MODELLING OF GROUNDWATER RECHARGE IN BRACKISH AQUIFER STORAGE RECOVERY WELLS

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 **"Modelling of groundwater recharge in brackish aquifer storage recovery wells"**, submitted for the degree of **Doctor of Philosophy** in the subject of **Soil Science** of the Chaudhary Charan Singh Haryana Agricultural University, Hisar, is a bonafide research work carried out by **Yashpal Singh Saharawat,** Admn. No. **2000A50D** 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 **"Modelling of groundwater recharge in brackish aquifer storage recovery wells"**, submitted by **Yashpal Singh Saharawat** Admn. No. **2000A50D** to the Chaudhary Charan Singh Haryana Agricultural University, Hisar in partial fulfilment 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 on the same, in collaboration with an External Examiner.

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DEAN, POST-GRADUATE STUDIES

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Hisar **(Yashpal Singh Saharawat)**

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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, 1999; Herezeg *et al.*, 2000; Vanderzalm *et al.*, 2002). The ASR well is a dual purpose well sequentially used for both excess water recharge in aquifer and for recovery of that 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.*, 2002 a) 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.*, 2002 a) at relatively small cost. The economic development of ASR for improving native water quality is dependent upon recovery behaviour of the recharged 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 recharged (Pyne, 1995). The RE is governed by movement and mixing of injected water in aquifer. The hydrogeological and operational factors, 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. Operational factors include quality of injected water, critical target water quality, successive number of ASR cycles, storage time, buffer storage volume and ratio of recovery to recharge rate.

However, success of ASR operations in such areas depends on availability of good quality water for recharge 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 recharged 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 ranges 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 exploitation 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.*, 2002 a), 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.*, 2002 a). 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 geo-chemical 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 Vecchoili, 1974; Booch 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 reducing 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 successive number of cycles 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. In this study, scientifically documented and evaluated (Diodato, 2000), HYDRUS-2D software package of Simunek *et al.* (1996) and PMWIN of Chiang and Kinzelbach (1996) have been used. HYDRUS-2D is having extensive interface capabilities for simulating saturated and unsaturated water, solute and heat flow under bare and cropped conditions. PMWIN is a three dimensional, complete simulation system for modelling groundwater flow (with MODFLOW of McDonald and Harbough, 1988) and solute transport process (with MT3D of Zheng, 1990). Both the models are well suited for field heterogeneities and would be used to predict the water level responses, solute transport and their mixing in a cavity type ASR well on short term and long term basis.

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

O1. To quantify the effect of number of successive cycles on (I) Rise and fall of water pressures (II) Physical and chemical interactions between brackish native and fresh injected water in ASR wells.

O2. To calibrate and validate the applicability of Hydrus-2D (H2D) model on ground water recharge and interactions.

O3. To test the efficacy of different types of horizontal filters on reducing the sedimentation load.

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 reasonable 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 trial. 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-physicochemical interaction

2.3 Modelling of groundwater recharge and solute transport

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). RE 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 Vechiolli, 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 to the situation where fresh water is injected into more saline aquifer (Ragone and Vechiolli, 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 Vechiolli, 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 this process is clogging, bacterial activity, ion exchange, adsorption, dissolution and precipitation.

2.2.1. 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 bio-fouling. 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 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.*, 1998). 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.

2.2.3. ION EXCHANGE

The ion exchange between aquifer soil and its water is governed by the concentration and valency of the cations. Pearson and Friedman (1971) 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 Vechiolli, 1975). Calcium replacement on exchange complex would increase hydraulic conductivity and Na^+ on exchange complex reduce the aquifer hydraulic conductivity. Ca^{2+} replaces Na^+ on the clay lattice in a saline groundwater during injection process (Hamlin, 1987).

2.2.4. DISSOLUTION

Dissolution of calcite by injecting low pH rainwater is important for increasing the calcium ion concentration. It may improve the tranmissivity of the aquifer and also improve the quality of the water for irrigation. Pearson and Friedman (1971) 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 decreased borate in recovered water. Storage of recharged water 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).

2.2.5. OXIDATION AND REDUCTION PROCESSES

Oxidation and reduction reaction processes becomes evident with the onset of injection phase and the deviation from the recharged water quality are indicative of the reactive processes. Ragone and Vechiolli (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~~d~~ within 4 m from the injection well. Up to 90 % reduction in total-N at some sites of Florida have 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.

2.3. MODELLING OF GROUNDWATER RECHARGE AND SOLUTE TRANSPORT

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 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.

Modelling water pressure 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 developed 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.

In this study, scientifically documented and evaluated (Diodato, 2000), HYDRUS-2D software package of Simunek *et al.* (1996) and PMWIN of Chiang and Kinzelbach (1996) have been used. HYDRUS-2D is having extensive interface capabilities for simulating saturated and unsaturated water, solute and heat flow under bare and cropped conditions. PMWIN is a three dimensional, complete simulation system for modelling groundwater flow (with MODFLOW of McDonald and Harbough, 1988) and solute transport process (with MT3D of Zheng, 1990). Both the models are well suited for field heterogeneities and would be used to predict the water level responses, solute transport and their mixing in a cavity type ASR well on short term and long term basis.

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. 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. Bristow *et al.* (2002) used HYDRUS-2D model to analyse impacts of soil properties, soil profile features on water and solute transport in irrigation systems and suggested that nutrients (nitrates) maintained near to and above the trickle emitter are more available to plants and less susceptible to leaching. Asghar *et al.* (2002) calibrated and validated PMWIN (Chiang and Kinzelbach, 1996) for water and solute transport for extracting fresh groundwater from salty groundwater aquifers by installing skimming wells. PMWIN can be successfully calibrated and validated for water and solute transport in scavenger wells (Ghulam Ali, *et al.*, 2004), canal seepages (Prasad *et al.*, 2001), stream-aquifer seepages in alluvial aquifers (Osman and Bruen, 2002).

Chapter III

Materials and Methods

Field studies to investigate the effect of successive number of cycles on ground water recharge and recovery efficiency were carried out in cavity type of ASR wells located at 1. Soil Research Farm, CCS HAU, Hisar, and 2. Regional Research Station (RRS), Balsamand. The effect of check barriers on reducing the sedimentation load was studied at Regional Research Centre, Sirsa.

Materials and methods at the above sites are presented under following subheadings.

3.1 Hydrogeology

3.2 ASR Facilities

3.3 Soil and water characterization

3.4 Numerical experiments

    3.4.1. Parameter estimation

    3.4.2. Statistical test

3.5. Filter study

3.1 HYDROGEOLOGY

The Haryana (India) soils are very deep >200m 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 L s^{-1} to 30 L s^{-1}; and deep aquifers in the quartzite and limestone in the depth range of 136 to 450m with well yield in the range of 1.5 L s^{-1} 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 sites of highly brackish native water was selected at Soil Research Farm, Hisar and RRS, Balsamand, Haryana, India (28°59' to 29°49' N latitude and 75°11' to 76°18' longitude at an elevation of 215m above mean sea level) where irrigation cavity type wells were installed with the recharge facility through a submersible pumps by removing the check valve permanently while installing the pump. The inner pipe diameter and outer pipe diameters were 0.075m and 0.275m at Hisar ASR well and 0.025m and 0.075m at Balsamand ASR site (Plate 1,2). The relevant ASR sites characteristics are given in Table 3.1.

Table 3.1: Relevant ASR sites characteristics

Hisar ASR site	Value	Balsamand ASR site	Value
Native water EC	28.4 dSm^{-1}	Native water EC	28.7 dSm^{-1}
Recharge water EC	0.50 dSm^{-1}	Recharge water EC	0.35 dSm^{-1}
pH of native water	8.4	pH of native water	7.90
pH of recharge water	7.65	pH of recharge water	7.40
Thickness of aquifer	15.0 m	Thickness of aquifer	3.0 m
Average depth of water table	1.2 m	Average depth of water table	22 m

The sites lithology and schematic diagrams of ASR facility at Hisar and Balsamand are shown in Figure 3.1. At Hisar ASR site water from canal was gravity recharged into cavity type ASR well in four successive ASR cycles employing siphon system. Completion of a recharge and recovery makes one cycle. In each cycle the volume recharged (V_i *) and recovered (V_i) was kept as 2000 m^3. At Balsamand ASR site good quality water was transported through underground water supply pipes for three successive ASR cycles and

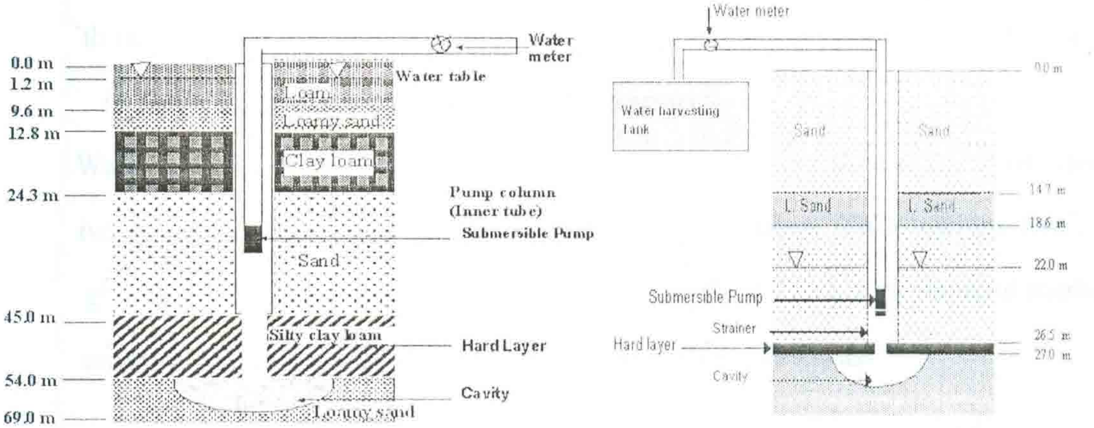
Plate 1: ASR Well Soil Research Farm, Hisar

Plate 2: ASR Well RRS, Balsamand

was gravity recharged employing siphon system. Residence time $\bar{t}$ was estimated for each cycle as:

$$\bar{t} = 0.5\,(t_i + t_r) + t_s \qquad (1)$$

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



Hisar Balsamand

Figure 3.1: Schematic diagrams of ASR wells

The detail of the successive ASR cycle test programme adopted in the study at Hisar and Balsamand is given in Table3.2.

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

Cycle number	Hisar					Balsamand				
	V_i* (m^3)	V_i (m^3)	$\bar{t}$ (d)	t_i (d)	t_r (d)	V_i* (m^3)	V_i (m^3)	t_i (d)	$\bar{t}$ (d)	t_r (d)
1	2000	2000	6	5	4	300	450	10	15	20
2	2000	2000	6	5	4	300	150	10	9.5	9
3	2000	2000	6	5	4	300	150	10	9.5	9
4	2000	2000	6	5	4	-	-	-	-	-

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

Storage time was kept zero in each cycle

3.3 SOIL AND WATER CHARACTERIZATION

Soil samples from different layers taken during the installation of ASR wells and 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 physicochemical properties. Soil analysis was done with the standard methods. The relevant physicochemical properties up to the aquifer are given in Table 3.3 of Hisar and Table 3.4 of Balsamand.

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-

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

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

3.4 NUMERICAL EXPERIMENTS

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

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x_i}\left[K\left(K_{ij}^{A}\frac{\partial h}{\partial x_j} + K_{iz}\right)\right] - S \tag{3}$$

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 ($L\ T^{-1}$).

Transport of a single ion in porous medium is described by the polar co-ordinates form of the widely used advection-dispersion equation (ADE) (Bear, 1972).

$$\frac{\partial(\theta C)}{\partial t} = \frac{\partial}{\partial r}\left(\theta D_{rr}\frac{\partial C}{\partial r} + \theta D_{rr}\frac{\partial C}{\partial z}\right) + \frac{1}{r}\left(\theta D_{rr}\frac{\partial C}{\partial r} + \theta D_{rz}\frac{\partial C}{\partial z}\right) + \frac{\partial}{\partial z}\left(\theta D_{zz}\frac{\partial C}{\partial z} + \theta D_{rz}\frac{\partial C}{\partial r}\right) - \left(\frac{\partial q_r C}{\partial r} + \frac{q_r C}{r} + \frac{\partial q_z C}{\partial z}\right) \tag{4}$$

where C is solute concentration in the soil water [ML^3], D_{rr}, D_{rz} and D_{zz} are the components of the dispersion tensor [L^{2}T^{-1}], The components are described by Bear (1972). Solution of ADE requires the knowledge of initial concentration within the flow region, concentration of recharged water as well as the solute transport properties.Third type of boundary condition (Cauchy type) used to prescribe the concentration flux along the cavity boundary condition. The equation for this is given as:

$$-\theta D_{ij}\frac{\partial C}{\partial x_j}n_i + q_i n_i C = q_i n_i C_0 \qquad (5)$$

where, $q_i n_i$ represent the outward fluid flux, n_i is the outward unit normal vector and C_o is the concentration of incoming fluid .

Processing MODFLOW for windows (PMWIN) (Chiang and Kinzelbach, 1996) is a complete simulation system for modelling groundwater flow and solute transport processes. This software is easy to use and maintain. The PMWIN combines (MODFLOW) for groundwater flow and (MT3D) for solute transport model. The MODFLOW, is a 3-D finite difference groundwater flow model, can simulate and predict the hydraulic behaviour of groundwater aquifers. Boundary conditions include specified head, specific flux, and head-dependent flux. The MT3D, is also a 3D finite difference groundwater solute transport model based on dispersion approach, can simulate and predict solute transport behaviour of groundwater aquifers. MT3D works independently of MODFLOW.

Table 3.3: Relevant soil physicochemical properties of Hisar ASR site

Depth (m)	EC (dS m^{-1})	pH	Texture	$CaCO_3$ (%)	Calcite 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

Table 3.4: Relevant soil physico-chemical properties at Balsamand ASR site

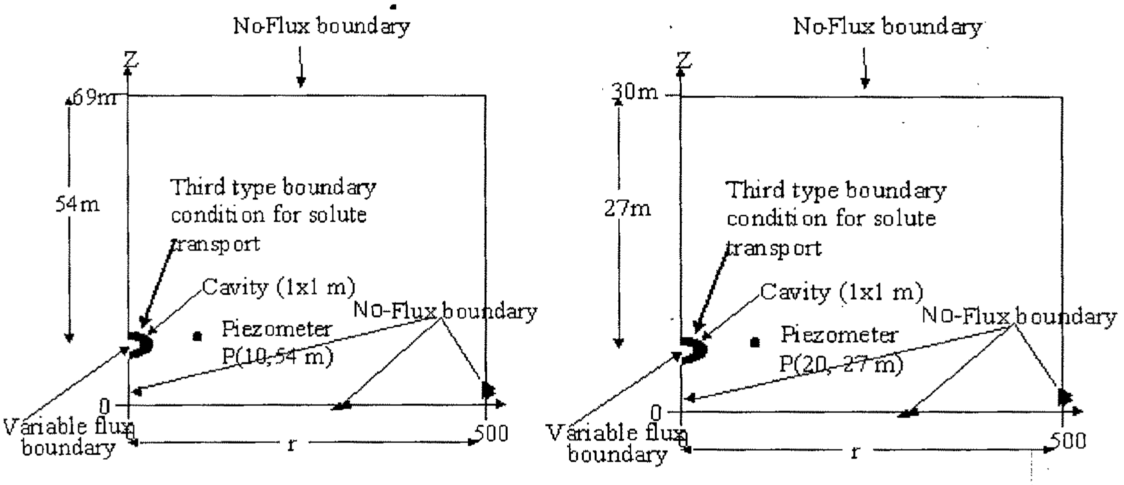
Depth (m)	EC (dS m^{-1})	pH	Texture	$CaCO_3$ (%)	Calcite concretion (%)	Gypsum (%)
0.0-14.7	3.1	7.8	Sand	1.4	12.0	0.014
14.7-18.6	2.9	8.3	Loamy sand	1.5	33	0.015
18.6-26.5	2.2	7.2	Sand	7.6	17.6	0.020
26.5-27.0	2.7	7.8	Sandy Loam	0.7	3.5	0.015
27.0-30.0	2.6	7.9	Loamy Sand	1.4	3.8	0.014

Calibration of HYDRUS-2D model was done for first cycle during water and solute transport using inverse modeling on hydraulic and diffusion coefficient parameters at both ASR sites. Validation was done for the next three successive ASR cycles at Hisar and two successive ASR cycles at Balsamand ASR site by HYDRUS-2D. HYDRUS-2D calibrated parameters were used in PMWIN for validation studies in successive ASR cycles. In total eight HYDRUS-2D runs were carried out at Hisar and six at Balsamand for simulating drawup and drawdown of piezometric pressure heads and solute transport in recovered water in successive ASR cycles as given in Table 3.5.

The physical flow region involved a soil profile 500 m wide at both sites and 69 m deep at Hisar and 30 m deep at Balsamand with an exocentric elliptical cavity of 1m horizontal radius and 1m vertical radius at 54 m depth at Hisar and 27 m depth at Balsamand as shown in figure 3.2. No flux boundary condition was given at soil surface, bottom and lateral sides of the flow regions. At cavity variable flux boundary condition was assigned for water flow and third type of boundary condition solute transport (Figure 3.2). Piezometers served as the observation nodes at the position shown in figure 3.2.

Table 3.4: Hydraulic parameters used in numerical experiments at Hisar (H) and Balsamand (B) ASR sites

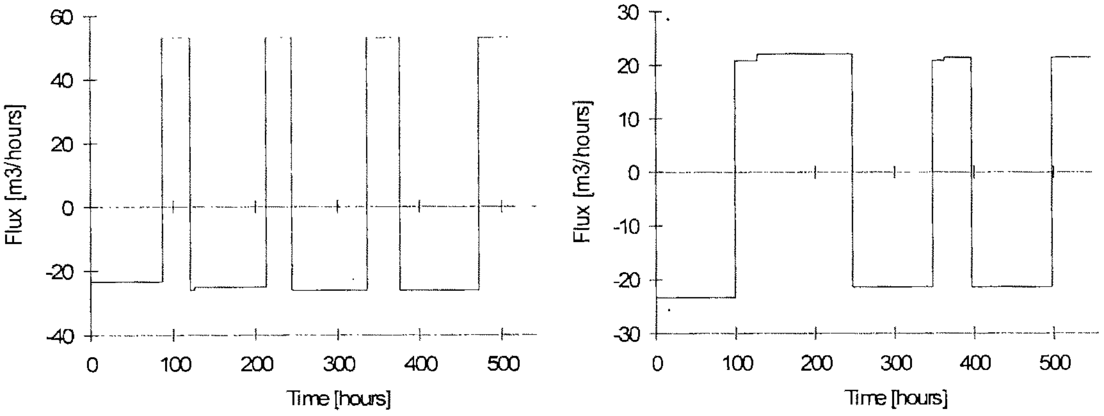
Parameter		θr (m^3m^{-3})		θs ($m^3 m^{-3}$)		α (m^{-1})		n		K_s (m d^{-1})		Dw (m^2h^{-1})	
H	B	H	B	H	B	H	B	H	B	H	B	H	B
Loam (M1)	Sand (M1)	0.032	0.014	0.47	0.53	0.050	0.08	2.6	2.6	0.8040	0.297	0.00057	0.00059
Loamy Sand M2)	Loamy sand (M2)	0.052	0.052	0.43	0.41	0.100	0.13	2.9	2.2	0.7290	0.145	0.00057	0.00059
Clay (M3)	Sand (M3)	0.075	0.045	0.54	0.43	0.015	0.015	2.5	2.6	0.0064	0.297	0.00057	0.00059
Loamy sand (M4)	Silty clay loam (M4)	0.065	0.057	0.52	0.41	0.014	0.001	2.2	2.2	0.072	0.0001	0.00057	0.00059
Silty clay loam (M5)	Loamy Sand (M5)	0.066	0.045	0.53	0.43	0.001	0.06	2.1	1.6	0.0002	0.52	0.00057	0.00059
Loamy Sand (M6)	-	0.052	-	0.40	-	0.070	-	2.9	-	0.2100		0.00057	



Hisar **Balsamand**

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

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



Hisar **Balsamand**

Figure 3.3: Recharge (-ve) and recovery fluxes (+ve) in successive cycles at ASR sites

3.4.1. 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:

$$\theta(h) = \frac{\theta s - \theta r}{[1+|\alpha h|^{n}]^{m}} \qquad h<0 \tag{6}$$

$$\theta(h) = \theta s \qquad h\geq 0 \tag{7}$$

$$K(h) = KsSe^{k}\left[1-\left(1-Se^{k/m}\right)^{m}\right] \tag{8}$$

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= (θ- θr)/ (θs- θr) 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 and diffusion coefficient was estimated through inverse modelling technique using the experimental pressure heads h from a piezometer (z = 54 m, r = 10m) at Hisar and from a piezometer (z = 27 m, r = 20m) at Balsamand; and recovered water solute (Cl^{-}) concentration as time pairs during the first ASR cycle at both ASR sites by using the observed θr, θs, α, n, and m as fixed parameters. Estimation of hydraulic parameter and diffusion coefficient through inverse modeling has become an accepted technique under field condition (Asghar *et al.,* 2002; Van Dam and Malik, 2003 and Ghulam Ali *et al.,* 2004). The hydraulic parameters and diffusion coefficient values are given in table 3.4 and figure 3.4 (a & b) for Hisar and figure 3.5 (a & b) for Balsamand.

