0.513
8.31	1.5	1.0	0.2	0.1	2.0	1.6	1.3	1.1	1.6	1.4	2.4	1.8	0.4	0.38	0.01	0.01	0.22	0.17	6.882	-1.70	-0.596
11.08	2.0	1.3	0.2	0.1	2.1	1.7	2.0	1.3	1.8	1.5	3.6	2.2	0.51	0.41	0.01	0.01	0.24	0.19	2.373	-2.30	-0.549
19.38	2.8	1.9	0.2	0.2	2.2	1.9	2.2	1.7	2.0	1.7	4.4	3.2	0.55	0.47	0.01	0.01	0.24	0.21	2.982	-2.40	-0.799
27.69	3.2	2.3	0.3	0.2	2.1	2.0	3.3	2.2	2.0	1.8	5.0	3.7	0.49	0.48	0.02	0.01	0.24	0.22	13.21	-3.40	-0.677
36.00	4.1	2.7	0.3	0.2	2.5	2.1	3.8	2.5	2.2	1.9	6.2	4.3	0.49	0.48	0.05	0.02	0.31	0.24	14.58	-4.10	-0.663

XVII

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
44.31	5.1	3.2	0.3	0.2	2.8	2.2	3.8	2.8	2.4	2.0	7.5	4.9	0.61	0.5	0.05	0.03	0.33	0.26	10.03	-4.20	-0.753
52.61	8.0	3.9	0.3	0.3	3.0	2.4	4.5	3.1	2.6	2.1	10.1	5.7	0.78	0.55	0.06	0.03	0.40	0.28	12.48	-4.90	-0.8
60.80	8.0	4.5	0.4	0.3	3.1	2.5	4.5	3.3	2.6	2.2	12.4	6.6	1.01	0.61	0.08	0.04	0.41	0.30	-3.15	-5.00	-0.896
68.98	13.5	5.6	0.4	0.3	7.0	3.0	4.8	3.4	5.0	2.5	15.6	7.7	1.19	0.68	0.09	0.05	0.45	0.32	9.111	-5.70	-0.975
77.16	23.4	7.5	0.5	0.3	7.4	3.5	5.4	3.6	7.0	3.0	29.2	10.0	2.03	0.82	0.11	0.05	0.50	0.34	-5.81	-5.80	-1.288
85.34	32.7	9.9	1.0	0.4	8.8	4.0	9.5	4.2	7.5	3.4	38.8	12.8	2.37	0.97	0.12	0.06	0.51	0.35	5.277	-10.80	-0.918
93.52	39.1	12.5	1.1	0.4	13.6	4.8	14.2	5.1	10.0	4.0	56.4	16.6	2.95	1.15	0.10	0.06	0.55	0.37	-2.95	-17.80	-0.701
101.70	45.6	15.2	1.1	0.5	16.6	5.8	20.7	6.3	12.0	4.6	69.4	20.9	4.22	1.4	0.11	0.07	0.51	0.38	-2.62	-25.30	-0.6

ASR cycle 3

BSV = 14000 m^3 & $\overline{t}$ = 13.5 d

V$_i$ = 2000 m^3

I	Na^+		K^+		Ca^{+2}		Mg^{+2}		HCO_3^-		Cl^-		SO_4^{2-}		BO_3^-		NO_3^-		EM	RSC	SAR
(%)	(me/l)																		(%)		
	Cr	Crw	Cr	Crw	Cr	Crw	Cr	Crw	Cr	Crw	Cr	Crw	Cr	Crw	Cr	Crw	Cr	Crw			
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
0.02	0.5	0.5	0.1	0.1	1.2	1.2	0.8	0.8	0.8	0.8	1.2	1.2	0.32	0.32	0.01	0.01	0.15	0.15	2.59	-1.2	0.48
0.25	0.5	0.5	0.1	0.1	1.2	1.2	0.8	0.8	1.0	1.0	1.0	1.0	0.30	0.30	0.00	0.00	0.20	0.20	1.86	-1.0	0.48
0.50	0.5	0.5	0.1	0.1	1.2	1.2	0.8	0.8	1.0	1.0	1.2	1.1	0.36	0.33	0.02	0.01	0.20	0.20	-9.24	-1.0	0.48
0.75	0.5	0.5	0.1	0.1	1.4	1.3	0.9	0.8	1.1	1.0	1.4	1.2	0.36	0.34	0.00	0.01	0.20	0.20	-6.51	-1.2	0.48
1.00	0.5	0.5	0.1	0.1	1.6	1.3	1.0	0.9	1.1	1.0	1.6	1.3	0.40	0.35	0.00	0.01	0.22	0.20	-3.77	-1.5	0.47
1.50	0.7	0.6	0.1	0.1	1.7	1.5	1.3	1.0	1.3	1.1	2.0	1.5	0.42	0.38	0.03	0.01	0.20	0.20	-6.32	-1.7	0.53
2.00	0.8	0.6	0.1	0.1	1.9	1.6	1.6	1.2	1.5	1.2	2.6	1.8	0.42	0.39	0.00	0.01	0.22	0.21	-9.8	-2.0	0.57
3.00	1.2	0.8	0.1	0.1	2.0	1.7	1.9	1.4	1.8	1.4	3.0	2.2	0.62	0.46	0.01	0.01	0.20	0.20	-8.06	-2.1	0.87
4.00	1.9	1.1	0.1	0.1	2.1	1.8	2.0	1.6	1.8	1.5	4.0	2.6	0.62	0.50	0.01	0.01	0.20	0.20	-9.01	-2.3	1.31
7.00	2.5	1.7	0.1	0.1	2.5	2.1	2.2	1.8	2.0	1.7	4.2	3.3	0.62	0.55	0.02	0.01	0.23	0.21	3.092	-2.7	1.62
10.00	3.4	2.2	0.1	0.09	2.7	2.3	2.3	1.97	2.0	1.8	5.2	3.87	0.67	0.59	0.02	0.01	0.30	0.24	4.128	-3.0	2.17
13.00	4.5	2.7	0.1	0.1	2.6	2.4	3.7	2.4	2.0	1.8	6.8	4.5	0.78	0.63	0.02	0.02	0.30	0.25	9.788	-4.3	2.54

XIX

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
16.00	6.4	3.4	0.1	0.1	2.7	2.4	3.9	2.7	2.2	1.9	8.3	5.2	1.00	0.70	0.01	0.02	0.40	0.28	9.33	-4.4	3.50
19.00	7.3	4.0	0.1	0.1	2.7	2.5	4.7	3.0	2.2	2.0	9.8	6.0	1.07	0.76	0.02	0.02	0.40	0.30	9.374	-5.2	3.79
22.00	7.9	4.5	0.1	0.1	2.9	2.5	4.7	3.2	2.4	2.0	12.4	6.8	1.13	0.81	0.04	0.02	0.35	0.31	-4.1	-5.2	4.07
25.00	9.2	5.1	0.2	0.1	3.0	2.6	5.3	3.5	2.6	2.1	13.4	7.6	1.71	0.92	0.03	0.02	0.30	0.31	-2.31	-5.7	4.51
28.00	12.0	5.8	0.2	0.1	3.5	2.7	6.1	3.7	3.4	2.2	15.2	8.4	1.88	1.02	0.02	0.02	0.35	0.31	4.368	-6.2	5.47
31.00	17.4	7.0	0.3	0.1	7.6	3.2	5.3	3.9	7.0	2.7	22.8	9.8	1.91	1.11	0.04	0.02	0.50	0.33	-5.4	-5.9	6.85
34.00	24.5	8.5	0.5	0.2	8.8	3.7	6.8	4.1	8.0	3.2	30.2	11.6	2.49	1.23	0.03	0.02	0.52	0.35	-1.56	-7.6	8.77
37.00	35.0	10.6	0.7	0.2	10.6	4.2	8.7	4.5	8.0	3.5	42.0	14.1	2.95	1.37	0.03	0.02	0.52	0.36	2.688	-11.3	11.27

ASR cycle 4

BSV = 14000 m^3 & $\overline{t}$ = 70.8 d

V$_i$ = 2000 m^3

I	Na^+		K^+		Ca^{+2}		Mg^{+2}		HCO_3^-		Cl^-		SO_4^{2-}		BO_3^-		NO_3^-		EM	RSC	SAR
(%)	(me/l)																		(%)		
	Cr	Crw	Cr	Crw	Cr	Crw	Cr	Crw	Cr	Crw	Cr	Crw	Cr	Crw	Cr	Crw	Cr	Crw			
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
0.05	3.8	3.8	0.04	0.04	1.4	1.40	0.8	0.80	1.0	1.00	1.6	1.6	0.32	0.32	0.003	0.003	0.15	0.15	-6.3	-1.8	2.88
0.70	5.2	5.2	0.08	0.08	1.6	1.60	1.8	1.80	1.6	1.60	5.2	5.2	0.68	0.68	0.003	0.003	0.22	0.22	-6.8	-2.7	3.36
1.40	4.9	5.0	0.18	0.13	2.2	1.90	2.5	2.15	2.0	1.80	7.6	6.4	0.88	0.78	0.003	0.003	0.25	0.24	-5.7	-2.4	3.30
2.09	5.1	5.0	0.16	0.14	2.2	2.00	2.2	2.17	2.0	1.87	7.0	6.6	0.77	0.78	0.005	0.004	0.23	0.23	-5.0	-2.1	3.54
2.78	5.1	5.0	0.16	0.14	2	2.00	2.1	2.15	2.0	1.90	6.8	6.6	0.77	0.78	0.008	0.005	0.23	0.23	7.9	-3.2	3.21
4.16	4.9	5.0	0.15	0.15	2.2	2.07	2.8	2.37	1.8	1.87	6.6	6.6	0.80	0.78	0.012	0.007	0.23	0.23	10.2	-3.3	3.05
5.55	4.9	5.0	0.16	0.15	2.2	2.10	3.0	2.52	1.9	1.87	6.4	6.6	0.74	0.77	0.013	0.009	0.23	0.23	7.2	-3.0	3.16
8.32	5.1	5.0	0.16	0.15	2.2	2.13	2.6	2.55	1.8	1.85	6.4	6.5	0.74	0.76	0.013	0.010	0.22	0.23	9.5	-3.2	3.27
11.09	6.4	5.3	0.16	0.15	2.2	2.15	2.6	2.56	1.6	1.79	6.4	6.5	0.89	0.79	0.014	0.011	0.22	0.23	8.5	-3.3	3.84
19.27	6.4	5.8	0.17	0.16	2.5	2.30	3.0	2.75	2.2	1.96	7.6	7.0	0.94	0.86	0.014	0.012	0.30	0.26	10.7	-4.0	3.67
27.45	8.6	6.6	0.22	0.18	2.6	2.39	3.4	2.94	2.0	1.97	8.0	7.3	0.94	0.88	0.007	0.011	0.35	0.285	2.7	-4.1	4.76
35.63	10.2	7.4	0.24	0.19	3	2.53	3.5	3.07	2.4	2.07	11.2	8.17	0.97	0.9	0.002	0.009	0.35	0.3	-3.1	-3.1	5.39

XXI

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
43.81	14.7	8.8	0.27	0.21	3.4	2.69	3.8	3.21	4.1	2.45	12.4	9.0	1.40	0.99	0.016	0.010	0.35	0.31	2.9	-3.9	6.63
51.99	21.8	10.9	0.35	0.23	5.9	3.20	4.0	3.33	6.0	3.01	16.2	10.1	1.71	1.11	0.005	0.009	0.36	0.32	8.1	-6.3	8.70
60.17	30.6	13.5	0.42	0.26	6.6	3.66	6.0	3.69	6.3	3.46	23.4	11.9	2.00	1.23	0.037	0.013	0.40	0.33	9.4	-8.6	11.08
68.35	19.7	14.3	0.54	0.29	7.1	4.07	8.2	4.23	6.7	3.84	32.8	14.4	2.23	1.35	0.080	0.021	0.48	0.35	9.7	-7.0	7.76
71.08	30.9	14.9	0.60	0.30	8	4.22	9.5	4.4	6.8	3.96	34.4	15.2	2.37	1.39	0.10	0.02	0.48	0.35	10.4	-10.7	10.45
73.81	32.5	15.6	0.65	0.31	8.4	4.38	9.4	4.6	7.5	4.09	35.6	15.9	2.49	1.43	0.11	0.03	0.50	0.36	9.8	-10.3	10.89
81.99	34.8	17.5	0.72	0.35	10.1	4.95	9.0	5.1	7.9	4.47	38.6	18.2	2.49	1.53	0.08	0.03	0.55	0.38	9.5	-11.2	11.24
90.17	36.2	19.2	0.89	0.40	12.6	5.64	12.8	5.8	8.9	4.87	49.2	21.0	3.18	1.68	0.11	0.04	0.60	0.40	0.8	-16.5	10.16
98.35	40.9	21.0	1.00	0.45	13.5	6.30	13.5	6.4	9.2	5.23	56.3	23.9	3.99	1.88	0.11	0.05	0.60	0.41	-1.9	-17.8	11.13

Appendix - IV

Table A IV: Depth of water table from ground surface in piezometer dwp and in observation wells dwo as a function of cummulative time from the start of experiment (9th sept,2003) in different cycles

			Recharge (First Cycle), BSV = 6000 m^3 & $\bar{t}$ = 172.8 h								Recharge with canal water			
Time	qi	V_i	dwp	Rise in dwp	dwo_{10}	Rise in dwo	dwo_5	Rise in dwo	dwo_{25}	Rise in dwo	dwo_{50}	Rise in dwo	dwo_{100}	Rise in dwo
(h)	(m^3/h)	(m^3)	(m)											
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0.00	0.00	0.00	1.60	0.00	1.09	0.00	0.71	0.00	1.19	0.00	1.40	0.00		
0.02	23.76	0.40	1.40	0.20										
0.03	23.76	0.79	1.35	0.25										
0.05	23.76	1.19	1.35	0.25										
0.07	23.76	1.58	1.35	0.25										
0.08	23.76	1.98	1.33	0.27										
0.10	23.76	2.38	1.29	0.31										
0.12	23.76	2.77	1.25	0.35										
0.13	23.76	3.17	1.20	0.40										
0.15	23.76	3.56	1.18	0.42										
0.17	23.76	3.96	1.18	0.42										
0.18	23.76	4.36	1.18	0.42										
0.20	23.76	4.75	1.20	0.40										
0.22	23.76	5.15	1.22	0.38										
0.23	23.76	5.54	1.23	0.37										
0.25	23.76	5.94	1.25	0.35										

XXIII

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0.27	23.76	6.34	1.25	0.35										
0.28	23.76	6.73	1.27	0.33										
0.30	23.76	7.13	1.26	0.34										
0.32	23.76	7.52	1.26	0.34										
0.33	23.76	7.92	1.26	0.34										
0.35	23.76	8.32	1.26	0.34										
0.37	23.76	8.71	1.28	0.32										
0.38	23.76	9.11	1.28	0.32										
0.40	23.76	9.50	1.27	0.33										
0.42	23.76	9.90	1.27	0.33										
0.43	23.76	10.30	1.27	0.33										
0.45	23.76	10.69	1.27	0.33										
0.47	23.76	11.09	1.27	0.33										
0.48	23.76	11.48	1.27	0.33										
0.50	23.76	11.88	1.27	0.33										
0.75	23.76	17.82	1.27	0.33										
1.00	23.76	23.76	1.27	0.33										
1.50	23.76	35.64	1.21	0.39										
2.00	23.76	47.52	1.21	0.39	1.04	0.05	0.69	0.02	1.19	0.00	1.35	0.05		
3.00	23.76	71.28	1.25	0.35										
4.00	23.76	95.04	1.20	0.40										
10.00	22.32	237.60	1.20	0.40										

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
16.00	22.32	380.16	1.25	0.35										
22.00	22.32	522.72	1.26	0.34	0.99	0.10	0.66	0.05	1.09	0.10	1.30	0.10		
28.00	22.32	665.28	1.10	0.50										
34.00	22.32	807.84	1.10	0.50										
40.00	22.32	950.40	1.10	0.50										
46.00	23.76	1092.96	1.06	0.54	0.84	0.25	0.59	0.12	1.01	0.18	1.30	0.10		
52.00	23.76	1235.52	1.04	0.56										
58.00	23.76	1378.08	1.00	0.60										
64.00	23.76	1520.64	1.00	0.60										
70.00	23.76	1663.20	1.00	0.60	0.76	0.33	0.54	0.17	0.92	0.27	1.20	0.20		
76.00	23.76	1805.76	1.05	0.55										
82.00	23.76	1948.32	1.00	0.60										
88.00	23.76	2090.88	1.00	0.60										
94.00	23.76	2233.44	1.00	0.60	0.74	0.35	0.54	0.17	0.89	0.30	1.18	0.22		
100.00	23.76	2376.00	1.00	0.60										
106.00	23.76	2518.56	1.00	0.60										
112.00	23.76	2661.12	1.00	0.60										
118.00	23.76	2803.68	1.00	0.60			0.54	0.17	0.84	0.35	1.15	0.25		
124.00	23.76	2946.24	1.05	0.55	0.74	0.35								
Tubewell started from 130-136 hrs														
130.00	23.76	3088.80	1.05	0.55										
136.00	23.76	3231.36	1.15	0.45										

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
142.00	23.76	3373.92	1.04	0.56	0.70	0.39	0.51	0.20	0.84	0.35	1.12	0.28		
148.00	23.76	3516.48	0.95	0.65										
154.00	23.76	3659.04	0.95	0.65										
160.00	23.76	3801.60	1.00	0.60	0.64	0.45	0.48	0.23	0.79	0.40	1.08	0.32		
166.00	23.76	3944.16	1.00	0.60										
172.00	23.76	4086.72	1.00	0.60										
Recharge off from 175-198 hrs														
175.00	23.76	4158.00	1.02	0.58										
178.00	0.00	4158.00	1.46	0.14										
184.00	0.00	4158.00	1.46	0.14										
190.00	0.00	4158.00	1.46	0.14	0.81	0.28	0.67	0.04	0.89	0.30	1.10	0.30		
198.00	0.00	4158.00	1.46	0.14	0.99	0.10	0.79	-0.08	0.91	0.28	1.10	0.30		
198.02	23.76	4158.40	1.20	0.40										
198.03	23.76	4158.79	1.15	0.45										
198.05	23.76	4159.19	1.15	0.45										
198.07	23.76	4159.58	1.05	0.55										
198.08	23.76	4159.98	1.05	0.55										
198.17	23.76	4161.96	1.00	0.60										
198.25	23.76	4163.94	1.00	0.60										
198.33	23.76	4165.92	0.98	0.62										
198.42	23.76	4167.90	0.98	0.62										
198.50	23.76	4169.88	0.95	0.65										

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
198.75	23.76	4175.82	0.90	0.70										
199.00	23.76	4181.76	0.90	0.70	0.91	0.18	0.69	0.02	0.89	0.30	1.09	0.31		
200.00	23.76	4205.52	0.88	0.72	0.79	0.30	0.54	0.17	0.85	0.34	1.07	0.33		
206.00	23.76	4348.08	0.85	0.75										
212.00	23.76	4490.64	0.85	0.75	0.68	0.41	0.46	0.25	0.77	0.42	1.04	0.36		
Tubewell started from 218-221 hrs														
218.00	23.76	4633.20	0.85	0.75	0.73	0.36	0.44	0.27	0.74	0.45	1.03	0.37		
218.02	23.76	4633.60	0.88	0.72										
218.03	23.76	4633.99	0.88	0.72										
218.05	23.76	4634.39	0.90	0.70										
218.07	23.76	4634.78	0.91	0.69										
218.08	23.76	4635.18	0.93	0.67										
218.10	23.76	4635.58	0.94	0.66										
218.12	23.76	4635.97	0.94	0.66										
218.13	23.76	4636.37	0.95	0.65										
218.15	23.76	4636.76	0.96	0.64										
218.17	23.76	4637.16	0.97	0.63										
218.18	23.76	4637.56	0.97	0.63										
218.20	23.76	4637.95	0.98	0.62										
218.22	23.76	4638.35	0.98	0.62										
218.23	23.76	4638.74	0.98	0.62										
218.25	23.76	4639.14	0.99	0.61	0.77	0.32	0.41	0.30	0.75	0.44	1.03	0.37		

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
218.28	23.76	4639.93	0.99	0.61										
218.32	23.76	4640.72	1.00	0.60										
218.35	23.76	4641.52	1.00	0.60										
218.38	23.76	4642.31	1.01	0.59										
218.42	23.76	4643.10	1.02	0.58										
218.45	23.76	4643.89	1.02	0.58										
218.48	23.76	4644.68	1.02	0.58										
218.50	23.76	4645.08	1.02	0.58										
218.75	23.76	4651.02	1.04	0.56										
219.00	23.76	4656.96	1.05	0.55	0.79	0.30	0.49	0.22	0.76	0.43	1.03	0.37		
219.50	23.76	4668.84	1.06	0.54										
220.00	23.76	4680.72	1.07	0.53										
221.00	23.76	4704.48	1.09	0.51	0.82	0.27	0.54	0.17	0.84	0.35	1.03	0.37		
Good quality tubewell off from 221 - 240 hrs														
222.00	23.76	4728.24	0.95	0.65										
228.00	23.76	4870.80	0.90	0.70										
234.00	23.76	5013.36	0.88	0.72										
Tubewell starts from 240-247 hrs														
240.00	23.76	5155.92	0.85	0.75	0.65	0.44	0.47	0.24	0.75	0.44	1.01	0.39		
240.02	23.76	5156.32	0.90	0.70										
240.03	23.76	5156.71	0.90	0.70										
240.05	23.76	5157.11	0.91	0.69										

XXVIII

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
240.07	23.76	5157.50	0.92	0.68										
240.08	23.76	5157.90	0.94	0.66										
240.17	23.76	5159.88	1.00	0.60										
240.25	23.76	5161.86	1.00	0.60										
240.33	23.76	5163.84	1.00	0.60										
240.42	23.76	5165.82	1.02	0.58										
240.50	23.76	5167.80	1.03	0.57										
240.75	23.76	5173.74	1.07	0.53										
241.00	23.76	5179.68	1.08	0.52										
241.50	23.76	5191.56	1.08	0.52	0.72	0.37	0.56	0.15	0.79	0.40	1.00	0.40		
242.00	23.76	5203.44	1.08	0.52										
243.00	23.76	5227.20	1.08	0.52	0.87	0.22	0.56	0.15	0.81	0.38	1.01	0.39		
244.00	23.76	5250.96	1.10	0.50	0.92	0.17	0.59	0.12	0.83	0.36	1.01	0.39		
245.00	23.76	5274.72	1.12	0.48	0.98	0.11	0.63	0.08	0.84	0.35	1.00	0.40		
246.00	23.76	5298.48	1.16	0.44	1.01	0.08	0.66	0.05	0.85	0.34	1.01	0.39		
247.00	23.76	5322.24	1.16	0.44	1.03	0.06	0.68	0.03	0.89	0.30	1.01	0.39		
252.00	23.76	5441.04	0.92	0.68	0.80	0.25	0.59	0.12	0.82	0.37	1.11	0.29		
258.00	23.76	5583.60	0.91	0.69	0.68	0.36	0.55	0.16	0.79	0.40	1.01	0.39		
264.00	23.76	5726.16	0.90	0.70	0.58	0.40	0.54	0.17	0.73	0.46	1.01	0.39		
270.00	23.76	5868.72	0.84	0.76	0.50	0.44	0.46	0.25	0.73	0.46	1.04	0.36		
276.00	23.76	6011.28	0.84	0.76	0.41	0.48	0.47	0.24	0.72	0.47	1.04	0.36		