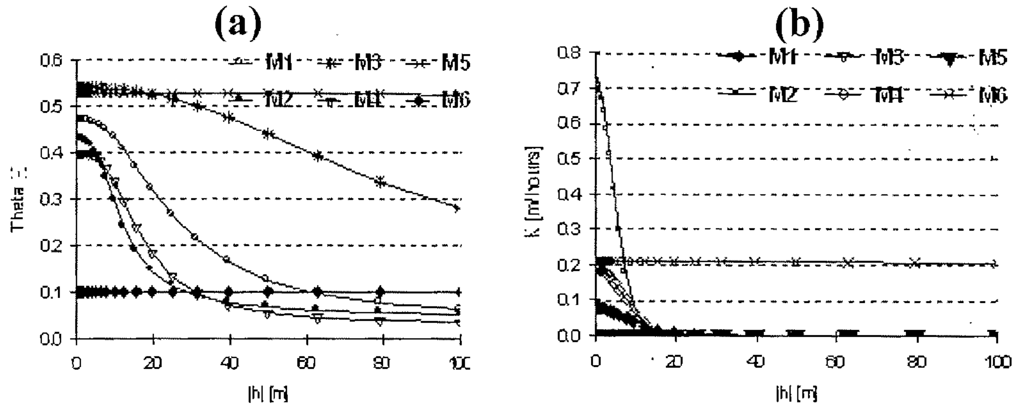


Figure 3.4: Soil hydraulic properties for lithology at Hisar ASR site

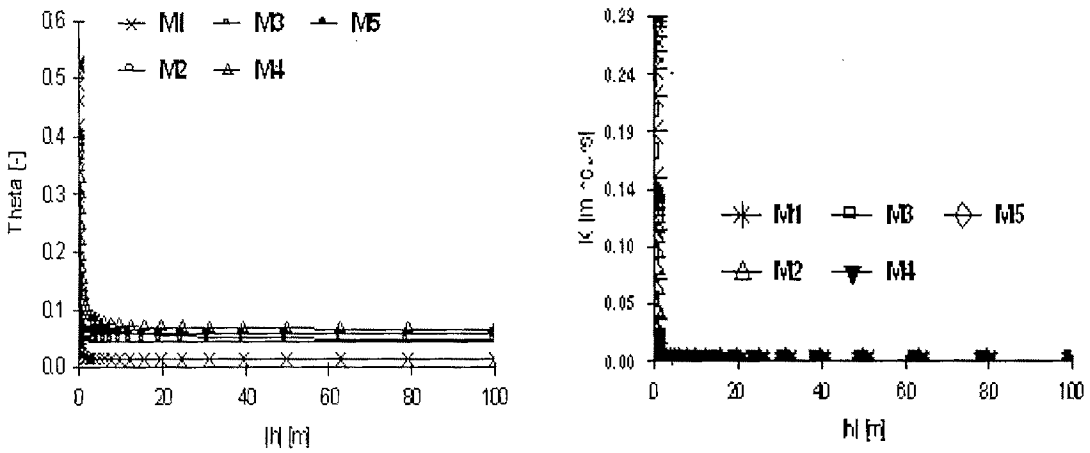


Figure 3.5: Soil hydraulic properties for lithology at Balsamand ASR site

3.4.2. STATISTICAL TEST

Statistical tests to assess simulation performance were:

Modelling efficiency (ME)

$$ME = 1 - \frac{\sum_{i=1}^{n} (O_i - S_i)^2}{\sum (O_i - \overline{O})^2} \tag{9}$$

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:

$$\overline{O} = \sum_{i=1}^{n} \frac{O_i}{n} \tag{10}$$

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:

$$RMSE = \sqrt{\left(\frac{1}{n}\sum_{i=1}^{N}[O_i - S_i(b)]^2\right)} \tag{11}$$

Paired t test for mean values

Paired t test was applied to compare the simulated and experimenatal cumulative chloride concentration of recovered water in successive ASR cycles at both ASR sites:

$$t_{cal} = \frac{d}{\sqrt{S^2\left[\frac{1}{n_1} + \frac{1}{n_2}\right]}} \tag{12}$$

d is the difference of mean defined as:

$$d = X_1 - X_2$$

$$S = \sqrt{\frac{n_1 x S_1^2 + n_2 x S_2^2}{(n_1 + n_2 - 2)}} \tag{13}$$

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.

3.5. FILTER STUDY

Field experiments were conducted to determine the effectiveness of check barriers at KVK Sirsa in 25 m long water channel. Three type of check barriers were constructed from the locally available material i.e. dead grass, gravel and cooler mat. The filter material was packed in netted frames made from steel rods. The sediment check barriers were placed vertically in a field channel at distance of 10 m from each other. The channel received water from a tubewell at the upstream end at distance of 15 m from the first barrier (Figure 3.6). The sediment load was artificially created by placing soil clods just below the discharge point of tubewell. The different sediment/check barriers were used in pairs to examine their effectiveness in removing sediment from the source water.

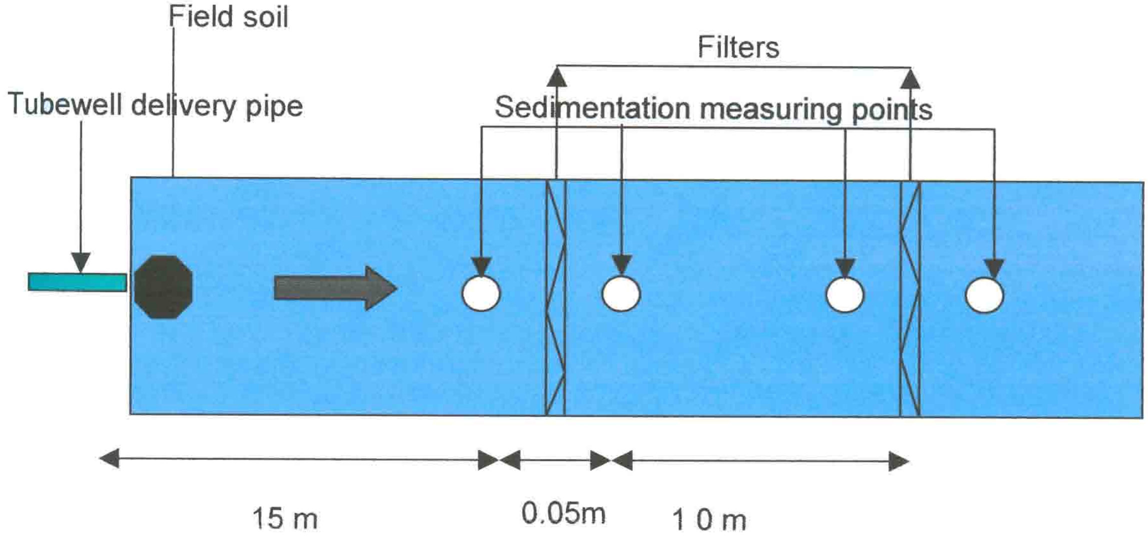


Figure 3.6: Schematic layout of the filter positions in water channel

Chapter IV

RESULTS AND DISCUSSION

Results are discussed under the following heads:

4.1 Effect of successive number of cycles on recovery efficiency at Soil Research farm, Hisar and RRS, Balsamand ASR sites
4.2 Geo physicochemical interactions at both ASR sites
4.3 Modelling of groundwater recharge and solute transport at both ASR sites
4.4. Effect of different types of filters on reducing sedimentation load

4.1. EFFECT OF SUCCESSIVE NUMBER OF ASR CYCLES ON RECOVERY EFFICIENCY AT SOIL RESEARCH FARM, HISAR AND RRS, BALSAMAND

4.1.1 RECHARGE AND RECOVERY RATES

Recharge rates were less than recovery rates due to shallow groundwater level condition at Hisar and were equal at Balsamand ASR site. Recharge and Recovery rates remained almost constant in each cycle at an average value of 23.23 $m^3 h^{-1}$ and 60.21 $m^3 h^{-1}$ at Hisar (Figure 4.1), respectively and 3.12 $m^3 h^{-1}$ at Balsamand ASR site (Figure 4.2).

The study clearly showed that recharge could be done in a cavity type ASR well under shallow and medium water table condition even when depth to water table depth was 0.54 – 2.2 m near canals and in monsoon season. Clogging was not observed at both the ASR sites, as recharge and recovery rates remained unaffected with successive ASR cycles.

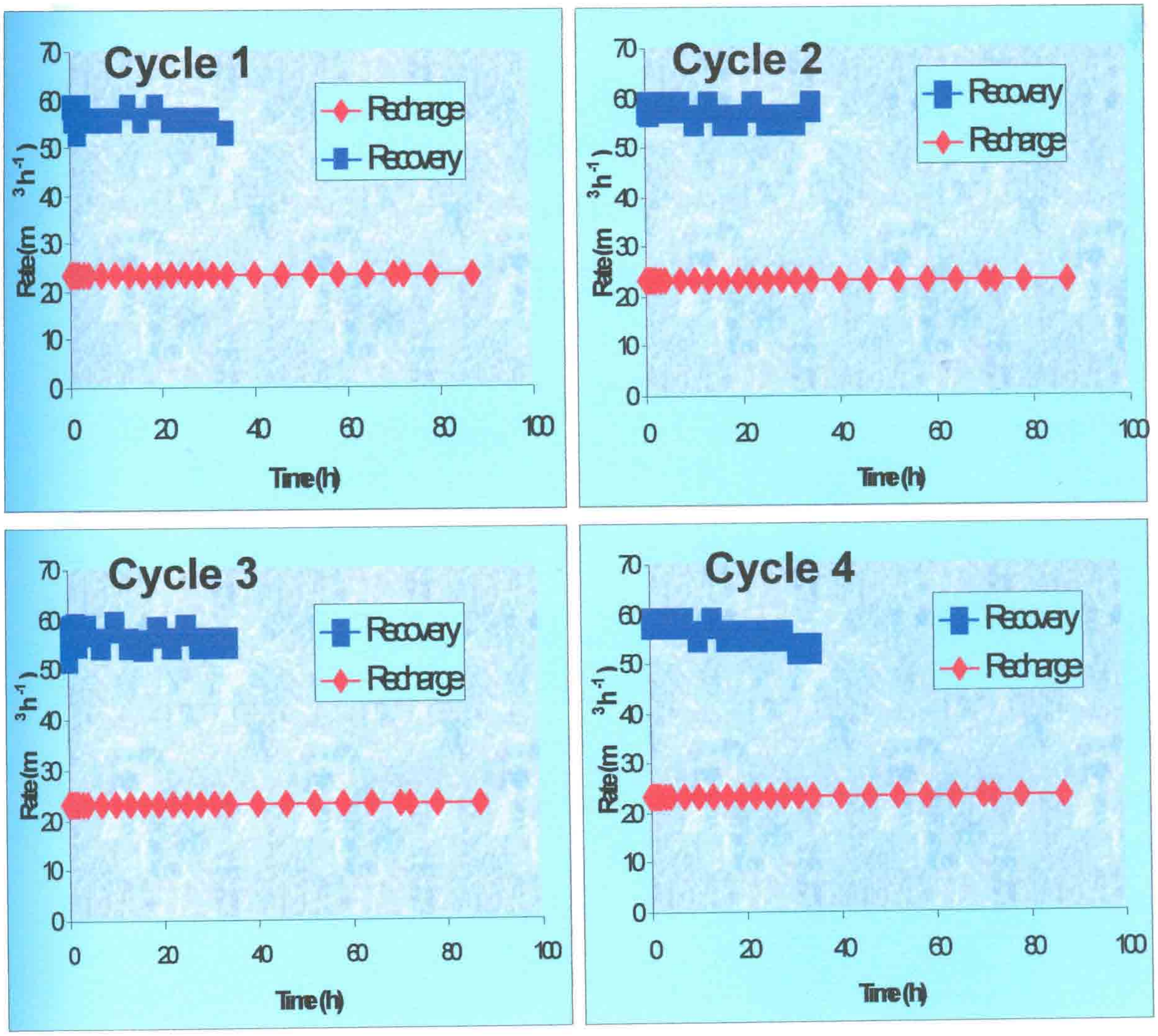


Figure 4.1: Recharge and recovery rates in successive cycles as a function of time at Hisar ASR site

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:

$$I = \left[\frac{\int_{tr1}^{tr2} qr(t)\,dt}{\int_{ti1}^{ti2} qi(t)\,dt} \right] = \left[\frac{V_r}{V_i} \right] \qquad (1)$$

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

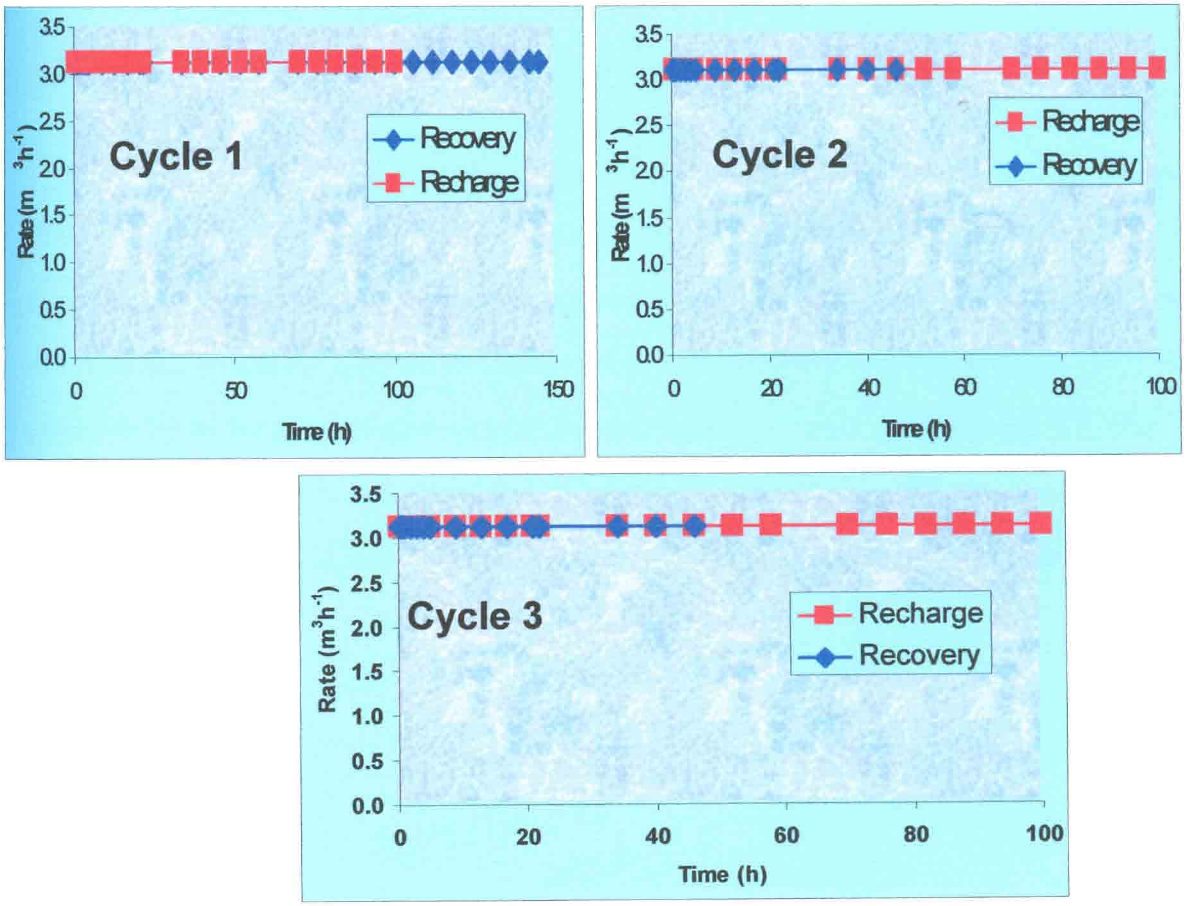


Figure 4.2: Recharge and recovery rates in successive cycles as a function of time at Balsamand ASR site

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

$$RE = \left[\frac{\int_{tr1}^{trt} q_r(t)dt}{\int_{ti1}^{ti2} q_i(t)dt}\right] = \left[\frac{V_r^*}{V_i}\right] \qquad (2)$$

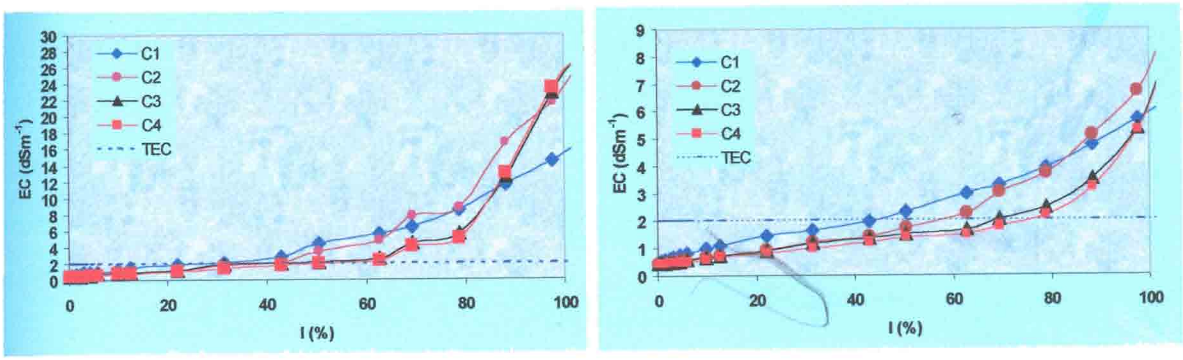
Where, V_r* = total recovered volume at target time trt. In this study desired water quality (electrical conductivity, EC) of the recovered water for irrigation purpose was taken as 2 dS m^{-1}. The EC_r (t) and EC_{rw} (t) are instantaneous and cumulative (weighted average) electrical conductivity as 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:

$$EC_{rw}(t) = \left[\frac{\int_{tr1}^{tr2} EC_r(t)qr(t)dt}{\int_{ti1}^{ti2} qr(t)dt}\right] = \frac{\sum EC_r(t)\Delta V_r}{\sum \Delta V_r} \qquad (3)$$

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 cumulative RE is useful when the recovered water may be stored in the storage tanks just before use and for quantifying the geo-chemical interactions.

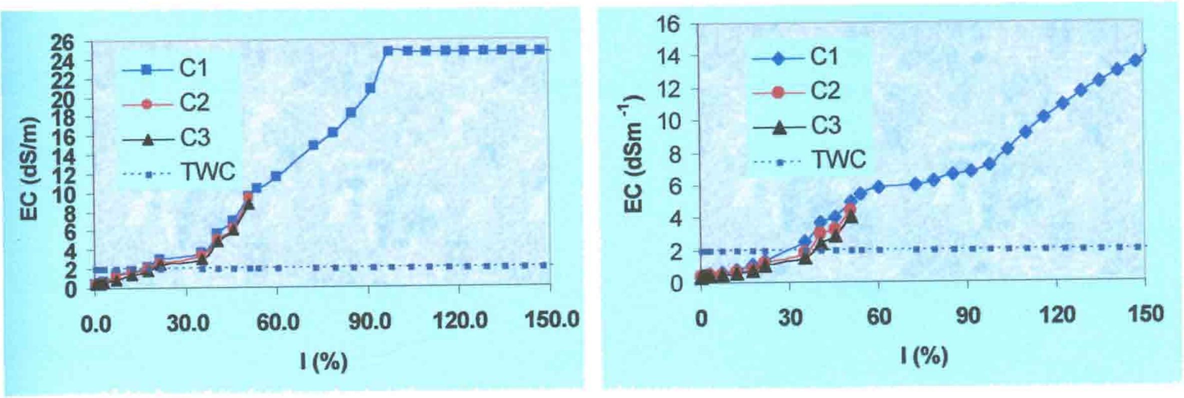
The cumulative electrical conductivity of recovered water EC_{rw} as a function of recovery times was estimated from equation (3). The EC_r and EC_{rw} of the recovered water increased with I (Figure 4.3 a & b at Hisar and c & d at Balsamand) signifying that there was increasing mixing as the recovered water was withdrawn radially away from the well (Pyne, 1995) at both the ASR sites.

(a) (b)



Hisar

(c) (d)

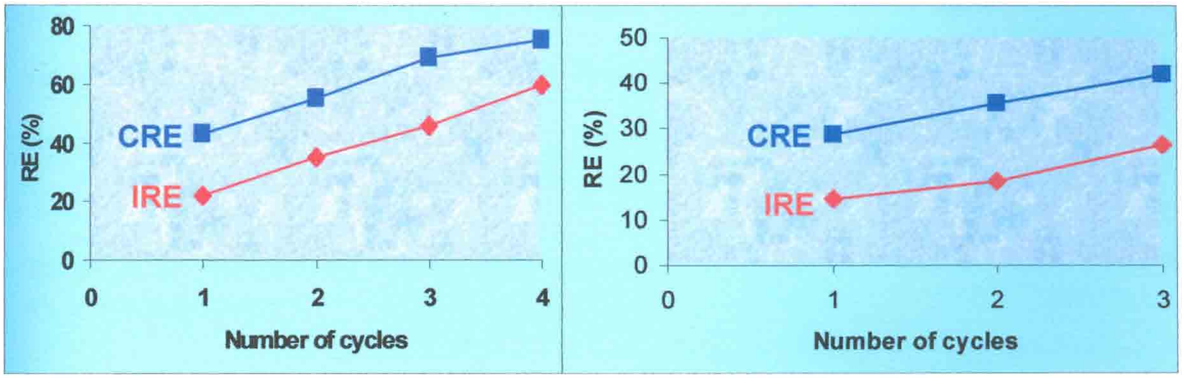


Balsamand

Figure 4.3: (a & c) Instantaneous electrical conductivity EC_r and (b & d) cumulative electrical conductivity EC_{rw} of the recovered water as a function of recovery percentage I with successive ASR cycles at both ASR sites

It further showed that EC_{rw} increased relatively slower with I than EC_r signifying high cumulative 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 (2) at target EC* of 2 dS m^{-1} as a function of successive cycles is shown in figure 4.4.



Hisar **Balsamand**

Figure 4.4: Instantaneous recovery efficiency IRE and cumulative recovery efficiency CRE as a function of successive number of ASR cycles at both ASR sites

It showed that both instantaneous recovery efficiency IRE and cumulative recovery efficiency CRE increased linearly with successive number of cycles as:

Hisar

$\mathrm{IRE} = 17.80 + 8.60\ \mathrm{SC}$ $r^2 = 0.976$ (4)

$\mathrm{CRE} = 33.05 + 11.0\ \mathrm{SC}$ $r^2 = 0.998$ (5)

Balsamand

$\mathrm{IRE} = 8.00 + 5.90\ \mathrm{SC}$ $r^2 = 0.999$ (6)

$\mathrm{CRE} = 22.16 + 6.65\ \mathrm{SC}$ $r^2 = 0.959$ (7)

The observed IRE and CRE at EC* of recovered water 2 dS $m^{-1}$was 42.9 % and 74.8% at Hisar and 26.6% and 44.4% at Balsamand ASR site (Table 4.1). The CRE was higher than IRE in each successive cycle. The increase in IRE and CRE with successive number of ASR cycles was more at Hisar than Balsamand as more quantity of water (Table 3.2) was recharged at Hisar than Balsamand ASR site. Therefore, more quantity of recharged was left in the aquifer after successive cycles and this left over recharged water acted as the buffer storage volume and increased the RE in successive cycle. Pyne (1995) has reported recovery efficiency varying form 25 – 100% at different sites in Florida depending upon BSV, aquifer water quality and aquifer hydraulic characteristics.

Table 4.2: Recovery efficiency as a function of successive ASR cycles at both ASR sites

Cycle No.	IRE		CRE	
	Hisar	Balsamand	Hisar	Balsamand
1	22.1	14.8	42.9	26.6
2	35.6	18.4	55.0	34.3
3	44.3	24.6	69.3	44.4
4	52.6	-	74.8	-

IRE = instantaneous recovery efficiency, CRE = cumulative recovery efficiency

The recovery efficiency at different target value for EC* (2, 4 & 6 dSm^{-1} at Hisar and 2 & 4 dSm^{-1} at Balsamand) of irrigation water was estimated from figures 4.5. It showed that the RE increased linearly with the increasing target EC* of the recovered water at both sites. The RE increased more at Hisar than Balsamand as more volume of water was recharged at Hisar than Balsamand. The RE increased linearly as:

Hisar

$$IRE = 35.13 + 8\ EC^* \qquad r^2 = 0.925 \qquad (8)$$

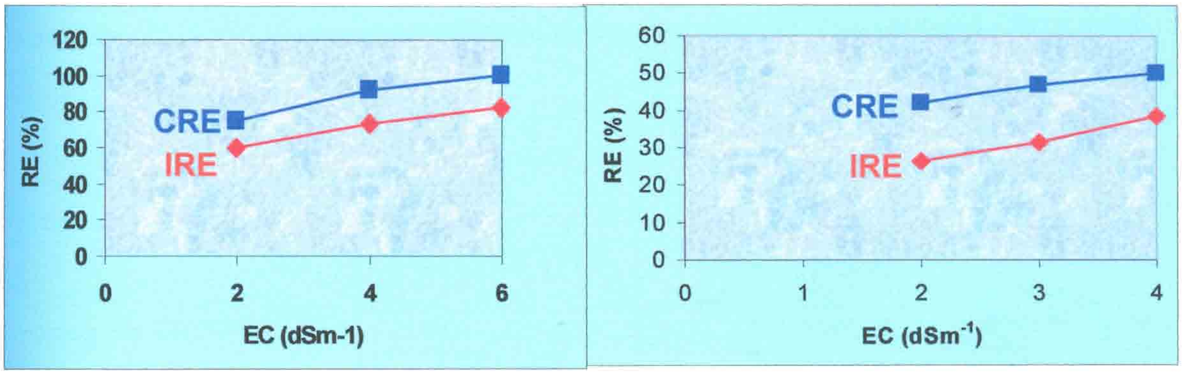
$$CRE = 63.57 + 6.6\ EC^* \qquad r^2 = 0.993 \qquad (9)$$

Balsamand

$$IRE = 13.93 + 6.3\ EC^* \qquad r^2 = 0.983 \qquad (10)$$

$$CRE = 34.3 + 6.1\ EC^* \qquad r^2 = 0.994 \qquad (11)$$

Malik *et al.,* (2002 a) 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 at both sites are presented in Figure 4.5.



Hisar **Balsamand**

Figure 4.5: Instantaneous recovery efficiency IRE and cumulative 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 successive ASR cycles at both sites and improvement is more when more quantity of good quality water is recharged.

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 Vechiolli, 1975; Pavelic *et al.*, 2002 a) as:

$$M(t) = \frac{C_{rw}(t) - C_i}{C_n - C_i} \times 100 \qquad (12)$$

Where, C_{rw} (t) is the cumulative (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 recharged and native water. The C_{rw} (t) can be estimated as:

$$C_{rw}(t) = \left[\frac{\int_{tr1}^{tr2} C_r(t) qr(t) dt}{\int_{ti1}^{ti2} qr(t) dt} \right] = \frac{\sum C_r(t) \Delta V_r}{\sum \Delta V_r} \qquad (13)$$

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 cumulative 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 4.2.

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

$$TA(t) = \int_{tr1}^{tr2} Cr(t)qr(t)dt = V_r \times C_{rw}(t) \qquad (14)$$

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

$$MA(t) = C_n\left[V_r \frac{M\ (Cl^-)}{100}\right] + C_i\left[V_r - V_r \frac{M(Cl^-)}{100}\right]_i \qquad (15)$$

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

Table 4.2: Possibility of different physicochemical processes between native groundwater and recharged 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

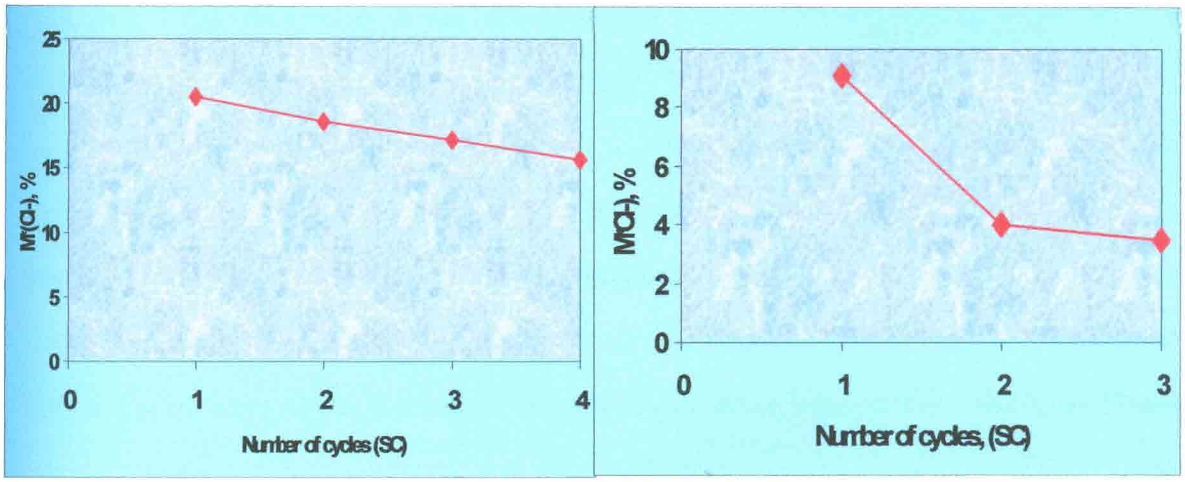
Chloride was taken as an indicator ion for quantifying the mixing process between native and recharged water. Cumulative native water percentage of chloride M (Cl^-) at any recovery percentage I quantifies the simple mixing process as the fraction of native water mixed in the recovered water, as Cl^- 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 with successive number of ASR cycles at both ASR sites i.e. Hisar as well as Balsamand (Figure 4.6) as:

Hisar

$$M^*(Cl-) = -0.0015\ SC + 21.95 \qquad r^2 = 0.993 \qquad (16)$$

Balsamand

$$M^*(Cl-) = -2.82\ SC + 11.15 \qquad r^2 = 0.823 \qquad (17)$$



Hisar **Balsamand**

Figure 4.6: Mixing percentage M*(Cl^-) as a function of buffer storage volume

It was because the recharged water left in the aquifer acted as a buffer zone, which restricts the direct mixing of recharged water with the native water and this leads to successive decrease in the proportion of native water in the recovered water with successive number of ASR cycles. It decreased from 20.5% to 15.7% with four successive ASR cycles at Hisar. At Balsamand ASR site with three successive cycles M*(Cl^-) decreased from 9.09% to 3.43% (Table 4.3). The decrease in M*(Cl^-) was more at Hisar than Balsamand as more quantity of water was recharged at Hisar ASR site. Within the cycles the decrease in M*(Cl^-) was more at Balsamand as during first cycle recharge to recovery ratio was 1:1.5 and in subsequent cycles it was 1:0.5. The M*(Cl^-) of 20.5% during first cycle at Hisar means that 20.7 % of native water is mixed with 79.3 % of recharged water to reach at 100 % recovery.

The cumulative native water percentage in the recovered water at 100 % recovery (M*) for different parameter (Table 4.3) as compared to that of chloride showed that Calcium, Bicarbonate, Borate and Potassium of the recharge water have been affected most by geo-chemical reactions between the native groundwater and recharged water at Hisar ASR site. Other parameters in the recovery water were mainly affected by simple mixing between native groundwater and recharged water.

Similarly, at Balsamand ASR site also the cumulative native water percentage in the recovered water at 100 % recovery (M*) for different parameter (Table 4.3) as compared to that of chloride showed that Bicarbonate, Borate, Nitrogen and Potassium of the recharge water have been affected most by geo-chemical reactions between the native groundwater and recharged water. Other parameters in the recovery water were mainly affected by simple mixing between native groundwater and recharged 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 successive ASR cycles at Hisar ASR site in Figure 4.7 and at Balsamand ASR site in Figure 4.8.

Table 4.3: Concentration of native (C_n) and recharged (C_i) water and cumulative concentration of recovered water C_{rw}* at 100 % recovery of different quality parameters at Hisar (H) and Balsamand (B)

Parameter	*Cn*		*Ci*		*Crw** (*M2**)							
	H	B	H	B	Ist		IInd		IIIrd		IVth	
					H	B	H	B	H	B	H	B
EC (dSm^{-1})	28.4	28.7	0.46	0.25	6.15 (20.1)	3.57 (13.23)	8.4 (28.1)	4.83 (16.56)	7.3 (24.3)	4.05 (15.18)	7.0 (23.5)	-
Cl^-(mmoll^{-1})	261	277	1.0	1.50	54.3 (20.5)	26.56 (9.09)	49.3 (18.6)	12.56 (4.01)	45.8 (17.2)	11.02 (3.45)	41.7 (15.7)	-
SO_4^{2-} (mmoll^{-1})	3.90	0.63	0.16	0.008	0.5 (17.0)	0.15 (10.91)	0.5 (13.9)	0.069 (4.21)	0.4 (11.8)	0.046 (2.54)	0.3 (10.8)	-
HCO_3^- (mmoll^{-1})	24	5.00	0.60	1.75	**11.17** **(45.18)**	**2.70** **(35.62)**	**9.9** **(39.96)**	**2.60** **(26.35)**	**9.1** **(36.54)**	**2.51** **(23.52)**	**8.5** **(33.73)**	-
BO_3^{2-} (mmoll^{-1})	0.30	0.045	0.005	0.015	**0.18** **(53.0)**	**0.092** **(22.85)**	**0.14** **(42.6)**	**0.054** **(11.60)**	**0.13** **(37.7)**	**0.052** **(11.18)**	**0.12** **(36.5)**	-
Na^+ (mmoll^{-1})	159.1	150	0.49	0.35	27.17 (16.92)	15.13 (9.8)	38.11 (23.80)	7.05 (4.48)	35.76 (22.32)	6.14 (3.86)	34.08 (21.00)	-
K^+ (mmoll^{-1})	2.11	1.30	0.16	0.10	**1.28** **(57.51)**	**0.30** **(17.0)**	**1.13** **(49.96)**	0.23 (10.97)	**1.06** **(46.41)**	**0.20** **(8.61)**	**0.93** **(39.41)**	-
Ca^{2+}(mmoll^{-1})	19.5	17.4	0.60	0.63	**7.45** **(36.22)**	3.57 (8.91)	**7.03** **(34.02)**	2.6 (4.2)	**5.96** **(28.35)**	2.4 (3.57)	**5.87** **(27.91)**	-
Mg^{2+} (mmoll^{-1}	48	62.9	0.40	0.98	15.02 (24.32)	16.90 (10.07)	11.04 (22.97)	7.16 (4.21)	10.94 (21.74)	6.23 (3.45)	9.14 (20.51)	-
Em (%)	8.20	6.4	4.56	8.5	-8.30	-4.8	-6.8	-8.2	-8.9	-7.8	-6.4	-
pH	8.45	7.90	7.65	7.40	8.20	7.71	8.10	7.62	8.07	7.58	8.09	-

(*M2**) is mixing percentage and given in parenthesis

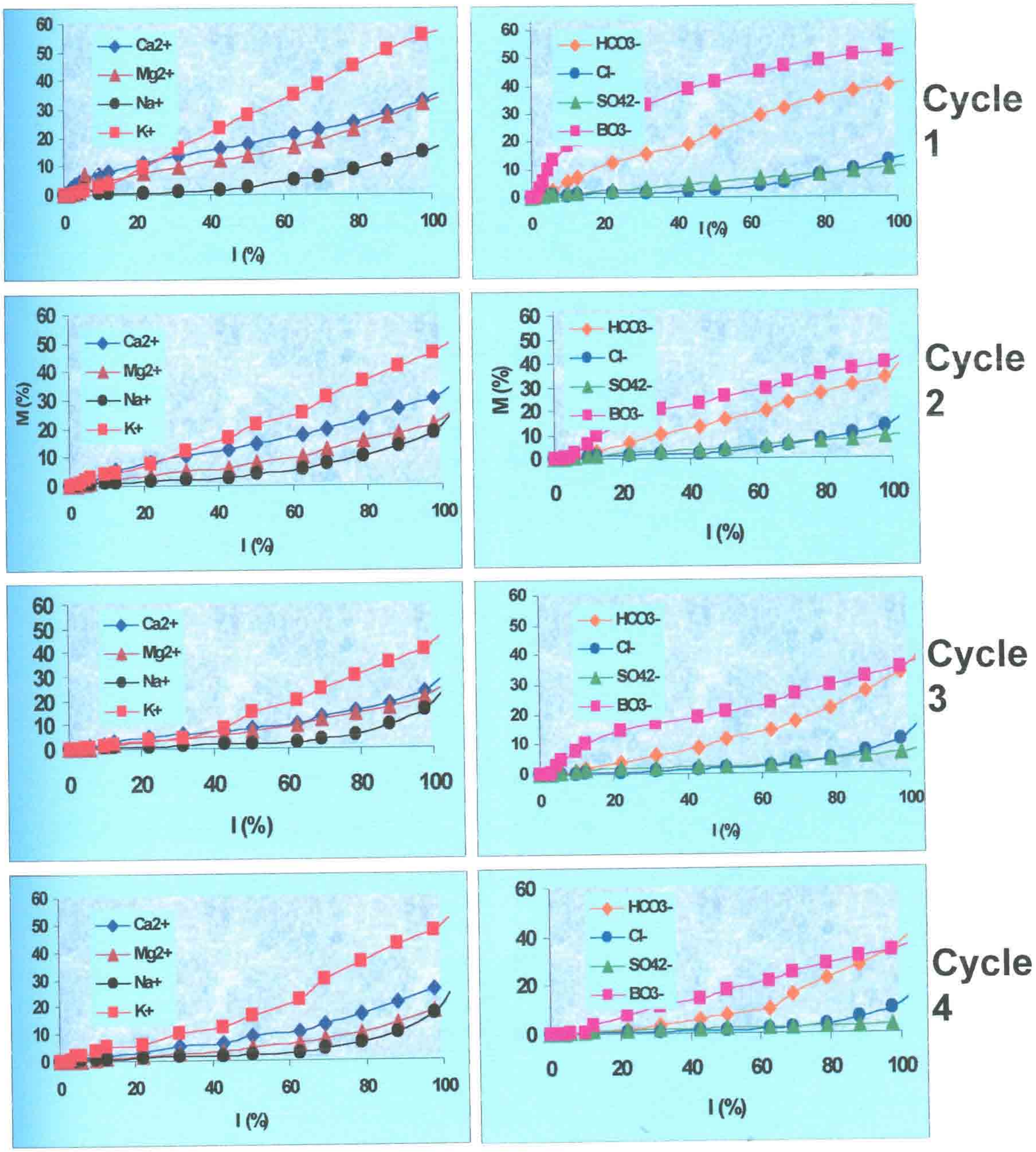


Figure 4.7: Mixing M of quality parameters versus recovery percentage I with successive number of ASR cycles at Soil Research Farm, Hisar