						Discharge(First Cycle)			Canal flowing during discharge					
Time	q_r (m^3/h)	V_r	dwp	Fall in dwp	dwo$_{10}$	Fall in dwo	dwo$_5$	Fall in dwo	dwo$_{25}$	Fall in dwo	dwo$_{50}$	Fall in dwo	dwo$_{100}$	Fall in dwo
300.00	0.00	0.00	1.00	0.00	0.59	0.00	0.44	0.00	0.55	0.00	0.95	0.00	1.06	0.00
300.02	64.80	1.08	1.80	-0.80										
300.03	64.80	2.16	2.25	-1.25										
300.05	64.80	3.24	2.96	-1.96										
300.07	64.80	4.32	3.40	-2.40										
300.08	64.80	5.40	3.75	-2.75										
300.10	64.80	6.48	4.22	-3.22										
300.12	64.80	7.56	4.44	-3.44										
300.13	64.80	8.64	4.57	-3.57										
300.15	64.80	9.72	4.68	-3.68										
300.17	64.80	10.80	4.85	-3.85										
300.18	64.80	11.88	4.98	-3.98										
300.20	64.80	12.96	5.10	-4.10										
300.22	64.80	14.04	5.20	-4.20										
300.23	64.80	15.12	5.26	-4.26										
300.25	64.80	16.20	5.30	-4.30	0.57	0.02	0.46	-0.02	0.54	0.01	0.94	0.01	1.05	0.01
300.27	64.80	17.28	5.40	-4.40										
300.28	64.80	18.36	5.54	-4.54										
300.30	64.80	19.44	5.60	-4.60										
300.32	64.80	20.52	5.65	-4.65										
300.33	64.80	21.60	5.70	-4.70										

XXX

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
300.35	64.80	22.68	5.74	-4.74										
300.37	64.80	23.76	5.82	-4.82										
300.38	64.80	24.84	5.90	-4.90										
300.40	64.80	25.92	5.92	-4.92										
300.42	64.80	27.00	5.98	-4.98										
300.43	64.80	28.08	6.02	-5.02										
300.45	64.80	29.16	6.08	-5.08										
300.47	64.80	30.24	6.10	-5.10										
300.48	64.80	31.32	6.14	-5.14										
300.50	64.80	32.40	6.18	-5.18	0.62	-0.03	0.46	-0.02	0.54	0.01	0.94	0.01	1.05	0.01
300.75	64.80	48.60	6.54	-5.54	0.57	0.02	0.46	-0.02	0.64	-0.09	0.94	0.01	1.05	0.01
301.00	64.80	64.80	6.70	-5.70	0.58	0.01	0.45	-0.01	0.64	-0.09	0.94	0.01	1.05	0.01
301.50	64.80	97.20	6.96	-5.96	0.58	0.01	0.45	-0.01	0.64	-0.09	0.94	0.01	1.05	0.01
302.00	64.80	129.60	7.05	-6.05	0.58	0.01	0.46	-0.02	0.64	-0.09	0.94	0.01	1.05	0.01
303.00	64.80	194.40	7.09	-6.09	0.59	0.00	0.46	-0.02	0.64	-0.09	0.94	0.01	1.05	0.01
304.00	64.80	259.20	7.16	-6.16	0.60	-0.01	0.48	-0.04	0.65	-0.10	0.95	0.00	1.06	0.00
307.00	63.00	448.20	7.36	-6.36	0.60	-0.01	0.48	-0.04	0.65	-0.10	0.96	-0.01	1.06	0.00
310.00	63.00	637.20	7.36	-6.36										
313.00	57.60	810.00	7.37	-6.37	0.68	-0.01	0.59	-0.15	0.69	-0.14	0.96	-0.01	1.07	-0.01
316.00	57.60	982.80	7.35	-6.35	0.69	-0.10	0.62	-0.18	0.69	-0.14	0.97	-0.02	1.07	-0.01
319.00	57.60	1155.60	7.34	-6.34	0.71	-0.12	0.67	-0.23	0.71	-0.16	0.97	-0.02	1.08	-0.02
322.00	57.60	1328.40	7.30	-6.30	0.78	-0.19	0.74	-0.30	0.78	-0.23	0.98	-0.03	1.10	-0.04

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
323.00	57.60	1386.00	7.32	-6.32	0.79	-0.22	0.76	-0.32	0.79	-0.24	0.99	-0.04	1.11	-0.05
351.00	0.00	1386.00	3.40	-2.40	0.81	-0.22	0.66	-0.22	0.70	-0.15	0.96	-0.01	1.08	-0.02
351.02	64.80	1387.08	4.10	-3.10										
351.03	64.80	1388.16	4.40	-3.40										
351.05	64.80	1389.24	4.60	-3.60										
351.07	64.80	1390.32	4.85	-3.85										
351.08	64.80	1391.40	4.93	-3.93										
351.10	64.80	1392.48	5.15	-4.15										
351.12	64.80	1393.56	5.27	-4.27										
351.13	64.80	1394.64	5.40	-4.40										
351.15	64.80	1395.72	5.50	-4.50										
351.17	64.80	1396.80	5.60	-4.60										
351.18	64.80	1397.88	6.67	-5.67										
351.20	64.80	1398.96	5.75	-4.75										
351.22	64.80	1400.04	5.82	-4.82										
351.23	64.80	1401.12	5.89	-4.89										
351.25	64.80	1402.20	5.93	-4.93										
351.27	64.80	1403.28	5.99	-4.99										
351.28	64.80	1404.36	6.03	-5.03										
351.30	64.80	1405.44	6.07	-5.07										
351.32	64.80	1406.52	6.12	-5.12										
351.33	64.80	1407.60	6.16	-5.16										

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
351.05	64.80	1408.68	6.20	-5.20										
351.37	64.80	1409.76	6.22	-5.22										
351.38	64.80	1410.84	6.26	-5.26										
351.40	64.80	1411.92	6.31	-5.31										
351.42	64.80	1413.00	6.34	-5.34										
351.43	64.80	1414.08	6.39	-5.39										
351.45	64.80	1415.16	6.40	-5.40										
351.47	64.80	1416.24	6.41	-5.41										
351.48	64.80	1417.32	6.43	-5.43										
351.50	64.80	1418.40	6.45	-5.45										
351.75	64.80	1434.60	6.73	-5.73										
352.00	64.80	1450.80	6.97	-5.97	0.86	-0.14	0.69	-0.25	0.71	-0.16	0.96	-0.01	1.08	-0.02
352.25	64.80	1467.00	7.07	-6.07										
352.50	64.80	1483.20	7.11	-6.11										
353.00	64.80	1515.60	7.25	-6.25	0.88	-0.16	0.71	-0.27	0.73	-0.18	0.96	-0.01	1.08	-0.02
353.50	64.80	1548.00	7.25	-6.25										
354.50	64.80	1612.80	7.35	-6.35	0.94	-0.18	0.73	-0.29	0.76	-0.21	0.97	-0.02	1.09	-0.03
357.50	64.80	1807.20	7.36	-6.36	1.02	-0.24	0.76	-0.32	0.79	-0.24	0.98	-0.03	1.10	-0.04
360.50	57.60	2001.60	7.36	-6.36	1.11	-0.31	0.80	-0.36	0.82	-0.27	1.00	-0.05	1.11	-0.05

			Recharge (Second cycle), BSV = 10000 m^3 & $\bar{t}$ = 145.2 h							Recharge through canal water				
Time (h)	*qi* (m^3/h)	V_i	dwp	Rise in dwp	dwo_{10}	Rise in dwo_{10}	dwo_5	Rise in dwo	dwo_{25}	Rise in dwo	dwo_{50}	Rise in dwo	dwo_{100}	Rise in dwo
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
377.50	0.00	0.00	1.55	0.00	0.74	0.00	0.64	0.00	0.78	0.00	1.07	0.00	1.12	0.00
377.52	23.76	0.40	1.40	0.15										
377.53	23.76	0.79	1.26	0.29										
377.55	23.76	1.19	1.13	0.42										
377.57	23.76	1.58	1.05	0.50										
377.58	23.76	1.98	1.00	0.55										
377.60	23.76	2.38	0.96	0.59										
377.62	23.76	2.77	0.94	0.61										
377.63	23.76	3.17	0.92	0.63										
377.65	23.76	3.56	0.92	0.63										
377.67	23.76	3.96	0.90	0.65										
377.68	23.76	4.36	0.90	0.65										
377.70	23.76	4.75	0.90	0.65										
377.72	23.76	5.15	0.89	0.66										
377.73	23.76	5.54	0.89	0.66										
377.75	23.76	5.94	0.89	0.66										
377.77	23.76	6.34	0.89	0.66										
377.78	23.76	6.73	0.89	0.66										
377.80	23.76	7.13	0.89	0.66										

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
377.82	23.76	7.52	0.89	0.66										
377.83	23.76	7.92	0.89	0.66										
377.85	23.76	8.32	0.89	0.66										
377.87	23.76	8.71	0.89	0.66										
377.88	23.76	9.11	0.89	0.66										
377.90	23.76	9.50	0.88	0.67										
377.92	23.76	9.90	0.88	0.67										
377.93	23.76	10.30	0.88	0.67										
377.95	23.76	10.69	0.88	0.67										
377.97	23.76	11.09	0.88	0.67										
377.98	23.76	11.48	0.88	0.67										
378.00	23.76	11.88	0.88	0.67	0.72		0.63	0.01	0.77	0.01	1.07	0.00	1.12	0.00
378.25	23.76	17.82	0.87	0.68										
378.50	23.76	23.76	0.87	0.68										
379.00	23.76	35.64	0.87	0.68										
379.50	23.76	47.52	0.87	0.68										
380.50	23.76	71.28	0.89	0.66	0.72	0.02	0.59	0.05	0.78	0.00	1.08	-0.01	1.12	0.00
381.50	23.76	95.04	0.89	0.66	0.72	0.02	0.54	0.10	0.78	0.00	1.08	-0.01	1.12	0.00
387.50	23.76	237.60	0.89	0.66	0.70	0.04	0.52	0.12	0.78	0.00	1.08	-0.01	1.12	0.00
393.50	23.76	380.16	0.89	0.66	0.68	0.06	0.52	0.12	0.75	0.03	1.07	0.00	1.12	0.00
399.50	23.76	522.72	0.89	0.66	0.67	0.07	0.51	0.13	0.74	0.04	1.07	0.00	1.12	0.00
405.50	23.76	665.28	0.89	0.66	0.65	0.09	0.50	0.14	0.74	0.04	1.04	0.03	1.12	0.00

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
411.50	23.76	807.84	0.89	0.66	0.63	0.11	0.50	0.14	0.73	0.05	1.04	0.03	1.10	0.02
417.50	23.76	950.40	0.89	0.66	0.64	0.10	0.51	0.13	0.73	0.05	1.00	0.07	1.09	0.03
423.50	23.76	1092.96	0.85	0.70	0.64	0.10	0.47	0.17	0.72	0.06	1.04	0.03	1.08	0.04
429.50	23.76	1235.52	0.85	0.70	0.64	0.10	0.47	0.17	0.71	0.07	1.04	0.03	1.08	0.04
435.50	23.76	1378.08	0.84	0.71	0.63	0.11	0.46	0.18	0.71	0.07	1.04	0.03	1.08	0.04
441.50	23.76	1520.64	0.84	0.71	0.62	0.12	0.45	0.19	0.69	0.09	1.03	0.04	1.07	0.05
447.50	23.76	1663.20	0.83	0.72	0.62	0.12	0.44	0.20	0.69	0.09	1.03	0.04	1.07	0.05
453.50	23.76	1805.76	0.82	0.73	0.64	0.10	0.44	0.20	0.69	0.09	1.02	0.05	1.07	0.05
459.50	23.76	1948.32	0.82	0.73	0.61	0.13	0.43	0.21	0.67	0.11	1.02	0.05	1.07	0.05
Rain for 3-4 hrs during 460 hrs														
465.50	23.76	2090.88	0.81	0.74	0.54	0.20	0.41	0.23	0.63	0.15	0.98	0.09	1.04	0.08
471.50	23.76	2233.44	0.79	0.76	0.53	0.21	0.40	0.24	0.62	0.16	0.98	0.09	1.04	0.08
477.50	23.76	2376.00	0.79	0.76	0.54	0.20	0.40	0.24	0.62	0.16	0.97	0.10	1.04	0.08
483.50	23.76	2518.56	0.79	0.76	0.54	0.20	0.40	0.24	0.62	0.16	0.96	0.11	1.02	0.10
489.50	23.76	2661.12	0.79	0.76	0.54	0.20	0.40	0.24	0.61	0.17	0.96	0.11	1.01	0.11
495.50	23.76	2803.68	0.79	0.76	0.54	0.20	0.40	0.24	0.61	0.17	0.96	0.11	1.01	0.11
Canal flow reduces to approx to 3 times till end of recharge														
501.50	23.76	2946.24	0.79	0.76	0.57	0.17	0.44	0.20	0.64	0.14	0.98	0.09	1.03	0.09
507.50	23.76	3088.80	0.79	0.76	0.59	0.15	0.52	0.12	0.62	0.16	0.94	0.13	1.00	0.12
513.50	23.76	3231.36	0.79	0.76	0.60	0.14	0.54	0.10	0.61	0.17	0.92	0.15	0.98	0.14
519.50	23.76	3373.92	0.79	0.76	0.61	0.13	0.54	0.10	0.63	0.15	0.92	0.15	0.98	0.14
525.50	23.76	3516.48	0.79	0.76	0.62	0.12	0.55	0.09	0.64	0.14	0.92	0.15	0.97	0.15