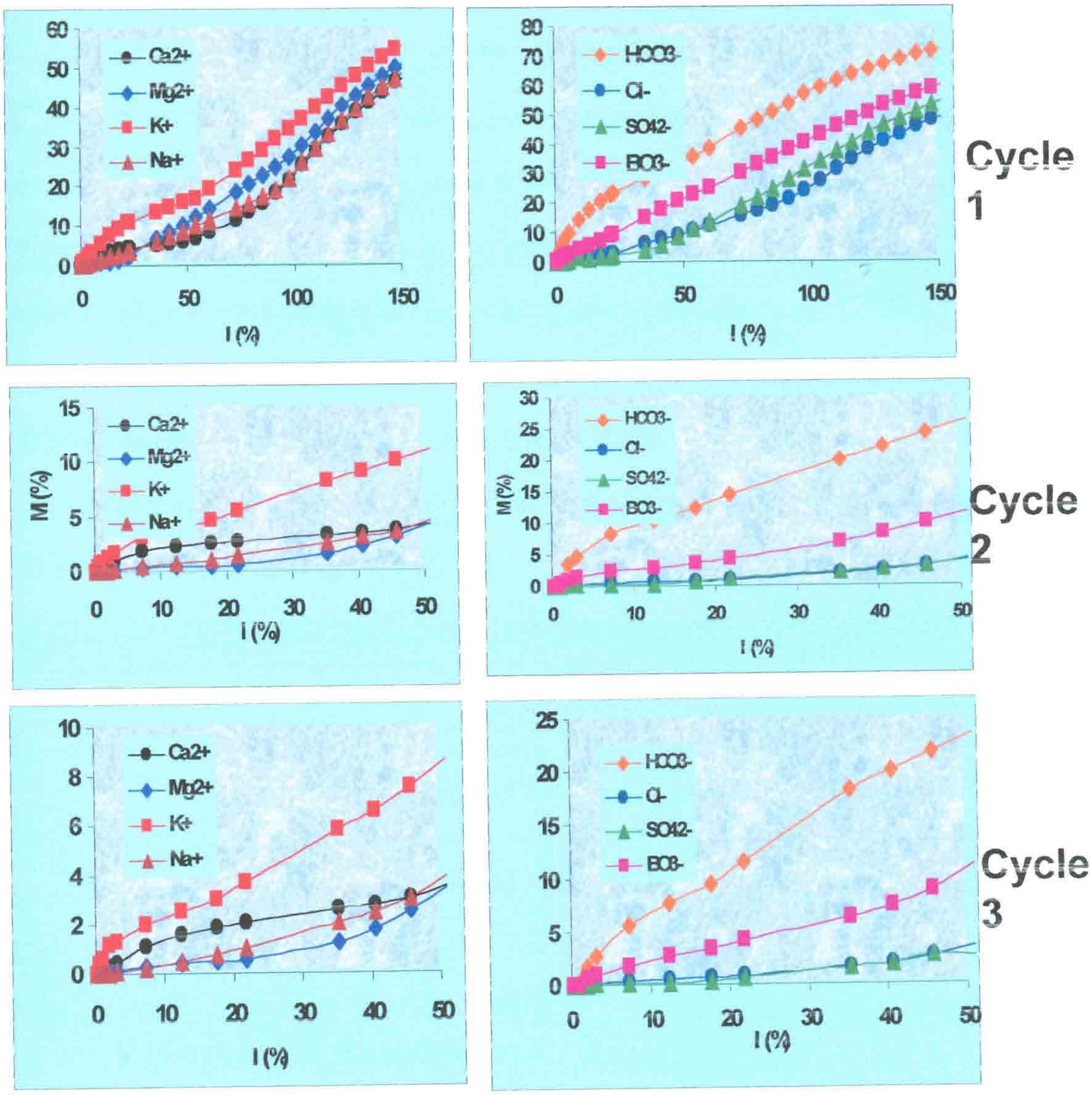
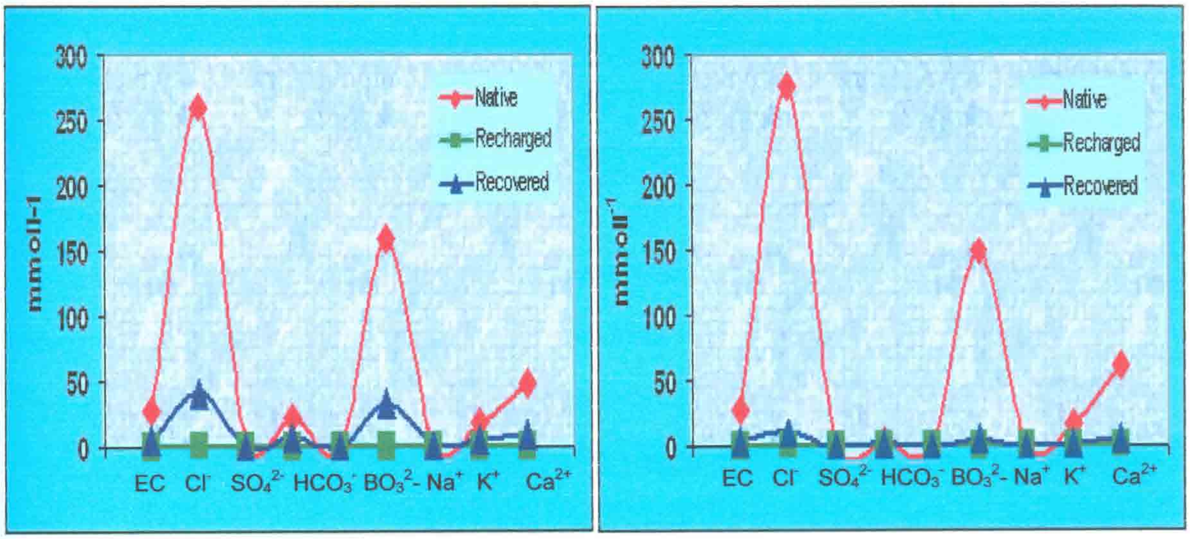


Figure 4.8: Mixing M of quality parameters versus recovery percentage I with successive number of ASR cycles at RRS, Balsamand

It showed an increase in mixing (M) with recovery percentage (I) for all the quality parameters at both ASR sites (Figure 4.7 & 4.8). It means that the water recovered was a mixture of recharged 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 at both AS R sites. 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 % at Hisar ASR site and at Balsamand ASR site M increased more sharply at I > 30 % . It was because the role of dispersion and regional movement of the recharged water bubble may have increased more sharply with increasing I > 60 % at Hisar and at I > 30 % at Balsamand. The increase was sharp at I > 30 % at Balsamand as at this site water was recovered only upto 50% of recharged water. The dependence of M on these factors was also emphasized by Pavelic *et al.*, (2002 a).

4.2.3 PHYSICAL AND CHEMICAL INTERACTIONS

The natural groundwater chemistry is dominated by sodium and chloride at Hisar as well as Balsamand ASR site (Figure 4.9).



Hisar **Balsamand**

Figure 4.9: Comparison of average major ion chemistry in native, recharged and recovery water during last ASR cycle at both ASR sites

Native groundwater salinity is approximately 18176 mgl^{-1} (EC = 28.4 dSm^{-1}) at Hisar and 18368 mgl^{-1} (EC = 28.7 dSm^{-1}) at Balsamand and is therefore unsuitable for

CALCITE DISSOLUTION:

The cumulative native water percentage value in the recovered water M* at recovery percentage I of 100 for Ca^{2+} and HCO_3^- (Table 4.3) were higher than that of simple mixing M* (Cl^-) value during successive ASR cycles at Soil Research Farm, Hisar ASR site. 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 4.2). 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 (16) as:

$$CaCO_3 + H_2CO_3 \rightarrow Ca(HCO_3)_2 \rightarrow Ca^{2+} + 2\ HCO_3^- \qquad (18)$$

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^-. On comparing HCO_3^- production (11679 mol_a) with Ca^{2+} production (5741 mol_c) from 2000 m^3 of recovered water during first cycle from Table 4.4, it was found that HCO_3^- were produced in 2:1 ratio of Ca^{2+} production. Similar trend was observed in subsequent cycles i.e. HCO_3^- was produced in 2:1 ratio of Ca^{2+} production. 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. Hence dissolution of calcite in equivalent amounts of Ca^{2+} and HCO_3^- was verified quantitatively in all ASR cycle at this site. The 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 4.3).

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 successive number of cycles because of the decreasing cumulative native water percentage in the recovered water M* (Ca^{2+} and HCO_3^-) with successive cycles (Table 4.3).

Similarly at RRS, Balsamand, cumulative native water percentage value in the recovered water M* at recovery percentage I of 100% for HCO_3^- (Table 4.3) were much higher than that of simple mixing M* (Cl^-) value during three successive ASR cycles. This means that if only simple mixing had occurred, the concentration of HCO_3^- in recovered water would have been within ± 10 % of M* (Cl^-). Therefore, it was a case where M* (HCO_3^-) > 1.10 M* (Cl^-) and C_n (HCO_3^-) > C_i (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 = 7.40) as compared to that of native groundwater water (pH = 7.84) may have caused dissolution of calcite ($CaCO_3$) present in the aquifer material (Table 4.2) to form HCO_3^- . The probable reason for HCO_3^- the release may be same of calcite dissolution as discussed above for Hisar ASR site.

POTASSIUM RELEASE

The cumulative 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 [illegible] higher than recharged water at both ASR sites (Table 4.3). It shows that potassium was released (Table 4.2) 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 at Hisar as well as Balsamand (Goyal *et al*., 1990).

For potassium it may be seen from Table 4.4 that 1653 mol$_c$ (19 kg) of potassium was produced after first cycle of 2000 m^3 recovered water at Hisar. Potassium release decreased with successive ASR cycles, as was a case for calcite dissolution. Similarly, at Balsamand ASR site also 283.3 mol$_c$ (14 kg) of potassium was produced after first cycle of 450 m^3 recovered water. Potassium release decreased with successive ASR cycles, as was a case for calcite dissolution. Malik *et al*., (2002 b) also reported K release in ASR of such an area of semi-arid region.

BORATE RELEASE

The cumulative native water percentage in the recovered water M* at recovery percentage I of 100 for BO_3^- was also [illegible] higher than that for chloride and concentration of BO_3^- in native water was much high than in recharged water at both ASR sites. 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 4.2). The low recharged water pH as compared to that of native groundwater pH at both ASR sites (Table 4.3) may have caused the dissolution of tourmaline, generally present in the aquifer material in semi arid region to form Borate (BO_3^-). Nevertheless, sodium was not found to produce at both sites (Table 4.4) 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 successive number of ASR cycles at both Hisar and Balsamand ASR site (Table 4.4).

Table 4.4: Effect of successive cycles on total amount TA, mixing amount MA and interaction amount IA of different constituent present in recovered water Hisar (H) and Balsamand (B) ASR sites

Parameter (mol)	TA		MA		IA	
	H	B	H	B	H	B
			First Cycle			
Bicarbonate (mol$_a$)	22791	1851	11112	613.6	11679	1238
Potassium (mol$_c$)	2614	346	960	346	1653 (19 kg)	283.3 (14 kg)
Borate (mol$_a$)	2614	97.3	130.9	5.31	231.0	91.99
Calcium (mol$_c$)	15190	-	9449	-	5741	-
			Second Cycle			
Bicarbonate (mol$_a$)	21386	420	10230	282	11156	138.3
Potassium (mol$_c$)	2438	61.5	882.6	61.52	1555 (18kg)	39.3 (6 kg)
Borate (mol$_a$)	308	8.23	119.7	2.43	188.26	5.8
Calcium (mol$_c$)	15144	-	8230	-	6913.2	-
			Third Cycle			
Bicarbonate (mol$_a$)	20030	403	9580.8	279.3	10449	123.8
Potassium (mol$_c$)	2331	55.0	825.2	55.03	1505 (17 kg)	33.82 (5 kg)
Borate (mol$_a$)	279	8.01	111.48	2.40	167.52	5.6
Calcium (mol$_c$)	13042	-	7701.6	-	5340.4	-
			Fourth Cycle			
Bicarbonate (mol$_a$)	18292	-	8884.8	-	9408.2	-
Potassium (mol$_c$)	2000	-	762.7	-	1236 (14 kg)	-
Borate (mol$_a$)	266	-	102.63	-	163.37	-
Calcium (mol$_c$)	12653	-	7134.6	-	5518.4	-

4.2.4 QUANTIFICATION OF QUALITY PARAMETERS FOR IRRIGATION

ELECTRICAL CONDUCTIVITY

Groundwater quality of the recovered water in terms of electrical conductivity EC was better than that of native water (Figure 4.9) at Hisar as well as Balsamand ASR site. Cumulative mixing M increased with recovery percentage I (Figure 4.10) as the proportion of native groundwater in recovered water increased with recovery percentage I at both sites.

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.

Cumulative 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 with successive number of ASR cycles at both ASR sites as:

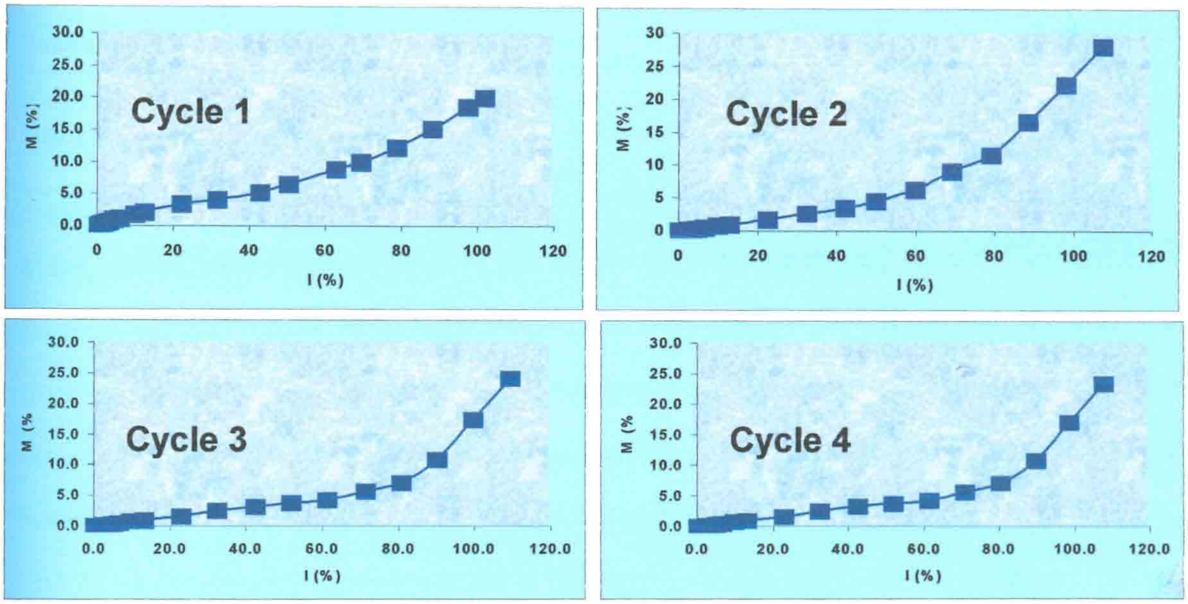
Hisar

$$RE = 11\ SC + 33.05 \qquad r^2 = 0.943 \qquad (19)$$

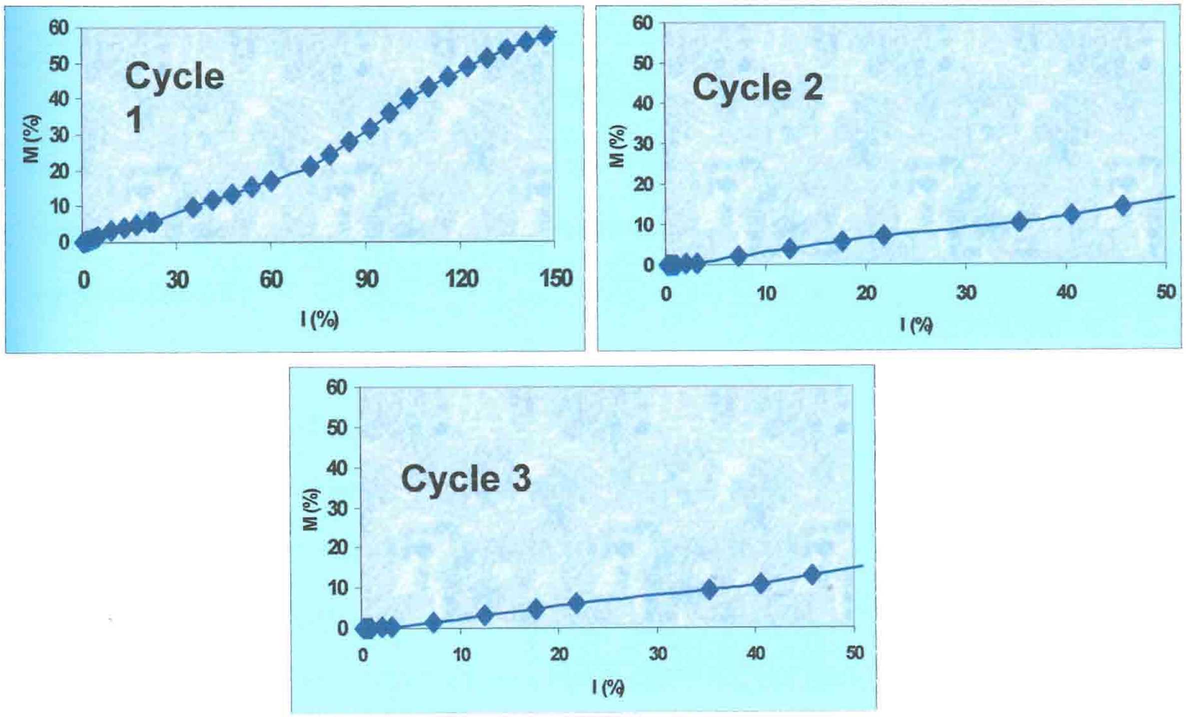
Balsamand

$$RE = 6.65\ SC + 22.16 \qquad r^2 = 0.943 \qquad (20)$$

Increased RE with successive cycle was due to decreased mixing with successive cycles. Pavelic *et al.*, (2002 a) and Pyne, (1998) had also reported the increase in RE with increasing in successive number of ASR cycles in brackish aquifer depending upon aquifer characteristics.



Hisar



Balsamand

Figure 4.10: Cumulative M of electrical conductivity EC_{rw} versus recovery percentage I during successive cycles at Soil Research Farm, Hisar and RRS, Balsamand

NUTRITIONAL VALUE .

Potassium of recovered water decreased with recovery percentage because the proportion of native groundwater in the recovered water decreased with I (Figure 4.8). It implied that first recovered water has higher potassium than water at the end of the season. This would be beneficial to crops as the nutritional value at initial stage is more than later stages of growth. The cumulative concentration C_{rw} as estimated from Equation 13 at target water quality decreased with successive cycles at both ASR sites This would add 19, 18, 17 and 14 kg potassium/irrigation of 0.06 m during four successive ASR cycles at soil research farm Hisar and 14, 6 and 5 kg of potassium at RRS Balsamand with three successive ASR cycles. This would save more than Rs 50/irrigation of 0.06 m on an average with successive number of cycles at both ASR sites.

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

Modelling results will be discussed unuer following heads

4.3.1. CALIBRATION AND VALIDATION OF HYDRUS-2D AND PMWIN FOR WATER FLOW

4.3.2. CALIBRATION AND VALIDATION OF THE HYDRUS-2D AND PMWIN FOR SOLUTE TRANSPORT

4.3.1. CALIBRATION AND VALIDATION OF HYDRUS-2D AND PMWIN FOR WATER FLOW

4.3.1.1. CALIBRATION

High regression coefficient R^2 (0.96 & 0.99), low value of objective function SSQ (1.12 & 0.92) and low mean RMSE (1.1 & 0.87) at Hisar and Balsamand ASR site, respectively, for piezometeric pressure head (Table 4.5) calibrated the model for first ASR cycle at both ASR sites.

Table 4.5: Calibration statistical tests of draw up and draw down in piezometric pressure heads during recharge (R) and recovery (D) at Hisar (H) and Balsamand (B) ASR sites

Time	n				RMSE (m)				ME			
(h.)	H		B		H		B		H		B	
	R	D	R	D	R	D	R	D	R	D	R	D
0.5	28	28	29	29	8.7	23.6	1.0	1.6	0.94	0.81	0.99	0.91
1	31	33	31	31	1.2	3.5	0.6	1.5	0.95	0.87	0.99	0.92
15	35	37	34	34	1.1	3.2	0.4	1.2	0.97	0.88	0.99	0.94
34	39	47	38	38	0.9	3.0	0.4	1.2	0.98	0.89	0.99	0.94
50	-	-	41	41	-	-	0.3	1.2	-	-	0.99	0.95
87	46	NA	44	44	0.8	NA	0.3	1.1	0.98	NA	0.99	0.95
100	NA	NA	50	50	NA	NA	0.3	1.0	NA	NA	0.99	0.96
150	NA	NA	NA	54	NA	NA	NA	1.1	NA	NA	NA	0.96

Drawup increased with time and decreased with radial distance during recharge. Similarly drawdown also decreased with time and with radial distance during recovery at both ASR sites i.e. soil research farm, Hisar and RRS Balsamand (Figure 4.11).

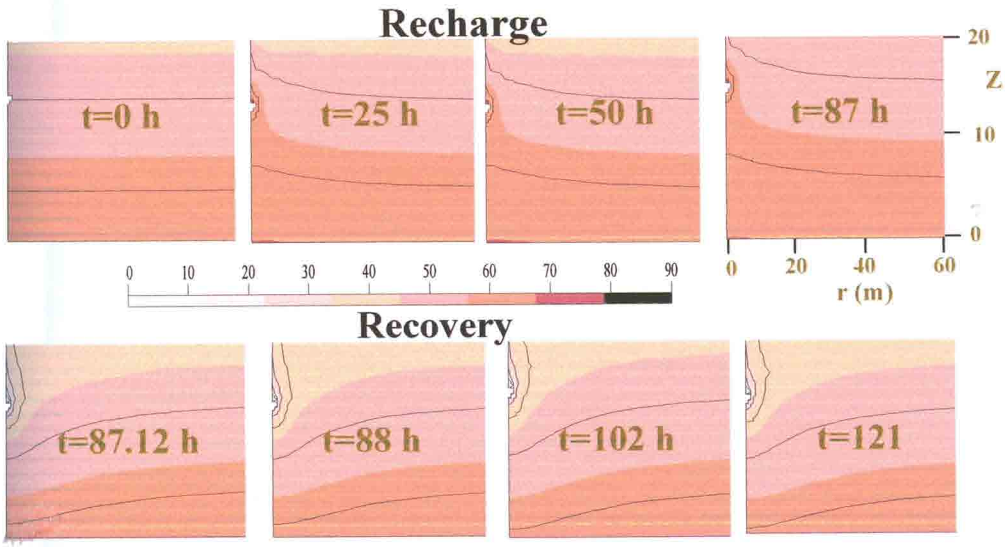


Figure 4.12: Development of pressure isolines at increasing time of recharge and recovery in first ASR cycle as a function of time at Hisar ASR site

Velocity isolines at different times decreased with increasing radial distances (r) and increased with time during recharge and recovery at both ASR sites (Figure 4.12).