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
531.50	23.76	3659.04	0.79	0.76	0.64	0.10	0.57	0.07	0.65	0.13	0.92	0.15	0.98	0.14
537.50	23.76	3801.60	0.79	0.76	0.64	0.10	0.59	0.05	0.66	0.12	0.93	0.14	0.99	0.13
543.50	23.76	3944.16	0.79	0.76	0.64	0.10	0.59	0.05	0.66	0.12	0.93	0.14	0.98	0.14
549.50	23.76	4086.72	0.82	0.73	0.67	0.07	0.60	0.04	0.68	0.10	0.94	0.13	0.99	0.13
555.50	23.76	4229.28	0.85	0.70	0.67	0.07	0.61	0.03	0.69	0.09	0.95	0.12	1.00	0.12
561.50	23.76	4371.84	0.85	0.70	0.69	0.05	0.61	0.03	0.69	0.09	0.95	0.12	1.00	0.12
567.50	23.76	4514.40	0.85	0.70	0.69	0.05	0.61	0.03	0.70	0.08	0.96	0.11	1.01	0.11
573.50	23.76	4656.96	0.85	0.70	0.70	0.04	0.62	0.02	0.71	0.07	0.97	0.10	1.02	0.10
579.50	23.76	4799.52	0.86	0.69	0.70	0.04	0.62	0.02	0.70	0.08	0.97	0.10	1.02	0.10
585.50	23.76	4942.08	0.88	0.67	0.71	0.03	0.63	0.01	0.70	0.08	0.97	0.10	1.02	0.10
591.50	23.76	5084.64	0.88	0.67	0.72	0.02	0.64	0.00	0.71	0.07	0.97	0.10	1.02	0.10
597.50	23.76	5227.20	0.88	0.67	0.73	0.01	0.65	-0.01	0.72	0.06	0.98	0.09	1.02	0.10
603.50	23.76	5369.76	0.90	0.65	0.74	0.00	0.66	-0.02	0.72	0.06	0.98	0.09	1.02	0.10
609.50	23.76	5512.32	0.91	0.64	0.75	-0.01	0.67	-0.03	0.73	0.05	0.99	0.08	1.03	0.09
615.50	23.76	5654.88	0.91	0.64	0.74	0.00	0.68	-0.04	0.74	0.04	0.99	0.08	1.03	0.09
621.50	23.76	5797.44	0.91	0.64	0.75	-0.01	0.68	-0.04	0.74	0.04	0.99	0.08	1.03	0.09
627.50	23.76	5940.00	0.91	0.64	0.76	-0.02	0.68	-0.04	0.75	0.03	1.00	0.07	1.04	0.08
633.50	23.76	6082.56	0.91	0.64	0.77	-0.03	0.68	-0.04	0.76	0.02	1.01	0.06	1.05	0.07

Discharge(Second Cycle)

Time	q_r (m^3/h)	V_r	dwp	Fall in dwp	dwo$_{10}$	Fall in dwo$_{10}$	dwo$_5$	Fall in dwo	dwo$_{25}$	Fall in dwo	dwo$_{50}$	Fall in dwo	dwo$_{100}$	Fall in dwo
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
652.50	0.00	0.00	1.27	0.00	0.78	0.00	0.69	0.00	0.77	0.00	1.02	0.00	1.07	0.00
652.52	65.52	1.09	1.80	-0.53										
652.53	65.52	2.18	2.22	-0.95										
652.55	65.52	3.27	2.85	-1.58										
652.57	65.52	4.36	3.45	-2.18										
652.58	65.52	5.45	3.87	-2.60										
652.60	65.52	6.54	4.25	-2.98										
652.62	65.52	7.63	4.55	-3.28										
652.63	65.52	8.72	4.84	-3.57										
652.65	65.52	9.81	5.01	-3.74										
652.67	65.52	10.90	5.23	-3.96										
652.68	65.52	11.99	5.35	-4.08										
652.70	65.52	13.08	5.50	-4.23										
652.72	65.52	14.17	5.60	-4.33										
652.73	65.52	15.26	5.70	-4.43										
652.75	65.52	16.35	5.78	-4.51										
652.77	65.52	17.44	5.85	-4.58										
652.78	65.52	18.53	5.93	-4.66										
652.80	65.52	19.62	6.02	-4.75										

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
652.82	65.52	20.71	6.10	-4.83										
652.83	65.52	21.80	6.17	-4.90										
652.85	65.52	22.89	6.22	-4.95										
652.87	65.52	23.98	6.27	-5.00										
652.88	65.52	25.07	6.33	-5.06										
652.90	65.52	26.16	6.37	-5.10										
652.92	65.52	27.25	6.40	-5.13										
652.93	65.52	28.34	6.42	-5.15										
652.95	65.52	29.43	6.45	-5.18										
652.97	65.52	30.52	6.49	-5.22										
652.98	65.52	31.61	6.53	-5.26										
653.00	65.52	32.70	6.55	-5.28	0.78	0.00	0.74	-0.05	0.77	0.00	1.02	0.00	1.07	0.00
653.25	60.10	47.73	6.75	-5.48	0.79	-0.01	0.74	-0.05	0.77	0.00	1.02	0.00	1.07	0.00
653.50	60.10	62.76	6.84	-5.57	0.79	-0.01	0.75	-0.06	0.77	0.00	1.02	0.00	1.07	0.00
654.00	60.10	92.81	7.14	-5.87	0.79	-0.01	0.75	-0.06	0.77	0.00	1.02	0.00	1.07	0.00
654.50	60.10	122.86	7.30	-6.03	0.80	-0.02	0.75	-0.06	0.78	-0.01	1.03	-0.01	1.08	-0.01
655.50	60.10	182.96	7.42	-6.15	0.81	-0.03	0.76	-0.07	0.78	-0.01	1.03	-0.01	1.08	-0.01
656.50	60.10	243.06	7.54	-6.27	0.82	-0.04	0.77	-0.08	0.79	-0.02	1.03	-0.01	1.08	-0.01
659.50	54.54	407.22	7.64	-6.37	0.87	-0.09	0.80	-0.11	0.82	-0.05	1.05	-0.03	1.11	-0.04
662.50	54.54	571.38	7.65	-6.38	0.89	-0.11	0.81	-0.12	0.84	-0.07	1.06	-0.04	1.12	-0.05
665.50	54.54	735.54	7.66	-6.39	0.90	-0.12	0.83	-0.14	0.85	-0.08	1.07	-0.05	1.13	-0.06

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
668.50	54.54	899.70	7.66	-6.39	0.91	-0.13	0.85	-0.16	0.87	-0.10	1.09	-0.07	1.14	-0.07
671.50	54.54	1063.86	7.66	-6.39	0.93	-0.15	0.89	-0.20	0.89	-0.12	1.10	-0.08	1.14	-0.07
674.50	54.54	1228.02	7.62	-6.35	0.95	-0.17	0.90	-0.21	0.90	-0.13	1.11	-0.09	1.15	-0.08
677.50	54.54	1392.18	7.62	-6.35	0.96	-0.18	0.92	-0.23	0.90	-0.13	1.11	-0.09	1.15	-0.08
680.50	54.54	1556.34	7.63	-6.36	0.96	-0.18	0.92	-0.23	0.90	-0.13	1.11	-0.09	1.15	-0.08
683.50	54.54	1720.50	7.64	-6.37	0.96	-0.18	0.92	-0.23	0.90	-0.13	1.11	-0.09	1.15	-0.08
686.50	54.54	1884.66	7.64	-6.37	0.97	-0.19	0.94	-0.25	0.90	-0.13	1.11	-0.09	1.15	-0.08
689.50	54.54	2048.82	7.64	-6.37	0.98	-0.20								

			Recharge (Third cycle), BSV = 14000 m^3 & t = $\bar{3}$25.2 h								Recharge through good quality tubewell			
Time	*qi* (m^3/h)	V_i	dwp	Rise in dwp	dwo_{10}	Rise in dwo_{10}	dwo_5	Rise in dwo	dwo_{25}	Rise in dwo	dwo_{50}	Rise in dwo	dwo_{100}	Rise in dwo
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
693.50	0.00	0.00	1.46	0.00	0.91	0.00	0.98	0.00	0.89	0.00	1.13	0.00	1.16	0.00
693.52	23.76	0.40	1.39	0.07										
693.53	23.76	0.79	1.30	0.16										
693.55	23.76	1.19	1.26	0.20										
693.57	23.76	1.58	1.23	0.23										
693.58	23.76	1.98	1.17	0.29										
693.60	23.76	2.38	1.16	0.30										
693.62	23.76	2.77	1.16	0.30										
693.63	23.76	3.17	1.16	0.30										
693.65	23.76	3.56	1.16	0.30										
693.67	23.76	3.96	1.16	0.30										
693.68	23.76	4.36	1.17	0.29										
693.70	23.76	4.75	1.18	0.28										
693.72	23.76	5.15	1.19	0.27										
693.73	23.76	5.54	1.20	0.26										
693.75	23.76	5.94	1.19	0.27										
693.77	23.76	6.34	1.18	0.28										
693.78	23.76	6.73	1.16	0.30										
693.80	23.76	7.13	1.16	0.30										

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
693.82	23.76	7.52	1.14	0.32										
693.83	23.76	7.92	1.13	0.33										
693.85	23.76	8.32	1.12	0.34										
693.87	23.76	8.71	1.12	0.34										
693.88	23.76	9.11	1.11	0.35										
693.90	23.76	9.50	1.11	0.35										
693.92	23.76	9.90	1.12	0.34										
693.93	23.76	10.30	1.14	0.32										
693.95	23.76	10.69	1.16	0.30										
693.97	23.76	11.09	1.17	0.29										
693.98	23.76	11.48	1.18	0.28										
694.00	23.76	11.88	1.19	0.27										
694.25	23.76	17.82	1.20	0.26										
694.50	23.76	23.76	1.20	0.26	0.99	-0.08	0.84	0.14	0.93	-0.04	1.13	0.00	1.17	-0.01
695.00	23.76	35.64	1.22	0.24	0.99	-0.08	0.86	0.12	0.93	-0.04	1.13	0.00	1.17	-0.01
695.50	23.76	47.52	1.22	0.24	1.03	-0.12	0.87	0.11	0.93	-0.04	1.13	0.00	1.17	-0.01
696.50	23.76	71.28	1.23	0.23	1.09	-0.18	0.88	0.10	0.95	-0.06	1.13	0.00	1.17	-0.01
697.50	23.76	95.04	1.24	0.22	1.11	-0.20	0.89	0.09	0.96	-0.07	1.13	0.00	1.17	-0.01
703.50	23.76	237.60	1.29	0.17	1.18	-0.27	0.92	0.06	1.01	-0.12	1.15	-0.02	1.18	-0.02
709.50	23.76	380.16	1.32	0.14	1.25	-0.34	0.97	0.01	1.06	-0.17	1.17	-0.04	1.20	-0.04
715.50	23.76	522.72	1.32	0.14	1.29	-0.38	0.99	-0.01	1.10	-0.21	1.19	-0.06	1.22	-0.06
721.50	23.76	665.28	1.32	0.14	1.34	-0.43	1.02	-0.04	1.14	-0.25	1.21	-0.08	1.23	-0.07

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
727.50	23.76	807.84	1.32	0.14	1.34	-0.43	1.02	-0.04	1.14	-0.25	1.21	-0.08	1.23	-0.07
733.50	23.76	950.40	1.32	0.14	1.40	-0.49	0.77	0.21	1.11	-0.22	1.25	-0.12	1.24	-0.08
Recharge stops from 739.5 - 745.5 hrs														
739.50	23.76	1092.96	1.32	0.14	1.42	-0.51	0.78	0.20	1.12	-0.23	1.27	-0.14	1.26	-0.10
745.50	0.00	1092.96	1.55	-0.09	1.11	-0.20	0.98	0.00						
745.52	22.32	1093.33	1.42	0.04										
745.53	22.32	1093.70	1.37	0.09										
745.55	22.32	1094.08	1.36	0.10										
745.57	22.32	1094.45	1.35	0.11										
745.58	22.32	1094.82	1.35	0.11										
745.60	22.32	1095.19	1.34	0.12										
745.62	22.32	1095.56	1.34	0.12										
745.63	22.32	1095.94	1.34	0.12										
745.65	22.32	1096.31	1.34	0.12										
745.67	22.32	1096.68	1.34	0.12										
745.68	22.32	1097.05	1.33	0.13										
745.70	22.32	1097.42	1.33	0.13										
745.72	22.32	1097.80	1.32	0.14										
745.73	22.32	1098.17	1.32	0.14										
745.75	22.32	1098.54	1.32	0.14										
746.25	22.32	1098.91	1.32	0.14										
746.50	22.32	1099.28	1.32	0.14	1.14	-0.23	0.98	0.00	1.03	-0.14	1.24	-0.11	1.27	-0.11

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
752.50	22.32	1099.66	1.32	0.14	1.29	-0.38	1.01	-0.03	1.08	-0.19	1.25	-0.12	1.28	-0.12
758.50	21.60	1229.26	1.39	0.07	1.42	-0.51	1.04	-0.06	1.16	-0.27	1.27	-0.14	1.30	-0.14
764.50	21.60	1358.86	1.40	0.06	1.64	-0.73	1.14	-0.16	1.23	-0.34	1.30	-0.17	1.32	-0.16
770.50	21.60	1488.46	1.38	0.08	1.70	-0.79	1.06	-0.08	1.26	-0.37	1.32	-0.19	1.34	-0.18
776.50	21.60	1618.06	1.38	0.08	1.71	-0.80	1.07	-0.09	1.28	-0.39	1.33	-0.20	1.35	-0.19
782.50	21.60	1747.66	1.38	0.08	1.73	-0.82	1.20	-0.22	1.30	-0.41	1.36	-0.23	1.39	-0.23
788.50	18.00	1855.66	1.33	0.13	1.74	-0.83	1.21	-0.23	1.35	-0.46	1.40	-0.27	1.39	-0.23
794.50	18.00	1963.66	1.34	0.12	1.78	-0.87	1.24	-0.26	1.39	-0.50	1.42	-0.29	1.43	-0.27
800.50	18.00	2071.66	1.35	0.11	1.78	-0.87	1.29	-0.31	1.41	-0.52	1.42	-0.29	1.43	-0.27
806.50	18.00	2179.66	1.37	0.09	1.79	-0.88	1.39	-0.41	1.45	-0.56	1.44	-0.31	1.45	-0.29
812.50	18.00	2287.66	1.39	0.07	1.81	-0.90	1.49	-0.51	1.49	-0.60	1.45	-0.32	1.47	-0.31
818.50	18.00	2395.66	1.35	0.11	1.83	-0.92	1.50	-0.52	1.50	-0.61	1.46	-0.33	1.48	-0.32
824.50	18.00	2503.66	1.35	0.11	1.83	-0.92	1.52	-0.54	1.52	-0.63	1.46	-0.33	1.50	-0.34
830.50	18.00	2611.66	1.36	0.10	1.85	-0.94	1.54	-0.56	1.54	-0.65	1.48	-0.35	1.51	-0.35
836.50	18.00	2719.66	1.35	0.11	1.86	-0.95	1.54	-0.56	1.54	-0.65	1.49	-0.36	1.51	-0.35
Recharge Stops from 836.5 - 848.5 hrs														
842.50	0.00	2719.66												
848.50	0.00	2719.66	1.45	0.01										
854.50	18.00	2827.66	1.35	0.11	1.73	-0.82	1.42	-0.44	1.50	-0.61	1.48	-0.35	1.53	-0.37
860.50	18.00	2935.66	1.34	0.12	1.79	-0.88	1.44	-0.46	1.49	-0.60	1.50	-0.37	1.53	-0.37
866.50	18.00	3043.66	1.34	0.12	1.81	-0.90	1.47	-0.49	1.50	-0.61	1.51	-0.38	1.55	-0.39
872.50	18.00	3151.66	1.34	0.12	1.84	-0.93	1.51	-0.53	1.54	-0.65	1.52	-0.39	1.56	-0.40

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
878.50	18.00	3259.66	1.34	0.12	1.89	-0.98	1.53	-0.55	1.54	-0.65	1.53	-0.40	1.58	-0.42
884.50	18.00	3367.66	1.34	0.12	1.89	-0.98	1.54	-0.56	1.54	-0.65	1.55	-0.42	1.60	-0.44
890.50	18.00	3475.66	1.34	0.12	1.91	-1.00	1.55	-0.57	1.56	-0.67	1.56	-0.43	1.61	-0.45
896.50	18.00	3583.66	1.33	0.13	1.92	-1.01	1.55	-0.57	1.58	-0.69	1.58	-0.45	1.62	-0.46
902.50	18.00	3691.66	1.33	0.13	1.93	-1.02	1.56	-0.58	1.61	-0.72	1.60	-0.47	1.63	-0.47
908.50	18.00	3799.66	1.34	0.12	1.93	-1.02	1.56	-0.58	1.62	-0.73	1.60	-0.47	1.63	-0.47
914.50	18.00	3907.66	1.34	0.12	1.93	-1.02	1.57	-0.59	1.65	-0.76	1.61	-0.48	1.64	-0.48
920.50	18.00	4015.66	1.44	0.02	1.93	-1.02	1.57	-0.59	1.68	-0.79	1.62	-0.49	1.65	-0.49
926.50	18.00	4123.66	1.48	-0.02	1.94	-1.03	1.58	-0.60	1.69	-0.80	1.63	-0.50	1.67	-0.51
932.50	16.20	4220.86	1.54	-0.08										
938.50	16.20	4318.06	1.60	-0.14	1.83	-0.92	1.49	-0.51	1.67	-0.78	1.64	-0.51	1.68	-0.52
944.50	14.40	4404.46	1.65	-0.19	1.84	-0.93	1.50	-0.52	1.68	-0.79	1.65	-0.52	1.68	-0.52
950.50	14.40	4490.86	1.70	-0.24	1.82	-0.91	1.50	-0.52	1.68	-0.79	1.65	-0.52	1.68	-0.52
956.50	14.40	4577.26	1.75	-0.29	1.88	-0.97	1.54	-0.56	1.71	-0.82	1.65	-0.52	1.68	-0.52
962.50	12.60	4652.86	1.74	-0.28	1.90	-0.99	1.56	-0.58	1.73	-0.84	1.66	-0.53	1.71	-0.55
968.50	10.80	4717.66	1.74	-0.28	1.92	-1.01	1.56	-0.58	1.75	-0.86	1.67	-0.54	1.75	-0.59
970.50	10.80	4739.26	1.74	-0.28										1.16
Recharge Off from 970.5 - 972.5 hrs														
972.50	0.00	4739.26												
974.50	10.80	4760.86	1.62	-0.16	1.83	-0.92	1.51	-0.53	1.70	-0.81	1.65	-0.52	1.72	-0.56
Tubewell off from 980.5 - 992.5h														
980.50	10.80	4825.66	1.66	-0.20	1.86	-0.95	1.53	-0.55	1.72	-0.83	1.66	-0.53	1.73	-0.57

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
986.50	10.80	4890.46	1.75	-0.29										
992.50	8.64	4942.30	1.75	-0.29	1.79	-0.88	1.44	-0.46	1.64	-0.75	1.64	-0.51	1.73	-0.57
998.50	8.64	4994.14	1.73	-0.27	1.72	-0.81	1.50	-0.52	1.69	-0.80	1.67	-0.54	1.75	-0.59
1004.50	8.64	5045.98	1.62	-0.16	1.72	-0.81	1.51	-0.53	1.66	-0.77	1.72	-0.59	1.75	-0.59
1010.50	8.64	5097.82	1.58	-0.12	1.79	-0.88	1.56	-0.58	1.69	-0.80	1.74	-0.61	1.77	-0.61
1016.50	8.64	5149.66	1.57	-0.11	1.90	-0.99	1.58	-0.60	1.74	-0.85	1.78	-0.65	1.78	-0.62
1022.50	8.64	5201.50	1.62	-0.16	1.90	-0.99	1.58	-0.60	1.72	-0.83	1.77	-0.64	1.78	-0.62
1028.50	8.64	5253.34	1.62	-0.16	1.90	-0.99	1.59	-0.61	1.74	-0.85	1.78	-0.65	1.79	-0.63
1034.50	8.64	5305.18	1.62	-0.16	1.98	-1.07	1.60	-0.62	1.76	-0.87	1.82	-0.69	1.80	-0.64
1040.50	8.64	5357.02	1.62	-0.16	2.04	-1.13	1.61	-0.63	1.79	-0.90	1.82	-0.69	1.82	-0.66
1046.50	8.64	5408.86	1.62	-0.16	2.04	-1.13	1.66	-0.68	1.83	-0.94	1.83	-0.70	1.84	-0.68
1052.50	8.64	5460.70	1.57	-0.11	2.04	-1.13	1.68	-0.70	1.84	-0.95	1.84	-0.71	1.84	-0.68
1058.50	8.64	5512.54	1.56	-0.10	2.05	-1.14	1.70	-0.72	1.85	-0.96	1.84	-0.71	1.85	-0.69
1064.50	8.64	5564.38	1.56	-0.10	2.07	-1.16	1.71	-0.73	1.86	-0.97	1.85	-0.72	1.85	-0.69
1070.50	8.64	5616.22	1.57	-0.11	2.06	-1.15	1.71	-0.73	1.88	-0.99	1.87	-0.74	1.86	-0.70
1076.50	8.64	5668.06	1.58	-0.12	2.06	-1.15	1.72	-0.74	1.89	-1.00	1.87	-0.74	1.86	-0.70
1082.50	8.64	5719.90	1.57	-0.11	2.07	-1.16	1.72	-0.74	1.90	-1.01	1.89	-0.76	1.86	-0.70
1088.50	8.64	5771.74	1.57	-0.11	2.09	-1.18	1.72	-0.74	1.91	-1.02	1.90	-0.77	1.88	-0.72
1094.50	8.64	5823.58	1.58	-0.12	2.09	-1.18	1.72	-0.74	1.93	-1.04	1.91	-0.78	1.88	-0.72
1100.50	8.64	5875.42	1.58	-0.12	2.09	-1.18	1.72	-0.74	1.93	-1.04	1.90	-0.77	1.89	-0.73
1106.50	8.64	5927.26	1.58	-0.12	1.79	-0.88	1.73	-0.75	1.93	-1.04	1.90	-0.77	1.90	-0.74

Recharge & Tubewell off from 413 - 519 h

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1112.50	0.00	5927.26	2.02	-0.56	1.74	-0.83	1.70	-0.72	1.80	-0.91	1.89	-0.76	1.89	-0.73
1118.50	0.00	5927.26	2.02	-0.56	1.70	-0.79	1.60	-0.62	1.77	-0.88	1.85	-0.72	1.89	-0.73
1124.50	0.00	5927.26	2.02	-0.56	1.69	-0.78	1.66	-0.68	1.73	-0.84	1.82	-0.69	1.88	-0.72
1130.50	0.00	5927.26	2.03	-0.57	1.69	-0.78	1.64	-0.66	1.73	-0.84	1.82	-0.69		
1136.50	0.00	5927.26	2.03	-0.57	1.68	-0.77	1.64	-0.66	1.72	-0.83	1.82	-0.69		
1142.50	0.00	5927.26	2.04	-0.58	1.67	-0.76	1.64	-0.66	1.71	-0.82	1.81	-0.68		
1148.50	0.00	5927.26	2.04	-0.58	1.67	-0.76	1.64	-0.66	1.71	-0.82	1.81	-0.68		
1154.50	0.00	5927.26	2.04	-0.58										
1160.50	0.00	5927.26	2.04	-0.58	1.66	-0.75	1.63	-0.65	1.69	-0.80	1.80	-0.67		
1166.50	0.00	5927.26	2.04	-0.58	1.66	-0.75	1.63	-0.65	1.68	-0.79	1.80	-0.67		
1172.50	0.00	5927.26	2.05	-0.59	1.66	-0.75	1.62	-0.64	1.68	-0.79	1.79	-0.66		
1178.50	0.00	5927.26	2.05	-0.59										
1184.50	0.00	5927.26	2.05	-0.59	1.65	-0.74	1.62	-0.64	1.66	-0.77	1.77	-0.64		
1190.50	0.00	5927.26	2.05	-0.59	1.65	-0.74	1.62	-0.64						
1196.50	0.00	5927.26	2.05	-0.59	1.65	-0.74	1.62	-0.64						
1202.50	0.00	5927.26	2.05	-0.59										
1208.50	0.00	5927.26	2.05	-0.59	1.65	-0.74	1.61	-0.63	1.67	-0.78	1.80	-0.67		
Tube well started at 1212.5 h till end														
1212.50	0.00	5927.26	2.35	-0.89										
1212.52	8.64	5927.40	2.23	-0.77										
1212.53	8.64	5927.54	2.12	-0.66										
1212.55	8.64	5927.68	2.02	-0.56										