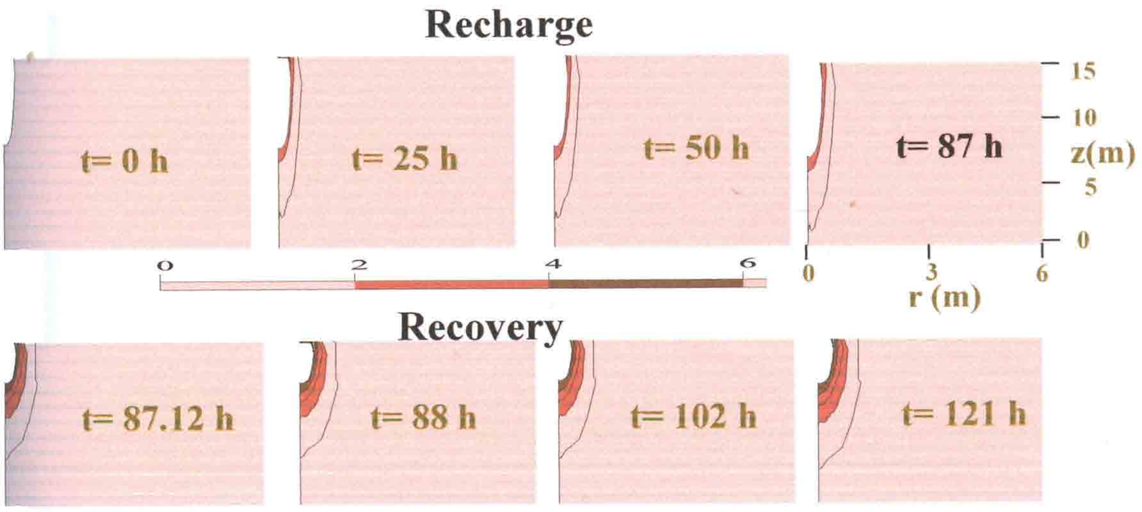


Figure 4.12: Development of velocity isolines at increasing time of recharge and recovery in 1st ASR cycle as a function of time

Velocity vectors intensity and directions shown by HYDRUS-2D were away from the cavity during recharge (Figure 4.13 a) and towards the cavity during recovery (Figure 4.13 b). Similarly, in PMWIN the recharge away from cavity (Figure 4.13 c) and towards cavity (Figure 4.13 d) is shown by pathlines.

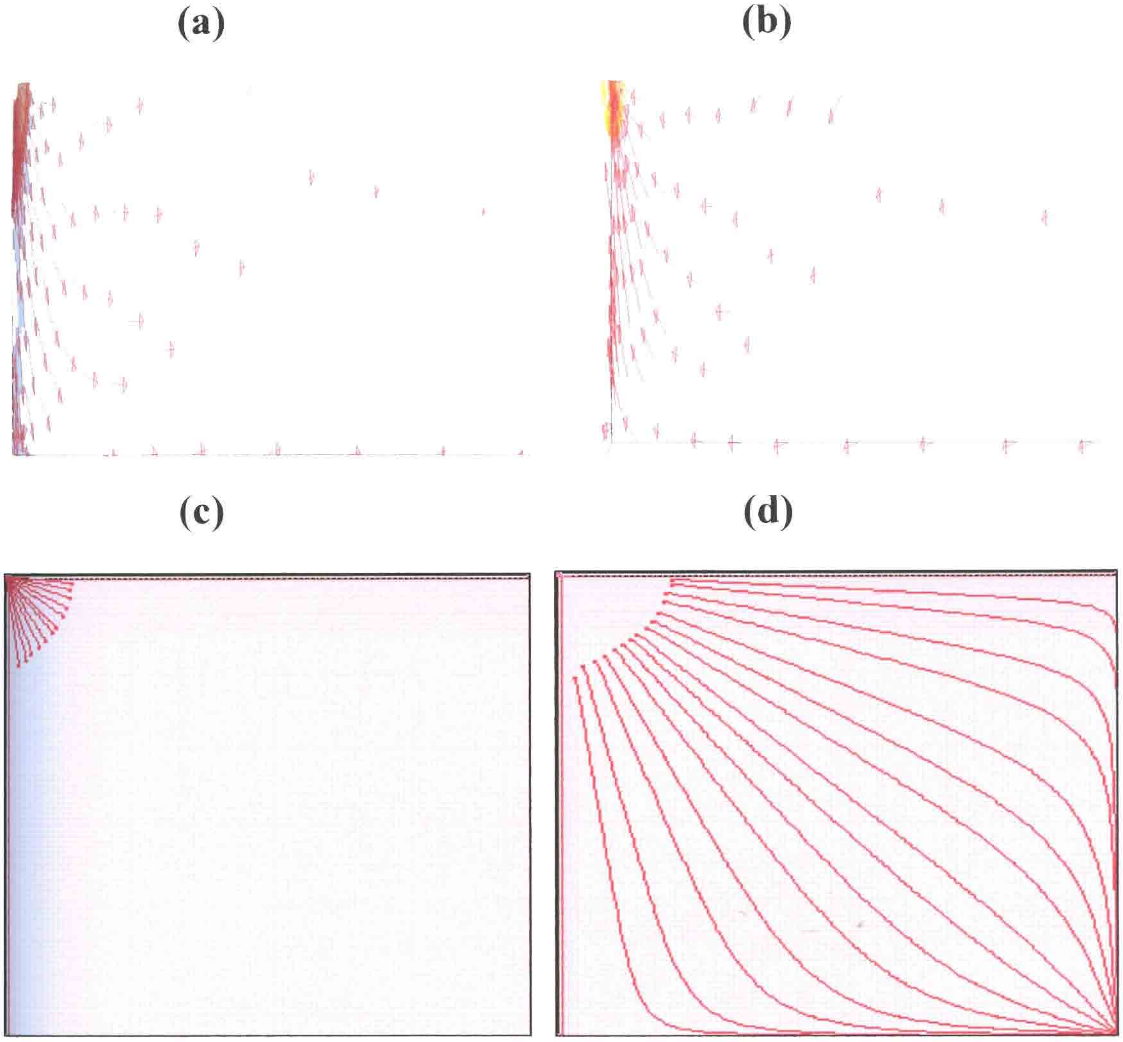
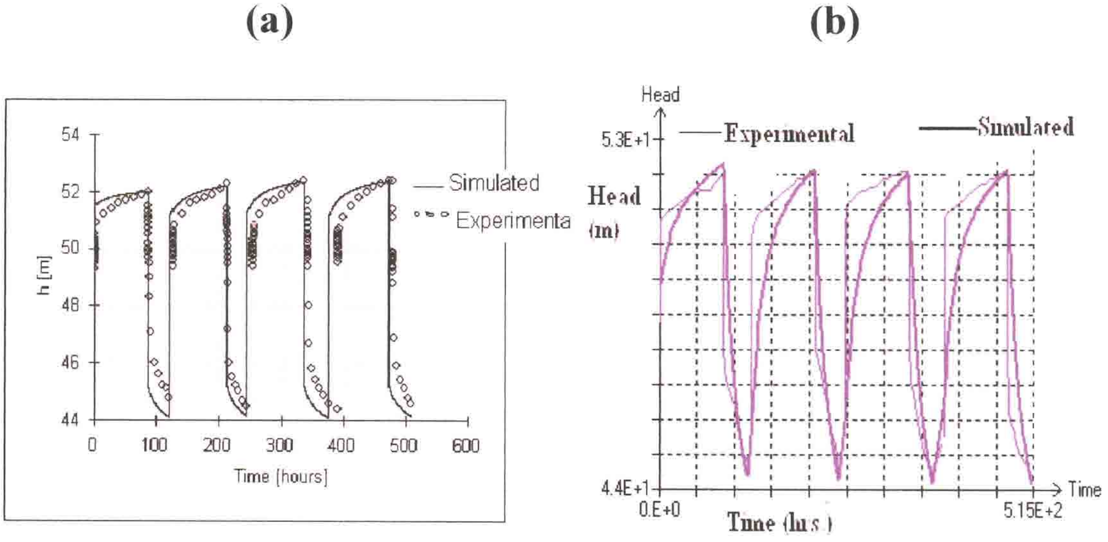


Figure 4.13: Velocity vectors showing intensity and direction during (a) recharge, (b) recovery by HYDRUS-2D (c) recharge (d) recovery by PMWIN

4.3.1.2. VALIDATION

There was good matching between experimental and simulated drawup & drawdown in piezometric pressure heads during the three successive ASR cycles at Hisar by HYDRUS-2D (Figure 4.14 a). Fairly low mean RMSE (1.1 & 3.1m) and high mean modelling efficiency (0.97 & 0.87) (Table 4.6), during recharge and recovery validated the HYDRUS-2D model for groundwater recharge studies at Hisar ASR site. The HYDRUS-2D calibrated hydraulic parameters were used for simulating piezometric pressure heads by PMWIN during four successive ASR cycles at Hisar ASR site. Good matching between experimental and simulated drawup & drawdown (Figure 4.14 b), fairly low mean RMSE (0.9 & 0.8 m) and high mean ME (0.97 & 0.95) (Table 4.7) validated the model for groundwater recharge studies at Balsamand ASR site.

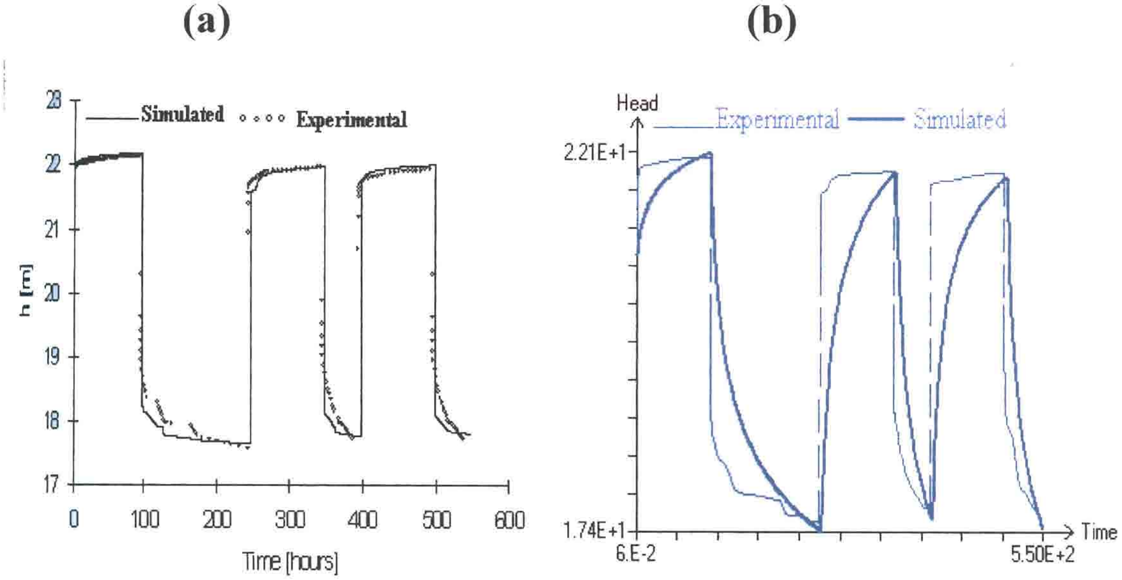


HYDRUS-2D PMWIN

Figure 4.14: Simulated versus experimental drawup and drawdown of piezometric head at during four successive ASR cycles at Hisar ASR site by (a) HYDRUS-2D (during calibration and validation) (b) PMWIN (using MODFLOW model) for validation

Similarly at the RRS, Balsamand ASR site also good matching of experimental and simulated piezometric pressure heads (Figure 4.15 a), fairly low mean RMSE, high mean

ME (Table, 4.6) validated the HYDRUS-2D model for piezometric pressure head studies at the present ASR site. HYDRUS-2D calibrated hydraulic parameters validated the PMWIN model also at the present study site (Figure, 4.15 b & Table 4.7).



HYDRUS-2D PMWIN

Figure 4.15: Simulated versus experimental drawup and drawdown of piezometric head at during three successive ASR cycles at RRS, Balsamand ASR site by (a) HYDRUS-2D (during calibration and validation) (b) PMWIN (using MODFLOW model) for validation

The under prediction of piezometric pressure heads by HYDRUS-2D (Figure 4.16 a & c) observed during the initial 0.5 h near the cavity centre during recharge and recovery at Hisar ASR site 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 and drawdown pressure heads after initial half an hour had a good matching at all the times at Hisar ASR site (figure 4.14 & 4.15). The initial observed pressure head were more than PMWIN simulated pressure head at both ASR sites. Nevertheless, the initial abrupt drawup and drawdown during experiment do not have much practical implications.

Table 4.6: Validation statistical tests for HYDRUS-2D of draw up and draw down in piezometric pressure heads at soil research farm, Hisar and RRS, Balsamand

Time	n				Hisar								Balsamand					
(h.)	H		B		IInd		IIIrd		IVth		ME		IInd		IIIrd		ME	
					RMSE (m)								RMSE (m)					
	R	D	R	D	R	D	R	D	R	D	R	D	R	D	R	D	R	D
1	31	33	31	31	1.2	3.5	1.2	3.8	1.2	3.8	0.97	0.85	0.6	0.8	0.6	0.8	0.98	0.89
15	35	37	34	34	1.1	3.1	1.1	3.3	1.2	3.5	0.96	0.86	0.6	0.8	0.6	0.8	0.99	0.89
34	39	47	38	38	1.1	2.9	1.1	3.1	1.2	3.2	0.98	0.87	0.5	0.8	0.5	0.8	0.99	0.91
50	-	-	41	41	-	-	-	-	-	-	-	-	0.5	0.8	0.5	0.8	0.99	0.91
87	46	NA	44	44	1.0	NA	1.0	NA	1.1	NA	0.99	NA	0.5	NA	0.5	NA	0.99	NA
100	NA	NA	50	50	NA	NA	NA	NA	NA	NA	NA	NA	0.4	NA	0.4	NA	0.99	NA

Table 4.6: Validation statistical tests for HYDRUS-2D of draw up and draw down in piezometric pressure heads at soil research farm, Hisar and RRS, Balsamand

Time	n				Hisar								Balsamand					
(h.)	H		B		IInd		IIIrd		IVth		ME		IInd		IIIrd		ME	
					RMSE (m)								RMSE (m)					
	R	D	R	D	R	D	R	D	R	D	R	D	R	D	R	D	R	D
1	31	33	31	31	1.2	3.5	1.2	3.8	1.2	3.8	0.97	0.85	0.6	0.8	0.6	0.8	0.98	0.89
15	35	37	34	34	1.1	3.1	1.1	3.3	1.2	3.5	0.96	0.86	0.6	0.8	0.6	0.8	0.99	0.89
34	39	47	38	38	1.1	2.9	1.1	3.1	1.2	3.2	0.98	0.87	0.5	0.8	0.5	0.8	0.99	0.91
50	-	-	41	41	-	-	-	-	-	-	-	-	0.5	0.8	0.5	0.8	0.99	0.91
87	46	NA	44	44	1.0	NA	1.0	NA	1.1	NA	0.99	NA	0.5	NA	0.5	NA	0.99	NA
100	NA	NA	50	50	NA	NA	NA	NA	NA	NA	NA	NA	0.4	NA	0.4	NA	0.99	NA

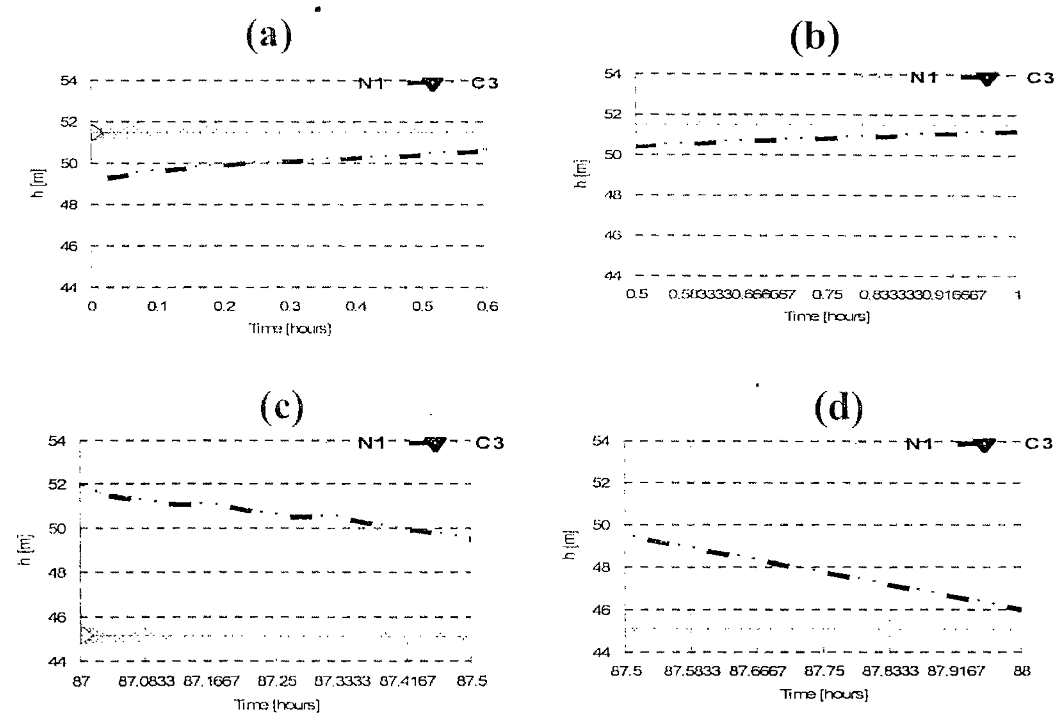


Figure 4.16: Simulated (N1) versus experimental (C3) piezometric pressure heads of (a) Initial 0.5 h (30 min) during drawup, (b) 0.5–1.0 h (30-60 min) during drawup, (c) Initial 0.5 h (30 min) during drawdown and (d) 0.5–1.0 h (30-60 min) during drawdown, in first ASR cycle

Therefore HYDRUS-2D and PMWIN may safely be used for projecting and optimizing the operational factors as successive cycles of the recharge water for the success of ASR technology. The models are quite fast and user friendly. So far, the HYDRUS-2D model has been used for predicting 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 applications of HYDRUS-2D have been reported to simulate groundwater recharge (Malik *et al.*, 2004). PMWIN has been used for groundwater flow and solute transport model. The similar calibration and validation studies in scavenger (Prasad and Rastogi, 2001) and in skimming have been reported by (Asghar *et al.*, 2002; and Ghulam Ali *et al.*, 2004).

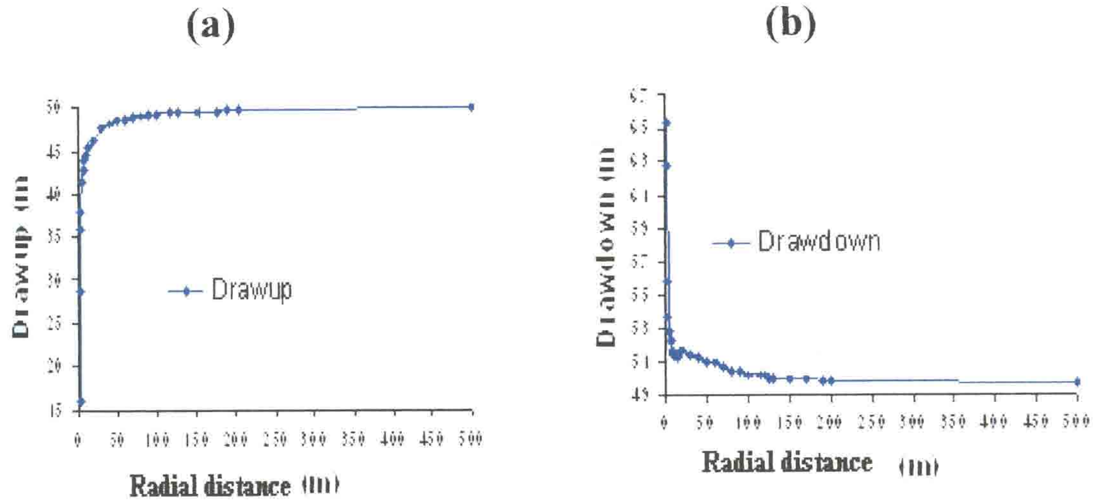
4.3.1.3. RADIAL INFLUENCING ZONE

Radial Influencing zone (r_{iz}) is taken as that radial distance z upto which there is 5% of the maximum drawup & drawdown during recharge and recovery of each cycle. It means r_{iz} would vary with recharge, recovery and successive number of ASR cycles during recharge (Figure 4.17 a (HYDRUS-2D), c (PMWIN)). It increased with successive number of ASR cycles with a mean value of 223 m at Hisar and 117 m at Balsamand. Increase in r_{iz} with successive cycles was because recharged water left in aquifer after each cycle acted as a buffer zone which restricts the direct mixing of recharged water with the native water and this leads to successive increase of radial influencing.zone with successive number of cycles It is more for recharge than for recovery at Hisar ASR site (Table 4.8, Figure 4.17 b (HYDRUS-2D), d (PMWIN)) because of the more time available (Table 3.2) for spatial movement of the recharged water during recharge. Radial spatial influencing zone during successive number of cycles at Hisar ASR site suggested that spacing between two ASR wells should be atleast 210 m. Similarly, at Balsamand ASR site both models predicted a mean influencing zone of 113 m. Lower influencing zone during 2nd and 3rd recovery cycles at Balsamand is as the recovery was done only 50% of the recharged water (Table 4.8, Table 3.2). Relatively lower r_{iz} have been reported in florida, USA (Pyne, 1995) and in Badhyan, India (Malik *et al.*, 2004) as 183 m and 40 m. Higher r_{iz} values at Hisar ASR site in this study were due to the existance of +ve hydraulic gradient from the canal nearby. The study also suggested that HYDRUS-2D and PMWIN may be adopted for simulations in ground water recharge studies in ASR systems.