XXXXVII

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1212.57	8.64	5927.82	1.96	-0.50										
1212.58	8.64	5927.96	1.89	-0.43										
1212.60	8.64	5928.10	1.87	-0.41										
1212.62	8.64	5928.24	1.85	-0.39										
1212.63	8.64	5928.38	1.83	-0.37										
1212.65	8.64	5928.52	1.82	-0.36										
1212.67	8.64	5928.66	1.82	-0.36										
1212.75	8.64	5929.38	1.76	-0.30										
1212.83	8.64	5930.10	1.52	-0.06										
1212.92	8.64	5930.82	1.44	0.02										
1213.00	8.64	5931.54	1.42	0.04	1.78	-0.87	1.55	-0.57	1.70	-0.81	1.84	-0.71	1.93	-0.77
1213.25	8.64	5933.70	1.36	0.10										
1213.50	8.64	5935.86	1.35	0.11										
1214.50	8.64	5944.50	1.34	0.12										
1215.50	8.64	5953.14	1.40	0.06										
1219.50	8.64	6004.98	1.66	-0.20	2.00	-1.09	1.65	-0.67	1.80	-0.91	1.90	-0.77	1.95	-0.79

Discharge(Third Cycle) Canal flows starts at 1349.5 hrs

Time	q_r (m^3/h)	V_r	dwp	Fall in dwp	dwo$_{10}$	Fall in dwo	dwo$_5$	Rise in dwo	dwo$_{25}$	Rise in dwo	dwo$_{50}$	Rise in dwo	dwo$_{100}$	Rise in dwo
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1349.50	0.00	0.00	1.85	0.00	1.66	0.00	1.61	0.00	1.72	0.00	1.88	0.00	1.96	0.00
1349.52	64.80	1.08	2.30	-0.45										
1349.53	64.80	2.16	2.95	-1.10										
1349.55	64.80	3.24	3.44	-1.59										
1349.57	64.80	4.32	3.90	-2.05										
1349.58	64.80	5.40	4.24	-2.39										
1349.60	64.80	6.48	4.60	-2.75										
1349.62	64.80	7.56	4.82	-2.97										
1349.63	64.80	8.64	5.04	-3.19										
1349.65	64.80	9.72	5.22	-3.37										
1349.67	64.80	10.80	5.39	-3.54										
1349.68	64.80	11.88	5.50	-3.65										
1349.70	64.80	12.96	5.61	-3.76										
1349.72	64.80	14.04	5.70	-3.85										
1349.73	64.80	15.12	5.80	-3.95										
1349.75	64.80	16.20	5.87	-4.02										
1349.77	64.80	17.28	5.95	-4.10										
1349.78	64.80	18.36	6.00	-4.15										
1349.80	64.80	19.44	6.07	-4.22										

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1349.82	64.80	20.52	6.13	-4.28										
1349.83	64.80	21.60	6.19	-4.34										
1349.85	64.80	22.68	6.25	-4.40										
1349.87	64.80	23.76	6.30	-4.45										
1349.88	64.80	24.84	6.35	-4.50										
1349.90	64.80	25.92	6.41	-4.56										
1349.92	64.80	27.00	6.44	-4.59										
1349.93	64.80	28.08	6.49	-4.64										
1349.95	64.80	29.16	6.55	-4.70										
1349.97	64.80	30.24	6.57	-4.72										
1349.98	64.80	31.32	6.60	-4.75										
1350.00	64.80	32.40	6.65	-4.80	1.64	0.02	1.60	0.01	1.72	0.00	1.88	0.00	1.96	0.00
1350.25	60.10	47.43	7.00	-5.15										
1350.50	60.10	62.46	7.20	-5.35	1.64	0.02	1.58	0.03	1.69	0.03	1.86	0.02	1.95	0.01
1351.00	60.10	92.51	7.36	-5.51	1.65	0.01	1.59	0.02	1.69	0.03	1.87	0.01	1.96	0.00
1351.50	60.10	122.56	7.45	-5.60	1.66	0.00	1.54	0.07	1.70	0.02	1.87	0.01	1.95	0.01
1352.50	54.54	177.10	7.68	-5.83	1.66	0.00	1.54	0.07	1.72	0.00	1.87	0.01	1.95	0.01
1353.50	54.54	231.64	7.76	-5.91										
1356.50	54.54	395.80	7.88	-6.03	1.68	-0.02	1.49	0.12	1.73	-0.01	1.88	0.00	1.96	0.00
1359.50	54.54	559.96	7.97	-6.12	1.66	0.00	1.52	0.09	1.73	-0.01	1.89	-0.01	1.96	0.00
1362.50	54.54	724.12	7.95	-6.10	1.68	-0.02	1.56	0.05	1.73	-0.01	1.89	-0.01	1.96	0.00
1365.50	54.54	888.28	7.96	-6.11	1.67	-0.01	1.46	0.15	1.73	-0.01	1.89	-0.01	1.96	0.00

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1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1368.50	54.54	1052.44	7.97	-6.12	1.67	-0.01	1.51	0.10	1.73	-0.01	1.89	-0.01	1.96	0.00
1371.50	54.54	1216.60	7.99	-6.14	1.67	-0.01	1.53	0.08	1.74	-0.02	1.90	-0.02	1.97	-0.01
1374.50	54.54	1380.76	7.99	-6.14	1.66	0.00	1.55	0.06	1.74	-0.02	1.90	-0.02	1.97	-0.01
1377.50	54.54	1544.92	7.99	-6.14	1.69	-0.03								
1380.50	54.54	1709.08	7.99	-6.14	1.69	-0.03								
1383.50	54.54	1873.24	7.99	-6.14	1.70	-0.04								
1386.50	54.54	2037.40	7.99	-6.14	1.70	-0.04								

Recharge (Fourth Cycle), BSV = 14000 m^3 & $\bar{t}$ = 1344 h

Time	q_i (m^3/h)	V_i	dwp	Rise in dwp	dwo_{10}	Rise in dwo_{10}	dwo_5	Rise in dwo	dwo_{25}	Rise in dwo	dwo_{50}	Rise in dwo	dwo_{100}	Rise in dwo
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1403.50	0.00	0.00	2.48	0.00	1.62	0.00	1.53	0.00	1.72	0.00	1.89	0.00	1.97	0.00
1403.52	10.80	0.18	2.37	0.11										
1403.53	10.80	0.36	2.13	0.35										
1403.55	10.80	0.54	1.94	0.54										
1403.57	10.80	0.72	1.83	0.65										
1403.58	10.80	0.90	1.78	0.70										
1403.60	10.80	1.08	1.75	0.73										
1403.62	10.80	1.26	1.72	0.76										
1403.63	10.80	1.44	1.69	0.79										
1403.65	10.80	1.62	1.68	0.80										
1403.67	10.80	1.80	1.66	0.82										
1403.68	10.80	1.98	1.64	0.84										
1403.70	10.80	2.16	1.64	0.84										
1403.72	10.80	2.34	1.62	0.86										
1403.73	10.80	2.52	1.61	0.87										
1403.75	10.80	2.70	1.61	0.87										
1403.77	10.80	2.88	1.60	0.88										
1403.78	10.80	3.06	1.59	0.89										
1403.80	10.80	3.24	1.58	0.90										

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1403.82	10.80	3.42	1.58	0.90										
1403.83	10.80	3.60	1.57	0.91										
1403.85	10.80	3.78	1.57	0.91										
1403.87	10.80	3.96	1.56	0.92										
1403.88	10.80	4.14	1.56	0.92										
1403.90	10.80	4.32	1.55	0.93										
1403.92	10.80	4.50	1.55	0.93										
1403.93	10.80	4.68	1.55	0.93										
1403.95	10.80	4.86	1.54	0.94										
1403.97	10.80	5.04	1.54	0.94										
1403.98	10.80	5.22	1.54	0.94										
1404.00	10.80	5.40	1.53	0.95										
1404.25	10.80	8.10	1.55	0.93										
1404.50	10.80	10.80	1.49	0.99	1.61	0.01	1.49	0.04	1.71	0.01	1.87	0.02	1.96	0.01
1405.00	10.80	16.20	1.48	1.00	1.61	0.01	1.49	0.04	1.70	0.02	1.87	0.02	1.96	0.01
1405.50	10.80	21.60	1.47	1.01	1.59	0.03	1.49	0.04	1.69	0.03	1.87	0.02	1.96	0.01
1406.50	10.80	32.40	1.46	1.02	1.59	0.03	1.49	0.04	1.67	0.05	1.86	0.03	1.95	0.02
1407.50	10.80	43.20	1.46	1.02	1.59	0.03	1.49	0.04	1.66	0.06	1.85	0.04	1.95	0.02
1413.50	10.80	108.00	1.42	1.06	1.56	0.06	1.48	0.05	1.64	0.08	1.84	0.05	1.93	0.04
1419.50	8.64	159.84	1.40	1.08	1.53	0.09	1.45	0.08	1.61	0.11	1.82	0.07	1.91	0.06
1425.50	8.64	211.68	1.36	1.12	1.50	0.12	1.42	0.11	1.59	0.13	1.80	0.09	1.90	0.07
1431.50	8.64	263.52	1.34	1.14	1.48	0.14	1.38	0.15	1.57	0.15	1.78	0.11	1.88	0.09

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1437.50	8.64	315.36	1.32	1.16	1.46	0.16	1.37	0.16	1.55	0.17	1.76	0.13	1.86	0.11
1443.50	8.64	367.20	1.30	1.18	1.45	0.17	1.36	0.17	1.52	0.20	1.74	0.15	1.84	0.13
1449.50	7.20	410.40	1.30	1.18	1.42	0.20	1.35	0.18	1.51	0.21	1.73	0.16	1.83	0.14
1455.50	8.64	462.24	1.31	1.17	1.43	0.19	1.35	0.18	1.51	0.21	1.73	0.16	1.83	0.14
1461.50	8.64	514.08	1.30	1.18	1.43	0.19	1.35	0.18	1.50	0.22	1.72	0.17	1.82	0.15
1467.50	8.64	565.92	1.29	1.19	1.42	0.20	1.34	0.19	1.48	0.24	1.70	0.19	1.80	0.17
1473.50	8.64	617.76	1.28	1.20	1.40	0.22	1.32	0.21	1.47	0.25	1.70	0.19	1.80	0.17
Recharge stops from 1478.5 -1479.5 hrs														
1479.50	8.64	660.96	1.40	1.08	1.40	0.22	1.32	0.21	1.47	0.25	1.70	0.19	1.80	0.17
1485.50	8.64	712.80	1.29	1.19	1.39	0.23	1.33	0.20	1.46	0.26	1.69	0.20	1.79	0.18
1491.50	8.64	764.64	1.28	1.20	1.39	0.23	1.34	0.19	1.44	0.28	1.67	0.22	1.77	0.20
1497.50	8.64	816.48	1.26	1.22	1.39	0.23	1.33	0.20	1.43	0.29	1.65	0.24	1.76	0.21
1503.50	8.28	866.16	1.25	1.23	1.39	0.23	1.33	0.20	1.43	0.29	1.65	0.24	1.76	0.21
1509.50	8.28	915.84	1.24	1.24										
Recharge stops from 1509.5 - 1515.5 hrs														
1515.50	0.00	915.84	1.41	1.07	1.39	0.23	1.36	0.17	1.43	0.29	1.65	0.24	1.76	0.21
1521.50	8.28	965.52	1.24	1.24	1.38	0.24	1.36	0.17	1.41	0.31	1.64	0.25	1.74	0.23
1527.50	8.28	1015.20	1.23	1.25	1.38	0.24	1.36	0.17	1.39	0.33	1.62	0.27	1.72	0.25
1533.50	8.28	1064.88	1.23	1.25	1.38	0.24	1.34	0.19	1.39	0.33	1.62	0.27	1.72	0.25
1539.50	8.28	1114.56	1.22	1.26	1.37	0.25	1.34	0.19	1.39	0.33	1.61	0.28	1.71	0.26
1545.50	8.28	1164.24	1.22	1.26	1.37	0.25	1.34	0.19	1.39	0.33	1.61	0.28	1.71	0.26
1551.50	8.28	1213.92	1.22	1.26	1.37	0.25	1.34	0.19	1.39	0.33	1.61	0.28	1.71	0.26