Table 4.8: Predicted radial spatial influence zone (r_{iz}) during successive number of cycles at both ASR sites by HYDRUS-2D and PMWIN

Cycle number	**HYDRUS-2D** r_{iz} **(m)**				**MODFLOW** r_{iz} **(m)**			
	Hisar		**Balsamand**		**Hisar**		**Balsamand**	
	R	**D**	**R**	**D**	**R**	**D**	**R**	**D**
1	210	70	113	115	210	80	106	108
2	218	76	118	80	212	82	107	74
3	224	82	121	82	214	83	111	78
4	227	85	-	-	216	84	-	-
Mean	223	78.25	117	92.33	213	82.25	108	86.66

R = recharge, D = discharge



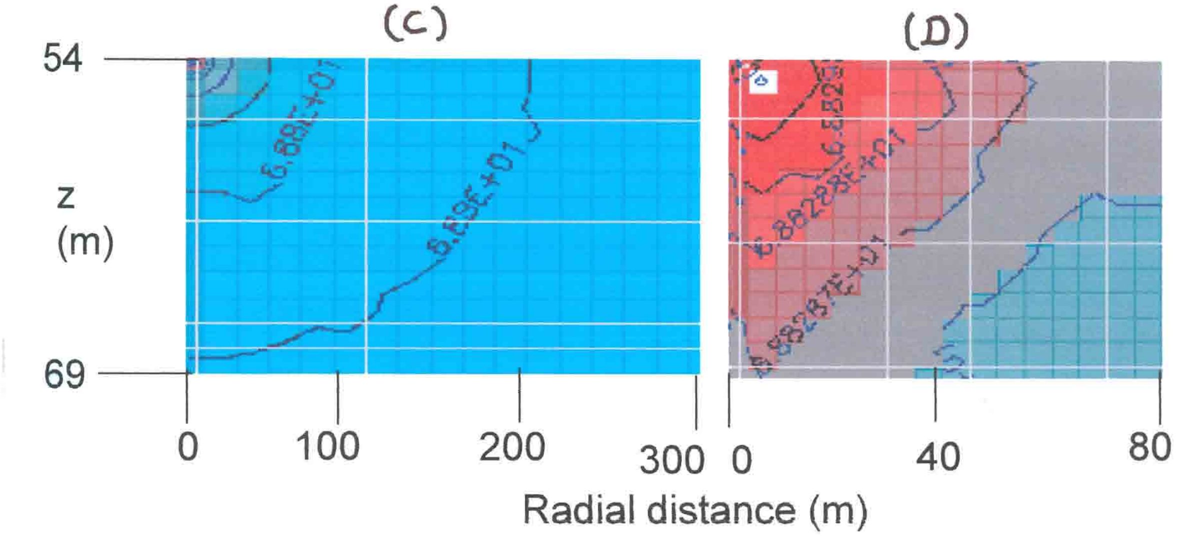


Figure 4.17: Radial Influence of the Ist ASR cycles during recharge as predicted by HYDRUS-2D (a) recharge (b) recovery and by PMWIN (c) recharge (d) recovery

4.3.1.4. MODEL PROJECTION

The model is used to project the effects of geo-hydrological parameters: radial hydraulic gradient, aquifer anisotropy, length of sand patch on confining silty clay layer at r = 50 m and aquifer saturated hydraulic conductivity (ks), 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.

4.3.1.4.1. EFFECT OF RADIAL HYDRAULIC GRADIENT

The radial hydraulic gradient had maximum effect on r_{iz} among the four factors studied. The r_{iz} decreased sharply with decrease in –ve radial hydraulic gradient from 0 to -0.8% and decreased slowly from -0.8% to -1.6% (Figure 4.18 a). During +ve hydraulic gradient, r_{iz} increased slowly with increase in hydraulic gradient from 0 to 0.8% and increased sharply with i from 0.8% to 1.6% (Figure 4.18 d). It is interesting to note that in case of +ve radial hydraulic gradient; the r_{iz} remained more than the targeted zone of 100 m for Indian farmers. So it is always risky to install an ASR well where the hydraulic gradient is +ve under the above given other geo-hydrological parameters. Practical significance of increase r_{iz} is that the recharge water is moving out from the recharge site and may not be of the use to the farmer recharging the water.

4.3.1.4.2. EFFECT OF AQUIFER ANISOTROPY

Anisotropy had the second largest impact on the r_{iz} . The r_{iz} decreased sharply with increase in anisotropy from 1 to 20 and decreased slowly with anisotropy from 20 to 40 (Figure 4.18 b). The targeted r_{iz} of 100 m was reached at anisotropy of 20.

4.3.1.4.3. EFFECT OF 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 10 m and increased slowly with increase length of sandy loam pathces from 10-30 m in the confining layer (Figure 4.18 c). The targeted r_{iz} was not reached upto 30 m of sand patch in confining layer.

4.3.1.4.4. EFFECT OFAQUIFER SATURATED HYDRAULIC CONDUCTIVITY

The r_{iz} increased sharply with increase in hydraulic conductivity of aquifer from 0.2 to 0.6 m/hr. and increased slowly in k from 0.6 to 2.0 m/hr (Figure 4.18 e). The r_{iz} remained more than the targeted zone of 100 m. So it is always risky to install ASR well where the aquifer saturated hydraulic conductivities are more than 0.2 m/hr. under the given other geo-hydrological parameters

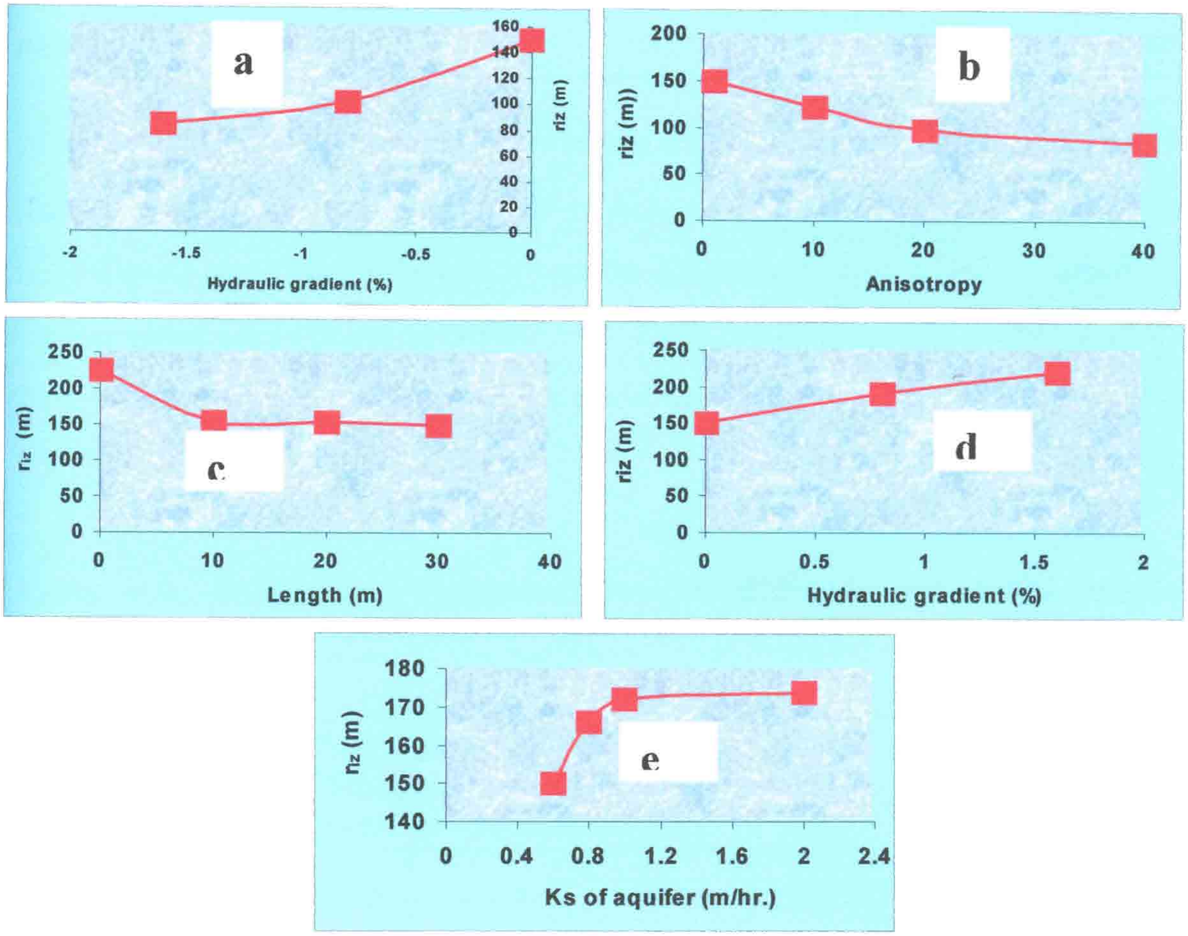


Figure 4.18: Projection of parameters by model a) decreasing radial hydraulic gradient b) Aquifer Anisotropy c) Length of sand patches in confining layer d) increasing radial hydraulic gradient e) Aquifer hydraulic conductivity

4.3.2. CALIBRATION AND VALIDATION OF THE HYDRUS-2D AND PMWIN FOR SOLUTE TRANSPORT

4.3.2.1. CALIBRATION FOR SOLUTE TRANSPORT (CHLORIDE TRANSPORT)

Matching of the predicted with experimental chloride concentartion in the recovered water (Figure 4.19), high regression coefficient R^2 (0.92 & 0.86), low value of objective function SSQ (1.14 & 1.18), low RMSE (1.04 m & 1.13 mmol), and high mean modelling efficiency (0.975 & 0.95) during recovery in first ASR cycle at Hisar and Balsamand ASR sites(Table 4.9), respectively. Figure 4.19 (a & b) showed that overall calibration of the HYDRUS-2D model was fairly well at both the ASR sites. Similar calibration results for solute transport were reported by (Asghar *et al.*, 2002) in skimming and (Ghulam ali *et al.*, 2004) in scavanger wells using PMWIN model model and (Bristow *et al.*, 2002) using HYDRUS-2D model.

Table 4.9: Calibration statistical test of chloride concentration in recovered water at Hisar (H) and Balsamand (B) ASR site

Time (h)	n		RMSE (mmol)		(ME)	
	H	B	H	B	H	B
1	4	4	1.24	1.00	0.97	0.97
15	10	10	1.13	0.98	0.97	0.98
34	14	14	0.98	0.96	0.98	0.99
50	NA	17	NA	1.1	NA	0.97
100	NA	32	NA	1.3	NA	0.93
150	NA	40	NA	0.94	NA	0.99

4.3.2.2. VALIDATION OF SOLUTE TRASNPORT (CHLORIDE)

Good matching between the experimental and simulated chloride concentration of the recovered water (Figure 4.19), fairly low RMSE and high mean ME (Table. 4.10) during successive ASR cycles at Hisar and Balsamand ASR site validated HYDRUS-2D and PMWIN (MT3D used for solute transport) fairly well. Similar results were reported by Asghar *et al.* (2002) in skimming well study by PMWIN and Bristow *et al.* (2002) for bromide transport in trickle irrigation using HYDRUS-2D model. So HYDRUS-2D and PMWIN may be utilized for solute transport in groundwater recharge studies in ASR wells.

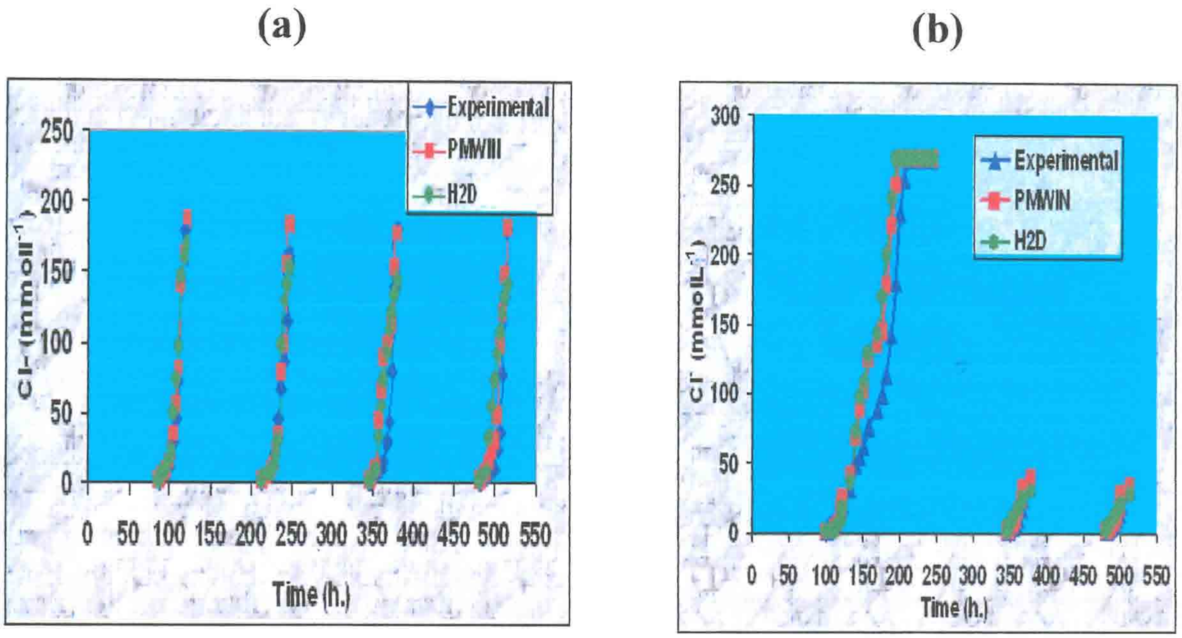
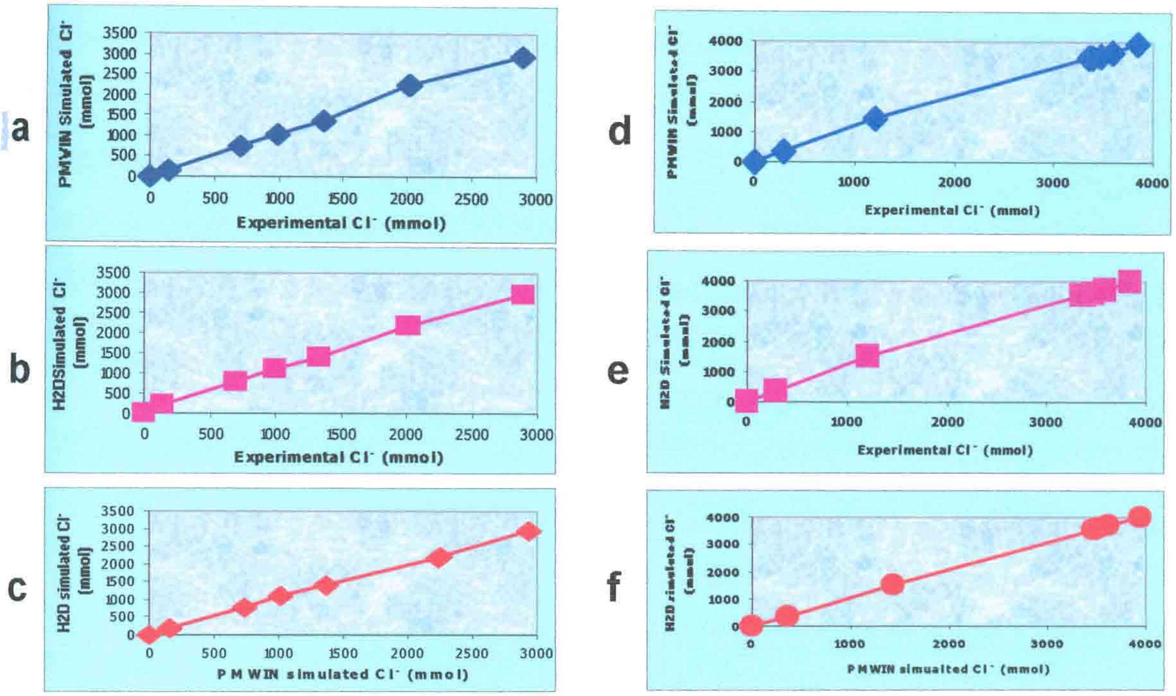


Figure 4.19: Simulated versus experimental chloride concentration in recovered water during successive ASR cycles at (a) soil research farm, Hisar and (b) RRS, Balsamand by HYDRUS-2D (H2D) and PMWIN (using MT3D model) for calibration and validation

The initial abrupt increase in chloride concentration by HYDRUS-2D and PMWIN do not have much practical implications as the cumulative chloride concentrations of experimental and predicted chloride in the cumulative recoverd after each cycle are almost equal (Figure 4.20 a, b for Hisar; c, d for Balsamand). High regression coefficient between experimental & HYDRUS-2D, experimental & PMWIN and HYDRUS-2D & PMWIN simulated cumulative chloride (Figure 4.20) validated the model fairly well. Non-significant differnce of means between eperimental and predicted (HYDRUS-2D and PMWIN) of cumulative chloride by paired t-test for mean values (Table, 4.11 & 4.12) also validated the models for solute transport in groundwater recharge studies in ASR wells at the present ASR sites.

Table 4.10: Validation statistical tests of chloride concentration in recovered water at Hisar (H) and Balsamand (B) ASR sites of HYDRUS-2D and PMWIN models

Time	n		Validation of HYDRUS-2D in ASR cycles number								Validation of MODFLOW in ASR cycles number									
(h)			IInd		IIIrd		IVth		Mean ME		Ist		IInd		IIIrd		IVth		Mean ME	
			RMSE (m)								RMSE (m)									
	H	B	H	B	H	B	H	B	H	B	H	B	H	B	H	B	H	B	H	B
1	4	4	1.0	0.9	1.0	1.0	1.0	1.0	0.97	0.97	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.99	0.98
15	10	10	2.1	1.9	2.4	1.8	2.3	1.7	0.87	0.96	2.6	1.7	2.3	1.6	2.2	1.6	2.0	1.7	0.92	0.94
34	14	14	1.8	1.6	1.8	1.8	2.0	1.9	0.94	0.96	1.2	1.4	1.1	1.5	1.0	1.4	1.0	1.4	0.96	0.96
50	-	17	NA	1.8	NA	1.7	NA	1.6	NA	0.97	NA	1.5	NA	1.4	NA	1.4	NA	1.3	NA	0.97
100	28	32	NA	NA	NA	NA	NA	NA	NA	NA	NA	1.5	NA	1.4	NA	NA	NA	NA	NA	0.97
150	NA	40	NA	NA	NA	NA	NA	NA	NA	NA	NA	1.0	NA	NA	NA	NA	NA	NA	NA	0.99



Hisar **Balsamand**

Figure 4.19: Comparison of Simulated versus experimental cumulative chloride in recovered water during at (a,b,c) soil research farm, Hisar and (d,e,f) RRS, Balsamand

Cumulative chloride with successive ASR cycles increased linearly as:

Hisar

Experimental and PMWIN simulated cumulative chloride

$$\text{Cumulative chloride} = 7.73 + 1.051\ Cl^- \qquad r^2 = 0.94 \qquad (21)$$

Experimental and H2D simulated cumulative chloride

$$\text{Cumulative chloride} = 43.63 + 1.035\ Cl^- \qquad r^2 = 0.82 \qquad (22)$$

PMWIN and H2D simulated cumulative chloride

$$\text{Cumulative chloride} = 39.58 + 0.982\ Cl^- \qquad r^2 = 0.86 \qquad (23)$$

Balsamand

Experimental and PMWIN simulated cumulative chloride

$$\text{Cumulative chloride} = 85.31 + 0.998\ Cl^- \qquad r^2 = 0.89 \qquad (24)$$

Experimental and H2D simulated cumulative chloride

Cumulative chloride = 104.98 + 1.0093 Cl^- r^2= 0.84 (25)

PMWIN and H2D simulated cumulative chloride

Cumulative chloride = 94.98 + 1.0091 Cl^- r^2= 0.89 (26)

Table 4.11: Experimental and simulated cumulative chloride concentration in the recovered water at Hisar ASR sites as a function of time

Time (h.)	Cumulative Cl^- (mmol)		
	Experimental	PMWIN	H2D
87.016	1	1	1
109	143.66	159.1	200.6
214	703.56	738.1	776.6
241	995.92	1017.2	1097.5
345	1342.7	1363.2	1400.5
376	2008.2	2235.1	2182.94
474	2020.6	2245.8	2194.94
512	2894.7	2934.2	2965.76

NS difference was found between experimental and MT3D simulated cumulative chloride concentration
NS difference was found between experimental and H2D simulated cumulative chloride concentration
NS difference was found between H2D and MT3D simulated cumulative chloride concentration

Table 4.12: Experimental and simulated cumulative chloride concentration in the in recovered water at Balsamand ASR sites as a function of time

Time (h.)	Cumulative Cl^- (mmol)		
	Experimental	PMWIN	H2D
100	1.5	1.5	1.5
150	284.9	369.8	366.8
200	1215.8	1428.3	1525.9
350	3360.5	3488.4	3512.4
375	3388.2	3460.1	3520.0
400	3475.4	3520.2	3585.3
500	3477.1	3522.9	3587.3
525	3585.8	3628.6	3690.1
543	3848.0	3940.0	3980.7

NS difference was found between experimental and MT3D simulated cumulative chloride concentration
NS difference was found between experimental and H2D simulated cumulative chloride concentration
NS difference was found between H2D and MT3D simulated cumulative chloride concentration

4.3.2.2. TECHNICAL COMPARISON OF PMWIN AND HYDRUS-2D MODELS

Comparison parameters	PMWIN	HYDRUS-2D
Dimensional	3D	2D
Combination	Three models 1. MODFLOW (water flow) 2. MT3D (solute transport) 3. PEST (inverse modeling)	Single model for water, solute and heat transport
Mesh generation	Automatic by assigning number and size of rows and columns. Easy to create mesh	Automatic by giving fixed points. Geometry creation takes time and number of fixed points affect the running of programme
Storage coefficient	Can be assigned	Can not be assigned
External stresses	Can be assigned in all directions	Only in axis-symmetric direction
Boundary conditions	Separate boundary condition can be assigned or each cell and each boundary	For boundary only separate condition can be applied
Dependency	Solute parameters can independently calibrated	Dependent on solute transport
Observation node	Can be given as spatial co-ordinate after model run	Must be applied before model run on fixed points

4.4. EFFECT OF DIFFERENT TYPES OF FILTERS ON REDUCING SEDIMENTATION LOAD

Field experiments were conducted at Regional Research Station, Sirsa to determine the effectiveness of check barriers, made from locally available materials, placed in the runoff stream to trap/reduce the sediment load. A check barriers is defined here as a long narrow temporary, entrenched and anchored, barrier across the flow direction used to intercept the flow velocity of the sediment laden water to provide some retention of sediment from the runoff water. Three type of check barriers were constructed from the locally available material i.e. dead grass, gravel and cooler mat. The filter material was packed in netted frames made from steel rods. The sediment check barriers were placed vertically in a field channel at distance of 10 m from each other. The channel received water from a tubewell at the upstream end at distance of 15 m from the first barrier. The sediment load was artificially created by placing soil clods just below the discharge point of tubewell. The different sediment check barriers were used in pairs to examine their effectiveness in removing sediment from the source water. Even though the sediment load of the source water got reduced by 65% at a distance of 25 m without any check barrier, the effect of installing the barriers in the channel was quite considerable. All the combinations of check barriers were able to reduce the sediment load by more than 90% of that in the source water. The best results were obtained when the barrier with cooler mat was placed at first place and dead grass barrier at the second place. This combination resulted into a reduction of 99% in the sediment load of the source water by bringing down the source sediment load level from 7800 mg l^{-1} to the level of 70 mg l^{-1}.

Table 4.13: Effect of different types of filters on reducing sedimentation load

S.No.	Filter at Ist position	Filter at 2nd position	%decrease
1.	Cooler pad filter	Grass filter	99.04
2.	Grass filter	Cooler pad filter	98.71
3.	Gravel filter	Grass filter	96.20
4.	Gravel filter	Cooler pad filter	94.50
5.	Grass filter	Gravel filter	94.44
6.	Cooler pad filter	Gravel filter	91.25
7.	Without filters/control		65.00

Chapter V

SUMMARY

The aquifer storage recovery ASR site of highly brackish native water was selected at Soil Research Farm, Hisar and RRS, Balsamand, 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 wells were 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 physicochemical properties. Soil analysis was done with the standard methods. Water samples of recovery water as a function of recovery time and that of recharged 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. Recharge and recovery rates were measured with mechanical water meters.

Canal water and transported good quality water was gravity recharged to study effect of four and three successive ASR cycles at Hisar and Balsamand, respectively. Water was recharged during successive cycles by employing pump column siphon system under different water table depth (0.54 - 22 m). Completion of a recharge and recovery makes one cycle. In each cycle the volume recharged and recovered was 2000 m^3, whereas, at Balsamand, 300 m^3 of water was recharged in each cycle and in first cycle 450 m^3 was recovered and in successive second and third ASR cycle 150 m^3 was recovered.

Recharge and recovery rates were constant at both sites i.e. 23.23 for recharge and 60.21 $m^3 h^{-1}$ for recovery at Hisar and 3.12 $m^3 h^{-1}$ for recharge and recovery at Balsamand. The instantaneous recovery efficiency IRE and cumulative recovery efficiency CRE increased with successive ASR cycles at both the ASR sites linearly as: IRE = 17.80 + 8.60 SC, CRE = 33.05 + 11.0 SC at Hisar and IRE = 8.00 + 5.90 SC, CRE = 22.16 + 6.65 SC at Balsamand.

The observed IRE and CRE at EC* of recovered water 2 dS $m^{-1}$was 42.9 % and 74.8% at Hisar and 26.6% and 44.4% at Balsamand ASR site. The CRE was higher than IRE in each successive cycle. The increase in IRE and CRE with successive number of ASR cycles was more at Hisar than Balsamand as more quantity of water was recharged at Hisar than Balsamand ASR site.

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 successive number of ASR cycles at both ASR sites i.e. Hisar as well as Balsamand. The cumulative 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 and

Potassium at Hisar and Bicarbonate, Borate and Potassium at Balsamand ASR site of the recharge water have been affected most by geo-chemical reactions between the native groundwater and recharged water. Other parameters in the recovery water were mainly affected by simple mixing between native groundwater and injected water. Groundwater quality of the recovered water was better than that of native water. Potassium concentration of the recovered water was more than that of recharged water during successive ASR cycles at both sites. Potassium and borate released from Illite and Tourmaline mineral, respectively, decreased with successive number of ASR cycles at both ASR sites.

A finite element flow models, HYDRUS-2D and PMWIN were used to simulate the drawup and drawdown in piezometric pressure heads during recharge and recovery in successive ASR cycles. The physical flow region involved a soil profile 500 m wide and 69 m (at Hisar) and 30 m (at Balsamand) deep with an exocentric elliptical cavity of 1 m horizontal radius and 1 m vertical radius at 54 m (Hisar) and 27 m (Balsamand) depth. No flux boundary condition was given at soil surface, bottom and lateral sides of the flow region. Third type solute boundary condition was used at cavity. Saturated hydraulic conductivity and diffusion coefficient was estimated through inverse modelling technique using the experimental pressure heads and Cl- concentration of recovered water as time pairs during the first ASR cycle from a piezometer ($z = 54$ m, $r_{iz} = 10$ m, at Hisar); and ($z = 27$ m, $r_{iz} = 20$ m, at Balsamand).

High regression coefficient, low value of objective function SSQ and low mean RMSE of piezometeric pressure head calibrated the model for groundwater and solute transport at both the ASR sites. High mean modelling efficiency ME and low RMSE of predicted and experimental piezometric pressure heads and solute concentration of recovered water validated the HYDRUS-2D and PMWIN (MODFLOW for water flow, MT3D for solute transport) for groundwater flow and solute transport at both the ASR sites. Non-significant difference by paired t-test was observed between experimental and predicted cumulative chloride after successive ASR cycles at both sites. Both the models predicted similar radial influencing zone during recharge and recovery at both sites. Radial influencing zone increased with successive number of cycles at both ASR sites. Radial influencing zone was more during recharge at Hisar ASR site as more time was available for spatial movement. Both the models are user friendly and easy to use. Mesh generation is more user friendly in PMWIN but it requires more time per model run. 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. Sedimentation load of the source water reduced by 65% at a distance of 25 m without any check barrier. All the combinations of check barriers were able to reduce the sediment load by more than 90% of that in the source water. The best results were obtained when the barrier with cooler mat was placed at first place and dead grass barrier at the second place. This combination resulted into a reduction of 99% in the sediment load of the source water by bringing down the source sediment load level from 7800 mg l^{-1} to the level of 70 mg l^{-1}.

Chapter VI

CONCLUSION AND PERSPECTIVE

Conclusion of the study under taken are presented as:

- Recharge rates were lower than recovery rates at soil research farm, Hisar due to shallow groundwater level and constant at RRS, Balsamand.
- Cumulative recovery efficiency was always greater than instantaneous recovery efficiency at both ASR sites.
- Recovery efficiency increased linearly with successive number of ASR cycles at both ASR sites.
- Cumulative recovery efficiency of 74.8 % and 44.4 % was achieved after four successive ASR cycles of 2000 m^3 at Hisar and three successive ASR cycles of 300 m^3 at Balsamand.
- The cumulative native water percentage in the recovered water M increased with recovery percentage I for all the quality parameters for all successive ASR cycles at both ASR sites.
- Simple mixing at 100 % recovery $M^*(Cl^-)$ decreased with successive ASR cycles at both ASR sites.
- Dissolution of calcite in equivalent amounts of Ca^{2+} and HCO_3^- was verified quantitatively in all successive ASR cycles.

- Release of Ca^{2+} and HCO_3^- from dissolution of calcite and of K^+ from Illite and of borate from Tourmaline decreased with successive ASR cycles at both the ASR sites.
- Recovery efficiency at target cumulative EC_{rw} of 2 dSm^{-1} increased linearly with successive ASR sites at both sites.
- One irrigation of 0.06 m would add 19, 18, 17 and 14 kg potassium with four successive ASR cycles at Hisar and 14, 6 and 5 kg potassium with three successive ASR cycles at Balsamand.
- Hydrus-2D simulated the drawup and drawdown of pressure head quite well during the whole period of recharge and recovery in four successive ASR cycles at Hisar and three successive ASR cycles at Balsamand.
- PMWIN simulated the drawup and drawdown of pressure head quite well during the whole period of recharge and recovery in four successive ASR cyclesat Hisar and three successive ASR cycles at Balsamand.
- PMWIN and HYDRUS-2D predicted the similar radial influencing zone of the ASR wells at Hisar and Balsamand ASR sites.
- Radial influencing zone increased with successive number of ASR cycles at both sites.
- 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 and PMWIN can be used for groundwater studies.
- HYDRUS-2D simulated the chloride concentration in recovered water quite well during the whole period of recharge and recovery in four successive ASR cycles at Hisar and three successive ASR cycles at Balsamand.
- PMWIN simulated the chloride concentration in recovered water quite well during the whole period of recharge and recovery in four successive ASR cyclesat Hisar and three successive ASR cycles at Balsamand.

- PMWIN and HYDRUS-2D simulated the almost similar cumulative chloride in recovered water after successive ASR cycles at Hisar and Balsamand.
- HYDRUS-2D and PMWIN can be utilized in solute transport studies in cavity type ASR wells.

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 desired depth especially in the brackish groundwater zones. The study would, therefore, serve the interest of researchers, industrialists, 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 and solute transport of ASR technology would be helpful in quantifying the temporal, spatial drawup and drawdown in water levels, assessing the environmental impacts and geo-physicochmical interactions in aquifers after recharging with fresh groundwater 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: Verse ate 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 diamante tetra-acetic acid EDTA (Verse ate solution). The end point was blue or bluish green color.

Calcium Ca^{2+}

Method used: Verse ate (EDTA) method

One ml of water sample was taken in china dish and add 5 ml of 16 % Noah 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.

$$HCO_3^- \text{ (meL}^{-1}) = \frac{\text{Volume of } H_2SO_4 \text{ used (ml) X N 1000}}{\text{ml of aliquot used}}$$

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 dilutes 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.

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

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 supertonic- 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 was: 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 $AlCl_3.6H_2O$ solutions. 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 and pH of the recovered water in different ASR cycles at Hisar ASR site

ASR cycle 1

$V_r = 2000\ m^3$ **$EC_n = 28.4\ dS\ m^{-1}$**

$V_i = 2000\ m^3$ **$EC_i = 0.55\ dS\ m^{-1}$**

Time (h)	qr ($m^3\ h^{-1}$)	Vr (m^3)	del Vr (m^3)	I (%)	EC ($dS\ m^{-1}$)		pH	
					Cr	Crw	Cr	Crw
1	2	3	4	5	6	7	8	9
0.02	66	1.10	1.10	0.10	0.51	0.51	7.85	7.85
0.25	66	1.10	16.50	0.83	0.54	0.54	7.85	7.85
0.50	63	1.05	15.00	1.58	0.66	0.60	7.91	7.88
0.75	63	1.05	15.75	2.36	0.72	0.64	7.91	7.89
1.00	63	1.05	15.75	3.15	0.89	0.70	7.91	7.90
1.50	60	1.00	27.00	4.50	0.95	0.78	7.95	7.91
2.00	60	1.00	30.00	6.00	0.98	0.83	7.96	7.93
3.00	66	1.10	78.00	9.90	1.25	0.99	7.96	7.94
4.00	63	1.05	54.00	12.60	1.56	1.11	8.00	7.95
7.00	63	1.05	189.00	22.05	1.92	1.46	8.01	7.98
10.00	63	1.05	189.00	31.50	2.15	1.67	8.01	7.99

13.00	66	1.10	228.00	42.90	2.84	1.98	8.05	8.00
16.00	63	1.05	150.00	50.40	4.40	2.34	8.03	8.01
19.00	66	1.10	246.00	62.70	5.60	2.98	8.05	8.01
22.00	63	1.05	132.00	69.30	6.50	3.31	8.10	8.02
25.00	63	1.05	189.00	78.75	8.54	3.94	8.15	8.03
28.00	63	1.05	189.00	88.20	11.60	4.76	8.17	8.03
31.00	63	1.05	189.00	97.65	14.56	5.71	8.19	8.03
34.00	60	1.00	87.00	102.00	16.20	6.16	8.21	8.04

qr - recovery rate; **Vr** - volume recovered at time (t); **I** - recovery percentage

Mean square error, **V**$_i$ - volume injected to be recovered, **ECn & ECi** - Electrical conductivity of native and injected water

ASR cycle 2

$V_r = 2000\ m^3$ $EC_n = 28.4\ dS\ m^{-1}$

$V_i = 2000\ m^3$ $EC_i = 0.55\ dS\ m^{-1}$

Time (h)	qr ($m^3\ h^{-1}$)	Vr (m^3)	del Vr (m^3)	I (%)	EC ($dS\ m^{-1}$)		pH	
					Cr	Crw	Cr	Crw
1	2	3	4	5	6	7	8	9
0.02	60.00	1.00	1.00	0.10	0.46	0.46	7.80	7.80
0.25	64.00	1.07	15.00	0.80	0.46	0.46	7.82	7.82
0.50	65.40	1.09	17.40	1.67	0.46	0.46	7.83	7.83
0.75	62.40	1.04	15.60	2.45	0.54	0.49	7.85	7.83
1.00	64.40	1.07	16.10	3.26	0.58	0.51	7.85	7.84
1.50	66.20	1.10	33.10	4.91	0.62	0.55	7.85	7.84
2.00	63.20	1.05	31.60	6.49	0.72	0.59	7.90	7.86
3.00	65.80	1.10	65.80	9.78	0.88	0.69	7.90	7.87
4.00	65.70	1.10	65.70	13.07	0.90	0.74	7.85	7.87
7.00	63.07	1.05	189.20	22.53	1.20	0.93	7.91	7.88
10.00	66.57	1.11	199.70	32.51	1.80	1.20	7.95	7.90
13.00	63.03	1.05	189.10	41.97	2.15	1.41	7.96	7.92
16.00	53.40	0.89	160.20	49.98	3.50	1.75	7.99	7.93

19.00	65.30	1.09	195.90	59.77	4.80	2.25	8.05	7.95
22.00	63.00	1.05	189.00	69.22	7.80	3.01	8.10	7.97
25.00	66.00	1.10	198.00	79.12	8.80	3.73	8.15	7.99
28.00	63.00	1.05	189.00	88.57	16.80	5.13	8.20	8.01
31.00	63.00	1.05	189.00	98.02	21.70	6.72	8.22	8.03
34.00	63.00	1.05	189.00	107.47	25.40	8.37	8.22	8.05

ASR cycle 3

V_r = 2000 m^3 **EC_n = 28.4 dS m^{-1}**

V_i = 2000 m^3 **EC_i = 0.55 dS m^{-1}**

Time	qr	Vr	del Vr	I	EC		pH	
(h)	(m^3 h^{-1})	(m^3)	(m^3)	(%)	(dS m^{-1})			
					Cr	Crw	Cr	Crw
1	2	3	4	5	6	7	8	9
0.02	66.00	1.10	1.10	0.06	0.46	0.46	7.80	7.80
0.25	65.79	1.10	15.35	0.82	0.48	0.46	7.82	7.82
0.50	65.80	1.10	16.45	1.65	0.46	0.46	7.83	7.83
0.75	63.00	1.05	15.75	2.43	0.52	0.49	7.85	7.83
1.00	66.00	1.10	16.50	3.26	0.56	0.51	7.85	7.84
1.50	66.00	1.10	33.00	4.91	0.60	0.55	7.85	7.84
2.00	66.00	1.10	33.00	6.56	0.78	0.59	7.90	7.86
3.00	66.00	1.10	66.00	9.86	0.81	0.69	7.90	7.87
4.00	66.00	1.10	66.00	13.16	0.95	0.74	7.85	7.87
7.00	66.00	1.10	198.00	23.06	1.15	0.93	7.91	7.88
10.00	63.00	1.05	189.00	32.51	1.82	1.20	7.95	7.90
13.00	66.00	1.10	198.00	42.41	1.98	1.41	7.96	7.92
16.00	63.00	1.05	189.00	51.86	2.15	1.75	7.99	7.93

19.00	63.00	1.05	189.00	61.31	2.54	2.25	8.05	7.95
22.00	66.00	1.10	198.00	71.21	4.40	3.01	8.10	7.97
25.00	63.00	1.05	189.00	80.66	5.60	3.73	8.15	7.99
28.00	63.00	1.05	189.00	90.11	12.50	5.13	8.20	8.01
31.00	63.00	1.05	189.00	99.56	22.80	6.72	8.22	8.03
34.00	66.00	1.10	198.00	109.46	26.80	8.37	8.22	8.05

ASR cycle 4

V_r = 2000 m^3 **EC_n = 28.4 dS m^{-1}**

V_i = 2000 m^3 **EC_i = 0.55 dS m^{-1}**

Time (h)	qr (m^3 h^{-1})	Vr (m^3)	del Vr (m^3)	I (%)	EC (dS m^{-1})		pH	
					Cr	Crw	Cr	Crw
1	2	3	4	5	6	7	8	9
0.02	66.00	1.10	1.10	0.06	0.46	0.46	7.80	7.80
0.25	66.00	1.10	15.40	0.83	0.48	0.46	7.82	7.82
0.50	66.00	1.10	16.50	1.65	0.46	0.46	7.83	7.83
0.75	66.00	1.10	16.50	2.48	0.52	0.49	7.85	7.83
1.00	66.00	1.10	16.50	3.30	0.56	0.51	7.85	7.84
1.50	66.00	1.10	33.00	4.95	0.60	0.55	7.85	7.84
2.00	66.00	1.10	33.00	6.60	0.78	0.59	7.90	7.86
3.00	66.00	1.10	66.00	9.90	0.81	0.69	7.90	7.87
4.00	66.00	1.10	66.00	13.20	0.95	0.74	7.85	7.87
7.00	66.00	1.10	198.00	23.10	1.15	0.93	7.91	7.88
10.00	63.00	1.05	189.00	32.55	1.82	1.20	7.95	7.90
13.00	66.00	1.10	198.00	42.45	1.98	1.41	7.96	7.92
16.00	63.00	1.05	189.00	51.90	2.15	1.75	7.99	7.93

19.00	63.00	1.05	189.00	61.35	2.54	2.25	8.05	7.95
22.00	63.00	1.05	189.00	70.80	4.40	3.01	8.10	7.97
25.00	63.00	1.05	189.00	80.25	5.60	3.73	8.15	7.99
28.00	63.00	1.05	189.00	89.70	12.50	5.13	8.20	8.01
31.00	60.00	1.00	180.00	98.70	22.80	6.72	8.22	8.03
34.00	60.00	1.00	180.00	107.70	26.80	8.37	8.22	8.05