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1557.50	8.28	1263.60	1.21	1.27	1.37	0.25	1.35	0.18	1.39	0.33	1.61	0.28	1.71	0.26
1563.50	8.28	1313.28	1.20	1.28	1.37	0.25	1.36	0.17	1.40	0.32	1.61	0.28	1.71	0.26
1569.50	8.28	1362.96	1.20	1.28	1.36	0.26	1.35	0.18	1.38	0.34	1.59	0.30	1.69	0.28
1575.50	8.28	1412.64	1.18	1.30										
1581.50	8.28	1462.32	1.16	1.32										
1587.50	8.28	1512.00	1.15	1.33	1.35	0.27			1.35	0.37	1.57	0.32	1.67	0.30
1593.50	8.28	1561.68	1.14	1.34	1.33	0.29			1.35	0.37	1.57	0.32	1.67	0.30
1599.50	8.28	1611.36	1.13	1.35	1.29	0.33			1.35	0.37	1.56	0.33	1.66	0.31
1605.50	8.28	1661.04	1.12	1.36	1.29	0.33			1.33	0.39	1.56	0.33	1.66	0.31
1611.50	8.64	1712.88	1.10	1.38	1.28	0.34			1.22	0.50	1.54	0.35	1.65	0.32
1617.50	8.64	1764.72	1.10	1.38	1.24	0.38								
1623.50	8.64	1816.56	1.09	1.39	1.21	0.41								
1629.50	8.64	1868.40	1.08	1.40	1.16	0.46								
1635.50	8.28	1918.08	1.08	1.40	1.09	0.53								
1641.50	8.28	1967.76	1.08	1.40	1.04	0.58								
1647.50	8.28	2017.44	1.07	1.41	1.01	0.61								

Discharge(Fourth Cycle) 1344 h storage time (t_s)

Time	qr (m^3/h)	V_r	dwp	Fall in dwp	dwo_{10}	Fall in dwo_{10}	dwo_5	Fall in dwo	dwo_{25}	Fall in dwo	dwo_{50}	Fall in dwo	dwo_{100}	Fall in dwo
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
2991.50	0.00	0.00	1.43	0.00	1.24	0.00								
2991.52	64.80	1.08	1.90	-0.47										
2991.53	64.80	2.16	2.70	-1.27										
2991.55	64.80	3.24	3.20	-1.77										
2991.57	64.80	4.32	3.80	-2.37										
2991.58	64.80	5.40	4.10	-2.67										
2991.60	64.80	6.48	4.20	-2.77										
2991.62	64.80	7.56	4.80	-3.37										
2991.63	64.80	8.64	5.20	-3.77										
2991.65	64.80	9.72	5.60	-4.17										
2991.67	64.80	10.80	5.80	-4.37										
2991.68	64.80	11.88	6.00	-4.57										
2991.70	64.80	12.96	6.10	-4.67										
2991.72	64.80	14.04	6.20	-4.77										
2991.73	64.80	15.12	6.25	-4.82										
2991.75	64.80	16.20	6.30	-4.87										
2991.77	64.80	17.28	6.35	-4.92										
2991.78	64.80	18.36	6.40	-4.97										
2991.80	64.80	19.44	6.48	-5.05										

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
2991.82	64.80	20.52	6.54	-5.11										
2991.83	64.80	21.60	6.60	-5.17										
2991.85	64.80	22.68	6.66	-5.23										
2991.87	64.80	23.76	6.70	-5.27										
2991.88	64.80	24.84	6.75	-5.32										
2991.90	64.80	25.92	6.78	-5.35										
2991.92	64.80	27.00	6.79	-5.38										
2991.93	64.80	28.08	6.80	-5.42										
2991.95	64.80	29.16	6.80	-5.46										
2991.97	64.80	30.24	6.81	-5.50										
2991.98	64.80	31.32	6.82	-5.55										
2992.00	64.80	32.40	6.84	-5.60										
2992.25	60.10	47.43	6.83	-5.87										
2992.50	60.10	62.46	6.80	-6.03	1.37	-0.13								
2993.00	60.10	92.51	6.82	-6.30										
2993.50	60.10	122.56	6.84	-6.30										
2994.50	54.54	177.10	6.85	-6.39										
2995.50	54.54	231.64	6.87	-6.51	1.37	-0.13								
2998.50	54.54	395.80	6.89	-6.52										
3001.50	54.54	559.96	6.90	-6.96	1.40	-0.16								
3004.50	54.54	724.12	6.94	-7.05	1.40	-0.16								
3007.50	54.54	888.28	6.97	-7.10	1.42	-0.18								

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
3010.50	54.54	1052.44	7.01	-7.17	1.43	-0.19								
3013.50	54.54	1216.60	7.05	-7.19	1.45	-0.21								
3016.50	54.54	1380.76	7.10	-7.22	1.46	-0.22								
Discharge stops from 1672.50 h to 2103.5 h														
3447.50	0.00	1380.76	1.70	-0.27	1.35	-0.11								
3448.50	54.54	1435.30	3.60	-2.17	1.37	-0.13								
3449.50	54.54	1489.84	5.45	-4.02	1.38	-0.14								
3450.50	54.54	1544.38	6.55	-5.55	1.39	-0.15								
3453.50	54.54	1708.54	6.75	-6.22	1.43	-0.19								
3456.50	54.54	1872.70	6.85	-6.51	1.48	-0.24								
3459.50	54.54	2036.86	7.09	-6.80	1.50	-0.26								

Recharge (Fifth Cycle), BSV = 14000 m^3 & $\bar{t}$ = 2712 h

Time	q_i (m^3/h)	V_i (m^3)	dwp	Rise in dwp	dwo$_{10}$	Rise in dwo$_{10}$	dwo$_5$	Rise in dwo	dwo$_{25}$	Rise in dwo	dwo$_{50}$	Rise in dwo	dwo$_{100}$	Rise in dwo
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
3459.50	0.00	0.00	2.36	0.00	1.35	0.00								
3459.52	11.52	0.19	2.11	0.25										
3459.53	11.52	0.38	1.95	0.41										
3459.55	11.52	0.58	1.82	0.54										
3459.57	11.52	0.77	1.73	0.63										
3459.58	11.52	0.96	1.65	0.71										
3459.60	11.52	1.15	1.57	0.79										
3459.62	11.52	1.34	1.52	0.84										
3459.63	11.52	1.54	1.49	0.87										
3459.65	11.52	1.73	1.46	0.90										
3459.67	11.52	1.92	1.43	0.93										
3459.68	11.52	2.11	1.41	0.95										
3459.70	11.52	2.30	1.39	0.97										
3459.72	11.52	2.50	1.36	1.00										
3459.73	11.52	2.69	1.34	1.02										
3459.75	11.52	2.88	1.32	1.04										
3459.77	11.52	3.07	1.30	1.06										
3459.78	11.52	3.26	1.28	1.08										
3459.80	11.52	3.46	1.27	1.09										

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
3459.82	11.52	3.65	1.25	1.11										
3459.83	11.52	3.84	1.25	1.11										
3459.85	11.52	4.03	1.24	1.12										
3459.87	11.52	4.22	1.23	1.13										
3459.88	11.52	4.42	1.21	1.15										
3459.90	11.52	4.61	1.20	1.16										
3459.92	11.52	4.80	1.20	1.16										
3459.93	11.52	4.99	1.20	1.16										
3459.95	11.52	5.18	1.19	1.17										
3459.97	11.52	5.38	1.19	1.17										
3459.98	11.52	5.57	1.19	1.17										
3460.00	11.52	5.76	1.19	1.17										
3460.25	11.52	8.64	1.09	1.27										
3460.50	11.52	11.52	1.05	1.31										
3461.00	11.52	17.28	1.00	1.36										
3461.50	10.80	22.68	0.98	1.38	1.32	0.03								
3462.50	10.80	33.48	0.97	1.39										
3463.50	10.80	44.28	0.96	1.40										
3469.50	10.80	109.08	0.94	1.42	1.29	0.06								
3475.50	10.80	173.88	0.92	1.44										
3481.50	10.80	238.68	0.89	1.47	1.15	0.20								
3487.50	10.80	303.48	0.88	1.48	1.14	0.21								

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1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
3493.50	10.80	368.28	0.86	1.50	1.18	0.17								
3499.50	10.80	433.08	0.84	1.52	1.09	0.26								
3505.50	10.80	497.88	0.82	1.54	1.07	0.28								
3511.50	10.80	562.68	0.82	1.54	1.09	0.26								
3517.50	10.80	627.48	0.81	1.55	1.11	0.24								
3523.50	10.80	692.28	0.81	1.55	1.09	0.26								
3529.50	10.80	757.08	0.80	1.56	1.08	0.27								
3535.50	10.80	821.88	0.79	1.57	1.07	0.28								
3541.50	8.64	873.72	0.79	1.57	1.05	0.30								
3547.50	8.64	925.56	0.78	1.58	1.05	0.30								
3553.50	8.64	977.40	0.76	1.60	1.03	0.32								
3559.50	8.64	1029.24	0.77	1.59	1.03	0.32								
3565.50	8.64	1081.08	0.78	1.58	1.05	0.30								
3571.50	8.64	1132.92	0.79	1.57	1.05	0.30								
Recharge with tubewell from 2231.5 - 2234.5														
3577.50	8.64	1184.76	1.09	1.27	1.28	0.07								
3583.50	8.64	1236.60	0.96	1.40	1.19	0.16								
3589.50	8.64	1288.44	0.94	1.42	1.14	0.21								
3595.50	8.64	1340.28	0.95	1.41	1.24	0.11								
3601.50	8.64	1392.12	0.93	1.43	1.30	0.05								
3607.50	8.28	1441.80	0.92	1.44	1.34	0.01								
3613.50	8.28	1491.48	0.92	1.44		1.35								

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Recharge with tubewell from 2275.5 - 2287.5														
3619.50	8.28	1541.16	0.95	1.41	1.51	-0.16								
3625.50	8.28	1590.84	1.23	1.13	1.60	-0.25								
3631.50	8.28	1640.52	1.39	0.97	1.64	-0.29								
3637.50	8.28	1690.20	1.18	1.18	1.71	-0.36								
Recharge stopped from 2297.5 to 2302.5														
3643.50	8.28	1723.32	1.45	0.91	1.47	-0.12								
3649.50	8.28	1748.16	1.12	1.24	1.38	-0.03								
Recharge with canal water from 2311.5 - till end														
3655.50	8.28	1797.84	0.88	1.48	1.19	0.16								
3661.50	8.28	1847.52	0.83	1.53	1.13	0.22								
3667.50	8.28	1897.20	0.85	1.51	1.07	0.28								
3673.50	8.28	1946.88	0.84	1.52										
3679.50	8.28	1996.56			1.25	0.10								

				Discharge (Fifth Cycle)				2712h storage time (t_s)				Canal not flowing		
Time	q_r (m^3/h)	V_r	dwp	Fall in dwp	dwo$_{10}$	Fall in dwo$_{10}$	dwo$_5$	Fall in dwo	dwo$_{25}$	Fall in dwo	dwo$_{50}$	Fall in dwo	dwo$_{100}$	Fall in dwo
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
6391.50	0.00	0.00	2.10	0.00										
6391.52	64.80	1.08	2.90	-0.80										
6391.53	64.80	2.16	3.88	-1.78										
6391.55	64.80	3.24	4.30	-2.20										
6391.57	64.80	4.32	5.00	-2.90										
6391.58	64.80	5.40	5.39	-3.29										
6391.60	64.80	6.48	5.70	-3.60										
6391.62	64.80	7.56	6.00	-3.90										
6391.63	64.80	8.64	6.33	-4.23										
6391.65	64.80	9.72	6.57	-4.47										
6391.67	64.80	10.80	6.71	-4.61										
6391.68	64.80	11.88	6.85	-4.75										
6391.70	64.80	12.96	6.96	-4.86										
6391.72	64.80	14.04	7.08	-4.98										
6391.73	64.80	15.12	7.17	-5.07										
6391.75	64.80	16.20	7.19	-5.09										
6391.77	64.80	17.28	7.21	-5.11										
6391.78	64.80	18.36	7.24	-5.14										
6391.80	64.80	19.44	7.30	-5.20										

XXXXXXIII

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
6391.82	64.80	20.52	7.36	-5.26										
6391.83	64.80	21.60	7.40	-5.30										
6391.85	64.80	22.68	7.44	-5.34										
6391.87	64.80	23.76	7.48	-5.38										
6391.88	64.80	24.84	7.52	-5.42										
6391.90	64.80	25.92	7.55	-5.45										
6391.92	64.80	27.00	7.58	-5.48										
6391.93	64.80	28.08	7.61	-5.51										
6391.95	64.80	29.16	7.64	-5.54										
6391.97	64.80	30.24	7.68	-5.58										
6391.98	64.80	31.32	7.71	-5.61										
6392.00	64.80	32.40	7.74	-5.64										
6392.25	60.10	47.43	8.01	-5.91										
6392.50	60.10	62.46	8.20	-6.10										
6393.00	60.10	92.51	8.41	-6.31										
6393.50	60.10	122.56	8.47	-6.37										
6394.50	54.54	177.10	8.58	-6.48										
6395.50	54.54	231.64	8.65	-6.55										
6398.50	54.54	395.80	8.60	-6.50										
6401.50	54.54	559.96	8.59	-6.49										
6404.50	54.54	724.12	8.55	-6.45										
6407.50	54.54	888.28	8.52	-6.42										

XXXXXXIV

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
6410.50	54.54	1052.44	8.54	-6.44										
6413.50	54.54	1216.60	8.56	-6.46										
6416.50	54.54	1380.76	8.60	-6.50										
6419.50	54.54	1544.92	8.66	-6.56										
6422.50	54.54	1709.08	8.72	-6.62										
6425.50	54.54	1873.24	8.80	-6.70										
6428.50	54.54	2037.40	8.94	-6.84										

Recharge (Sixth Cycle), BSV - 14000 m^3, $\bar{t}$ = 2724 h

Recharge with canal water

Time	q_i (m^3/h)	V_i (m^3)	dwp	Rise in dwp	dwo$_{10}$	Rise in dwo$_{10}$	dwo$_5$	Rise in dwo	dwo$_{25}$	Rise in dwo	dwo$_{50}$	Rise in dwo	dwo$_{100}$	Rise in dwo
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
6428.50	0.00	0.00	2.40	0.00										
6428.52	11.52	0.19	2.25	0.15										
6428.53	11.52	0.38	2.18	0.22										
6428.55	11.52	0.58	2.09	0.31										
6428.57	11.52	0.77	2.01	0.39										
6428.58	11.52	0.96	1.95	0.45										
6428.60	11.52	1.15	1.92	0.48										
6428.62	11.52	1.34	1.88	0.52										
6428.63	11.52	1.54	1.86	0.54										
6428.65	11.52	1.73	1.85	0.55										
6428.67	11.52	1.92	1.84	0.56										
6428.68	11.52	2.11	1.84	0.56										
6428.70	11.52	2.30	1.83	0.57										
6428.72	11.52	2.50	1.82	0.58										
6428.73	11.52	2.69	1.81	0.59										
6428.75	11.52	2.88	1.81	0.59										
6428.77	11.52	3.07	1.80	0.60										
6428.78	11.52	3.26	1.79	0.61										
6428.80	11.52	3.46	1.79	0.61										

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
6428.82	11.52	3.65	1.79	0.61										
6428.83	11.52	3.84	1.79	0.61										
6428.85	11.52	4.03	1.78	0.62										
6428.87	11.52	4.22	1.78	0.62										
6428.88	11.52	4.42	1.78	0.62										
6428.90	11.52	4.61	1.78	0.62										
6428.92	11.52	4.80	1.77	0.63										
6428.93	11.52	4.99	1.77	0.63										
6428.95	11.52	5.18	1.77	0.63										
6428.97	11.52	5.38	1.77	0.63										
6428.98	11.52	5.57	1.77	0.63										
6429.00	11.52	5.76	1.76	0.64										
6429.25	10.80	8.46	1.75	0.65										
6429.50	10.80	11.16	1.74	0.66										
6430.00	10.80	16.56	1.74	0.66										
6430.50	10.80	21.96	1.74	0.66										
6431.50	10.80	32.76	1.74	0.66										
6432.50	10.80	43.56	1.74	0.66										
6438.50	10.80	108.36	1.70	0.70										
6444.50	10.80	173.16	1.67	0.73										
6450.50	10.80	237.96	1.77	0.63										
6456.50	10.80	302.76	1.74	0.66										

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
6462.50	10.80	367.56	1.7	0.7										
6468.50	10.80	432.36	1.67	0.73										
6474.50	10.80	497.16	1.64	0.76										
6480.50	10.80	561.96	1.57	0.83										
6486.50	10.80	626.76	1.53	0.87										
6492.50	10.80	691.56	1.49	0.91										
6498.50	10.80	756.36	1.49	0.91										
6504.50	10.80	821.16	1.47	0.93										
6510.50	8.64	873.00	1.45	0.95										
6516.50	8.64	924.84	1.42	0.98										
6522.50	8.64	976.68	1.44	0.96										
6528.50	8.64	1028.52	1.44	0.96										
6534.50	8.64	1080.36	1.43	0.97										
6540.50	8.64	1132.20	1.43	0.97										
6546.50	8.64	1184.04	1.43	0.97										
6552.50	8.64	1235.88	1.41	0.99										
6558.50	8.64	1287.72	1.41	0.99										
6564.50	8.64	1339.56	1.42	0.98										
6570.50	8.64	1391.40	1.41	0.99										
6576.50	8.28	1441.08	1.40	1.00										
6582.50	8.28	1490.76	1.40	1.00										
6588.50	8.28	1540.44	1.40	1.00										

XXXXXXVII

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
6594.50	8.28	1590.12	1.40	1.00										
6600.50	8.28	1639.80	1.40	1.00										
6606.50	8.28	1689.48	1.38	1.02										
6612.50	8.28	1739.16	1.37	1.03										
6618.50	8.28	1788.84	1.36	1.04										
6624.50	8.28	1838.52	1.36	1.04										
6630.50	8.28	1888.20	1.33	1.07										
6636.50	8.28	1937.88	1.32	1.08										
6642.50	8.28	1987.56	1.33	1.07										

	Discharge (Sixth Cycle)				2586 h storage time (t_s)									
Time	q_r (m^3/h)	V_r	dwp	Fall in dwp	dwo_{10}	Fall in dwo_{10}	dwo_5	Fall in dwo	dwo_{25}	Fall in dwo	dwo_{50}	Fall in dwo	dwo_{100}	Fall in dwo
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
9228.50	0.00	0.00	2.29	0.00										
9228.52	64.80	1.08	2.90	-0.61										
9228.53	64.80	2.16	3.63	-1.34										
9228.55	64.80	3.24	4.40	-2.11										
9228.57	64.80	4.32	5.05	-2.76										
9228.58	64.80	5.40	5.56	-3.27										
9228.60	64.80	6.48	5.98	-3.69										
9228.62	64.80	7.56	6.30	-4.01										
9228.63	64.80	8.64	6.59	-4.30										
9228.65	64.80	9.72	6.84	-4.55										
9228.67	64.80	10.80	7.00	-4.71										
9228.68	64.80	11.88	7.18	-4.89										
9228.70	64.80	12.96	7.32	-5.03										
9228.72	64.80	14.04	7.45	-5.16										
9228.73	64.80	15.12	7.54	-5.25										
9228.75	64.80	16.20	7.64	-5.35										
9228.77	64.80	17.28	7.71	-5.42										
9228.78	64.80	18.36	7.79	-5.50										
9228.80	64.80	19.44	7.87	-5.58										

XXXXXXX

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
9228.82	64.80	20.52	7.95	-5.66										
9228.83	64.80	21.60	8.00	-5.71										
9228.85	64.80	22.68	8.07	-5.78										
9228.87	64.80	23.76	8.13	-5.84										
9228.88	64.80	24.84	8.21	-5.92										
9228.90	64.80	25.92	8.25	-5.96										
9228.92	64.80	27.00	8.30	-6.01										
9228.93	64.80	28.08	8.36	-6.07										
9228.95	64.80	29.16	8.42	-6.13										
9228.97	64.80	30.24	8.47	-6.18										
9228.98	64.80	31.32	8.51	-6.22										
9229.00	64.80	32.40	8.55	-6.26										
9229.25	60.10	47.43	8.94	-6.65										
9229.50	60.10	62.46	9.03	-6.74										
9230.00	60.10	92.51	9.27	-6.98										
9230.50	60.10	122.56	9.31	-7.02										
9231.50	54.54	177.10	9.35	-7.06										
9232.50	54.54	231.64	9.39	-7.10										
9235.50	54.54	395.80	9.46	-7.17										
		Canal Flow starts at 6658.5												
9238.50	54.54	559.96	9.48	-7.19										
9241.50	54.54	724.12	9.21	-6.92										

														XXXXXXXI
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
9244.50	54.54	888.28	9.23	-6.94										
9247.50	54.54	1052.44	9.25	-6.96										
9250.50	54.54	1216.60	9.25	-6.96										
9253.50	54.54	1380.76	9.26	-6.97										
9256.50	54.54	1544.92	9.26	-6.97										
9259.50	54.54	1709.08	9.27	-6.98										
9262.50	54.54	1873.24	9.29	-7.00										
9265.50	54.54	2037.40	9.25	-6.96										

ABSTRACT

Title of Thesis : **Effect of buffer storage volume and storage time on brackish ASR well recovery behaviour**

Full name of degree holder : **VISHAL GOYAL**

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Year of award of degree : 2004-05

Major Subject : Soil Science

Total number of pages in thesis : 1-68, i-xi, I-XXXXXXXI

Number of words in abstract : 250 approximate

Key Words : ASR cavity well, Buffer storage volume, Storage time, Recovery efficiency, Simulation

Canal water was gravity injected to create buffer storage volume BSV of 6000, 10000 and 14000 m^3 in 1, 2 and 3 ASR cycle employing siphon system under shallow water table depth. Residence times of 70.8, 118.35 and 113.2 days were allowed at a BSV of 14000 m^3 in 4th, 5th and 6th ASR cycle. Injection rates decreased from 23.23 $m^3 h^{-1}$ to 13.29 $m^3 h^{-1}$ while recovery rates remained constant in each cycle at average value of 60.21 $m^3 h^{-1}$. The integrated recovery efficiency CRE increased with BSV linearly. The CRE was 108 % at BSV of 14000 m^3 after residence time of 13.55 days. Recovery efficiency decreased with increasing residence time.

Simple mixing $M^*(Cl^-)$ increased with recovery percentage (I) for all the quality parameters. It decreased linearly with BSV and increased with residence time. Calcite dissolution decreased with BSV and increased with residence time of 70.8 days. For one irrigation of 0.06 m, 9 kg of potassium could be added through irrigation from 1st ASR cycle.

The HYDRUS-2D simulated the drawup and drawdown in piezometric pressure heads successfully during recharge and recovery in Aquifer Storage and recovery (ASR) cycles. Radial influencing zone increased with BSV with a mean

value of 122 m during recharge. The model projected the decrease in radial influencing zone with increase in aquifer anisotropy and increasing length of sand patch in the confining layer. The study suggests that hydrus 2D may be adopted for simulations in ground water recharge studies in ASR well.

13-5 7/2/05

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