Appendix - III

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

ASR cycle 1

$V_r = 2000\ m^3$ $V_i = 2000\ m^3$

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
0.06	0.5	0.5	0.2	0.2	0.6	0.6	0.4	0.4	0.6	0.6	1.0	1.0	0.16	0.16	0.01	0.01	0.15	0.15	9.2	-0.4	0.69
0.83	0.5	0.5	0.2	0.2	0.7	0.7	0.4	0.4	0.6	0.6	1.0	1.0	0.17	0.17	0.01	0.01	0.15	0.15	8.6	-0.5	0.66
1.65	0.5	0.5	0.2	0.2	1.0	0.8	0.6	0.5	0.8	0.7	1.3	1.1	0.18	0.17	0.01	0.01	0.16	0.15	-4.5	-0.8	0.55
2.48	0.7	0.6	0.2	0.2	1.5	1.1	0.8	0.6	1.1	0.8	1.8	1.4	0.19	0.18	0.03	0.01	0.17	0.15	-8.5	-1.2	0.62
3.30	0.8	0.6	0.2	0.2	1.8	1.2	1.0	0.7	1.4	1.0	2.4	1.6	0.20	0.18	0.05	0.02	0.2	0.18	-7.4	-1.4	0.68
4.95	0.9	0.7	0.2	0.2	2.0	1.5	1.4	0.9	1.5	1.1	3.0	2.0	0.21	0.19	0.07	0.04	0.21	0.18	-6.3	-1.9	0.69
6.60	0.8	3.5	0.2	0.3	2.2	3.5	2.5	3.5	2.2	3.5	3.6	3.5	0.22	0.20	0.08	0.05	0.21	0.19	4.4	-2.5	0.50
9.90	1.0	0.8	0.3	0.2	2.4	1.9	3.3	2.1	3.2	2.1	4.0	3.0	0.23	0.21	0.09	0.06	0.21	0.19	-8.2	-2.5	0.59
13.20	1.5	1.0	0.3	0.2	2.8	2.1	4.1	2.5	4.0	2.5	4.8	3.4	0.25	0.22	0.10	0.07	0.22	0.21	-8.3	-2.9	0.81
23.10	1.9	1.4	0.5	0.3	3.5	2.7	5.2	3.7	5.1	3.6	6.3	4.7	0.30	0.25	0.13	0.10	0.22	0.21	9.3	-3.6	0.93
32.55	2.6	1.7	0.8	0.5	4.2	3.2	6.7	4.6	6.3	4.4	7.6	5.5	0.32	0.27	0.15	0.11	0.23	0.22	-4.3	-4.6	1.10
42.45	4.7	2.5	1.0	0.6	5.0	3.7	8.1	5.5	7.6	5.3	11.4	7.1	0.42	0.31	0.18	0.13	0.23	0.22	-5.5	-5.5	1.82

XV

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
51.90	15.4	4.4	1.2	0.7	6.0	4.0	9.8	6.2	11.2	6.2	20.0	9.0	0.5	0.3	0.19	0.14	0.23	0.22	7.9	-4.6	5.48
61.35	22.5	8.0	1.4	0.8	7.0	4.6	13.0	7.5	13.6	7.6	30.2	13.2	0.6	0.4	0.20	0.15	0.24	0.22	-7.4	-6.4	7.12
70.80	32.3	10.3	1.6	0.9	8.0	4.9	16.4	8.3	14.2	8.2	45.3	16.2	0.6	0.4	0.21	0.16	0.29	0.23	-9.0	-10.2	9.25
80.25	43.2	14.2	2.0	1.0	9.2	5.4	22.6	10.1	15.2	9.1	72.0	22.9	0.7	0.4	0.22	0.16	0.40	0.23	-4.5	-16.6	10.83
89.70	55.8	18.7	2.1	1.2	11.3	6.1	28.3	12.0	16.8	9.9	142.5	35.7	0.8	0.5	0.22	0.17	0.52	0.26	-8.9	-22.8	12.55
98.70	73.3	24.0	2.1	1.2	14.4	6.9	32.5	14.0	18.4	10.7	178.5	49.5	0.9	0.5	0.22	0.18	0.54	0.26	-0.9	-28.5	15.15
107.70	98.6	27.2	2.1	1.3	20.5	7.4	38.2	15.0	21.2	11.2	160.0	54.3	0.9	0.5	0.22	0.18	0.57	0.28	-4.6	-37.5	18.20
C_i	0.5		0.16		0.6		0.4		0.6		1.0		0.16		0.010						
C_n	159.1		2.1		39.0		86.0		24.0		261		1		0.300						

C_i & C_n - concentration of salts in recharged water and native water respectively

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

ASR cycle 2

$V_r = 2000\ m^3$ $V_i = 2000\ m^3$

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
0.06	0.5	0.5	0.2	0.2	0.6	0.6	0.4	0.4	0.6	0.6	1.0	1.0	0.16	0.16	0.01	0.01	0.15	0.15	-5.36	-0.40	0.693
0.83	0.5	0.5	0.2	0.2	0.6	0.6	0.4	0.4	0.6	0.6	1.0	0.9	0.16	0.15	0.01	0.00	0.15	0.15	-3.88	-0.40	0.693
1.65	0.5	0.5	0.2	0.2	0.7	0.6	0.5	0.4	0.6	0.6	1.2	1.1	0.16	0.16	0.01	0.00	0.15	0.15	-5.36	-0.60	0.671
2.48	0.9	0.6	0.2	0.2	0.8	0.7	0.6	0.5	0.7	0.6	1.7	1.3	0.17	0.16	0.01	0.01	0.15	0.15	-4.52	-0.70	1.076
3.30	1.0	0.7	0.2	0.2	0.9	0.7	0.8	0.6	1.0	0.7	2.0	1.5	0.18	0.16	0.01	0.01	0.15	0.15	-7.91	-0.70	1.085
4.95	1.6	1.0	0.3	0.2	1.0	0.8	1.0	0.7	1.3	0.9	2.6	1.8	0.19	0.17	0.01	0.01	0.15	0.15	2.383	-0.70	1.6
6.60	1.8	1.2	0.3	0.2	1.2	0.9	1.4	0.9	1.4	1.0	3.3	2.2	0.21	0.18	0.03	0.01	0.15	0.15	9.884	-1.20	1.579
9.90	2.2	1.5	0.3	0.2	2.3	1.4	1.8	1.2	1.6	1.2	5.0	3.1	0.23	0.2	0.05	0.03	0.22	0.17	6.882	-2.50	1.537
13.20	2.9	1.9	0.3	0.3	2.4	1.6	2.1	1.4	2.5	1.5	5.5	3.7	0.25	0.21	0.07	0.04	0.24	0.19	2.373	-2.00	1.933
23.10	3.6	2.6	0.4	0.3	2.9	2.2	2.8	2.0	3.4	2.3	6.3	4.8	0.28	0.24	0.09	0.06	0.24	0.21	2.982	-2.30	2.132
32.55	5.2	3.4	0.6	0.4	3.8	2.6	3.5	2.5	5.0	3.1	7.6	5.7	0.32	0.26	0.10	0.07	0.24	0.22	13.21	-2.30	2.722
42.45	9.0	4.7	0.8	0.5	4.2	3.0	5.0	3.0	6.8	4.0	11.4	7.0	0.35	0.28	0.11	0.08	0.31	0.24	14.58	-2.40	4.196

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
51.90	15.4	6.4	1.0	0.6	5.1	3.4	7.8	3.8	8.2	4.6	20.0	9.0	0.42	0.31	0.14	0.09	0.33	0.26	10.03	-4.70	6.064
61.35	22.5	9.0	1.1	0.7	6.8	3.9	9.0	4.6	9.6	5.5	30.2	12.5	0.56	0.35	0.15	0.10	0.40	0.28	12.48	-6.20	8.005
70.80	32.3	12.2	1.4	0.8	7.2	4.4	13.5	5.9	11.4	6.3	45.3	17.0	0.6	0.38	0.17	0.11	0.41	0.30	-3.15	-9.30	10.04
80.25	48.3	16.7	1.7	0.9	9.8	5.0	15.2	7.0	13.2	7.1	67.2	23.3	0.63	0.41	0.19	0.12	0.45	0.32	9.111	-11.80	13.65
89.70	70.5	22.4	1.8	1.0	11.8	5.7	18.3	8.2	14.8	8.0	88.0	30.2	0.68	0.44	0.20	0.13	0.50	0.34	-5.81	-15.30	18.17
98.70	90.9	29.0	1.8	1.1	13.2	6.4	22.4	9.6	15.6	8.7	115.3	38.4	0.72	0.47	0.21	0.14	0.51	0.35	5.277	-20.00	21.54
107.70	132.2	38.1	1.9	1.1	14.0	7.0	26.0	11.0	23.0	9.9	162.0	49.3	0.82	0.5	0.22	0.14	0.55	0.37	-2.95	-17.00	29.56

ASR cycle 3

V_r = 2000 m^3 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
0.06	0.5	0.5	0.2	0.2	0.6	0.6	0.4	0.4	0.6	0.6	1.0	1.0	0.16	0.16	0.01	0.01	0.15	0.15	2.59	-0.4	0.693
0.83	0.5	0.5	0.2	0.2	0.6	0.6	0.4	0.4	0.6	0.6	1.0	1.0	0.16	0.16	0.01	0.01	0.20	0.20	1.86	-0.4	0.69
1.65	0.5	0.5	0.2	0.2	0.6	0.6	0.4	0.4	0.6	0.6	1.0	1.0	0.16	0.16	0.01	0.01	0.20	0.20	-9.24	-0.4	0.69
2.48	0.5	0.5	0.2	0.2	0.7	0.6	0.4	0.4	0.6	0.6	1.0	1.0	0.16	0.16	0.01	0.01	0.20	0.20	-6.51	-0.5	0.66
3.30	0.7	0.5	0.2	0.2	0.8	0.7	0.4	0.4	0.8	0.7	1.2	1.1	0.18	0.17	0.01	0.01	0.22	0.20	-3.77	-0.4	0.90
4.95	1.2	0.8	0.2	0.2	0.9	0.8	0.5	0.4	1.1	0.8	1.4	1.2	0.19	0.17	0.03	0.01	0.20	0.20	-6.32	-0.3	1.43
6.60	1.4	0.9	0.2	0.2	1.0	0.8	0.8	0.5	1.2	0.9	1.8	1.3	0.20	0.18	0.04	0.02	0.22	0.21	-9.8	-0.6	1.48
9.90	1.3	1.0	0.2	0.2	1.3	1.0	1.4	0.8	1.4	1.1	2.2	1.6	0.22	0.19	0.05	0.03	0.20	0.20	-8.06	-1.3	1.12
13.20	1.7	1.2	0.2	0.2	1.8	1.2	1.8	1.1	1.7	1.2	2.8	1.9	0.23	0.20	0.06	0.04	0.20	0.20	-9.01	-1.9	1.27
23.10	2.1	1.6	0.3	0.2	2.0	1.5	2.5	1.7	2.4	1.7	3.5	2.6	0.24	0.22	0.07	0.05	0.23	0.21	3.092	-2.1	1.40
32.55	3.5	2.15	0.3	0.24	2.3	1.8	3.2	2.12	3.7	2.3	5.3	3.38	0.25	0.23	0.08	0.06	0.30	0.24	4.128	-1.8	2.11
42.45	4.5	2.7	0.6	0.3	2.8	2.0	5.0	2.8	4.6	2.8	8.8	4.6	0.27	0.24	0.09	0.07	0.30	0.25	9.788	-3.2	2.28

XIX

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
51.90	6.0	3.3	1.0	0.4	3.2	2.2	6.8	3.5	6.2	3.5	11.2	5.8	0.30	0.25	0.10	0.07	0.40	0.28	9.33	-3.8	2.68
61.35	7.7	4.0	1.1	0.5	4.5	2.6	9.5	4.4	8.1	4.2	14.8	7.2	0.34	0.26	0.13	0.08	0.40	0.30	9.374	-5.9	2.91
70.80	18.4	6.0	1.2	0.6	6.0	3.0	11.4	5.4	9.2	4.9	29.2	10.3	0.42	0.28	0.15	0.09	0.35	0.31	-4.1	-8.2	6.24
80.25	33.6	9.2	1.5	0.7	7.5	3.6	14.2	6.4	13.7	5.9	43.7	14.2	0.62	0.32	0.18	0.10	0.30	0.31	-2.31	-8.0	10.20
89.70	65.4	15.1	1.8	0.9	9.0	4.1	18.2	7.7	15.4	6.9	80.4	21.1	0.63	0.36	0.19	0.11	0.35	0.31	4.368	-11.8	17.73
98.70	120.6	25.1	2.0	1.0	13.2	5.0	24.6	9.3	18.2	8.0	140.2	32.4	0.72	0.39	0.20	0.12	0.50	0.33	-5.4	-19.6	27.74
107.70	142.8	35.8	2.1	1.1	15.6	6.0	27.6	10.9	21.0	9.1	180.5	45.8	0.80	0.43	0.21	0.13	0.52	0.35	-1.56	-22.2	30.72

ASR cycle 4

$V_r = 2000\ m^3$ $V_i = 2000\ m^3$

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
0.06	0.5	0.5	0.2	0.2	0.6	0.60	0.4	0.40	0.6	0.60	1.0	1.0	0.16	0.16	0.005	0.005	0.15	0.15	-6.3	-0.4	0.69
0.83	0.5	0.5	0.2	0.2	0.6	0.60	0.4	0.40	0.6	0.60	1.0	1.0	0.16	0.16	0.005	0.005	0.22	0.22	-6.8	-0.4	0.69
1.65	0.5	0.5	0.2	0.2	0.6	0.65	0.4	0.40	0.6	0.60	1.0	1.0	0.17	0.17	0.005	0.005	0.25	0.24	-5.7	-0.4	0.69
2.48	0.5	0.5	0.2	0.2	0.7	0.70	0.4	0.40	0.6	0.60	1.0	1.0	0.17	0.17	0.005	0.005	0.23	0.23	-5.0	-0.5	0.66
3.30	0.6	0.6	0.2	0.2	0.8	0.75	0.4	0.43	0.7	0.63	1.2	1.1	0.18	0.17	0.005	0.005	0.23	0.23	7.9	-0.5	0.77
4.95	0.9	0.8	0.3	0.2	0.9	0.83	0.5	0.48	0.9	0.72	1.4	1.2	0.19	0.18	0.007	0.006	0.23	0.23	10.2	-0.5	1.08
6.60	1.2	1.0	0.2	0.2	1	0.90	0.6	0.54	1.1	0.81	2.1	1.4	0.20	0.18	0.008	0.006	0.23	0.23	7.2	-0.5	1.34
9.90	1.6	1.3	0.3	0.2	1.1	1.03	0.7	0.83	1.2	0.94	2.6	1.8	0.21	0.19	0.010	0.008	0.22	0.23	9.5	-0.6	1.69
13.20	1.8	1.6	0.3	0.3	1.3	1.23	1.4	1.02	1.3	1.03	2.9	2.1	0.22	0.20	0.040	0.016	0.22	0.23	8.5	-1.4	1.55
23.10	2.4	2.4	0.3	0.3	1.8	1.60	1.6	1.44	1.6	1.28	3.6	2.7	0.23	0.21	0.050	0.030	0.30	0.26	10.7	-1.8	1.84
32.55	3.6	3.0	0.5	0.3	2.1	1.80	2.0	1.86	2.5	1.63	4.9	3.4	0.25	0.22	0.070	0.042	0.35	0.285	2.7	-1.6	2.51
42.45	4.5	3.6	0.5	0.4	2.3	2.27	2.9	2.36	3.9	2.16	6.2	4.02	0.26	0.23	0.080	0.051	0.35	0.3	-3.1	-1.3	2.79

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
51.90	5.4	4.1	0.6	0.4	3.8	2.62	4.0	3.04	4.7	2.62	9.2	5.0	0.28	0.24	0.120	0.063	0.35	0.31	2.9	-3.1	2.73
61.35	6.5	6.9	0.8	0.5	4.2	3.16	6.1	3.68	6.2	3.17	11.2	5.9	0.30	0.25	0.140	0.075	0.36	0.32	8.1	-4.1	2.86
70.80	22.3	10.0	1.0	0.5	6.1	3.83	7.2	4.71	11.2	4.24	23.5	8.3	0.32	0.26	0.160	0.086	0.40	0.33	9.4	-2.1	8.65
80.25	30.2	16.7	1.2	0.6	8.2	4.58	11.4	6.34	13.5	5.33	36.5	11.6	0.33	0.27	0.180	0.098	0.48	0.35	9.7	-6.1	9.65
89.70	66.5	27.6	1.6	0.7	10.2	5.49	18.5	8.1	15.2	6.37	78.8	18.7	0.42	0.28	0.19	0.11	0.48	0.35	10.4	-13.5	17.55
98.70	120.4	39.4	1.8	0.8	13.2	6.41	23.2	10.0	16.7	7.32	132.6	29.1	0.45	0.30	0.20	0.12	0.50	0.36	9.8	-19.7	28.22
107.70	156.6	36.1	2.1	0.9	15.6	5.87	28.5	9.1	21.4	8.49	180.6	41.7	0.60	0.32	0.21	0.12	0.55	0.38	9.5	-22.7	33.35

Appendix - IV

Table A IV: Depth of water head in piezometer d_{hp} during recharge in first ASR cycle at Soil Reseach Farm, Hisar

Time	qi	V_i	d_{ph}	Drawup in d_{ph}	Time	qi	V_i	d_{ph}	Drawup in d_{ph}	Time	qi	V_i	d_{ph}	Drawup in d_{ph}
(h)	(m^3/h)	(m^3)			(h)	(m^3/h)	(m^3)			(h)	(m^3/h)	(m^3)		
1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
0.00	0.00	0.00	48.60	0.00	0.27	23.76	6.34	50.00	0.00	3.00	23.76	71.28	50.90	0.00
0.02	23.76	0.48	49.10	0.50	0.28	23.76	6.65	50.05	0.05	9.00	23.76	213.84	51.10	0.20
0.03	23.76	0.71	49.30	0.20	0.30	23.76	7.13	50.10	0.05	15.00	23.76	356.40	51.20	0.10
0.05	23.76	1.19	49.40	0.10	0.32	23.76	7.60	50.05	-0.05	21.00	23.76	498.96	51.30	0.10
0.07	23.76	1.66	49.50	0.10	0.33	23.76	7.84	50.10	0.05	27.00	23.76	641.52	51.40	0.10
0.08	23.76	1.90	49.55	0.05	0.35	23.76	8.32	50.15	0.05	33.00	22.32	736.56	51.50	0.10
0.10	23.76	2.38	49.60	0.05	0.37	23.76	8.79	50.20	0.05	39.00	22.32	870.48	51.60	0.30
0.12	23.76	2.85	49.65	0.05	0.38	23.76	9.03	50.20	0.00	45.00	22.32	1004.40	51.50	-0.10
0.13	23.76	3.09	49.70	0.05	0.40	23.76	9.50	50.25	0.05	51.00	22.32	1138.32	51.70	0.20
0.15	23.76	3.56	49.75	0.05	0.42	23.76	9.98	50.25	0.00	57.00	22.32	1272.24	51.70	0.00
0.17	23.76	4.04	49.80	0.05	0.43	23.76	10.22	50.25	0.00	63.00	22.32	1406.16	51.80	0.10
0.18	23.76	4.28	49.85	0.05	0.45	23.76	10.69	50.30	0.05	69.00	23.76	1639.44	52.00	0.20
0.20	23.76	4.75	49.90	0.05	0.47	23.76	11.17	50.35	0.05	75.00	23.76	1782.00	51.90	-0.10
0.22	23.76	5.23	49.95	0.05	0.48	23.76	11.40	50.50	0.15	81.00	23.76	1924.56	52.00	0.10
0.23	23.76	5.46	50.00	0.05	0.50	23.76	11.88	50.50	0.00	87.00	23.76	2067.12	52.00	0.00
0.25	23.76	5.94	50.00	0.00	1.00	23.76	23.76	50.70	0.20					

Table B V: Depth of water head in piezometer d_{hp} during recovery in first ASR cycle at Soil Reseach Farm, Hisar

Time (h)	qi (m^3/h)	V_i (m^3)	d_{ph}	Drawdown in d_{ph}	Time (h)	qi (m^3/h)	V_i (m^3)	d_{ph}	Drawdown in d_{ph}	Time (h)	qi (m^3/h)	V_i (m^3)	d_{ph}	Drawdown in d_{ph}
1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
87	0.00	0	52.00	52.00	87.27	64.80	17.50	50.50	-0.10	88.00	64.80	64.80	49.00	-0.30
87.02	64.80	1.30	51.60	-0.40	87.28	64.80	18.14	50.40	-0.10	88.50	64.80	97.20	48.70	-0.30
87.03	64.80	1.94	51.50	-0.10	87.30	64.80	19.44	50.50	0.10	89.00	64.80	129.60	48.30	-0.40
87.05	64.80	3.24	51.40	-0.10	87.32	64.80	20.74	50.40	-0.10	90.00	64.80	194.40	47.60	-0.70
87.07	64.80	4.54	51.30	-0.10	87.33	64.80	21.38	50.50	0.10	91.00	64.80	259.20	47.10	-0.50
87.08	64.80	5.18	51.20	-0.10	87.35	64.80	22.68	50.30	-0.20	94.00	64.80	453.60	46.40	-0.70
87.10	64.80	6.48	51.15	-0.05	87.37	64.80	23.98	50.20	-0.10	97.00	64.80	648.00	46.00	-0.40
87.12	64.80	7.78	51.10	-0.05	87.38	64.80	24.62	50.10	-0.10	100.00	64.80	842.40	45.80	-0.20
87.13	64.80	8.42	51.05	-0.05	87.40	64.80	25.92	50.00	-0.10	103.00	64.80	1036.80	45.60	-0.20
87.15	64.80	9.72	51.00	-0.05	87.42	64.80	27.22	50.00	0.00	106.00	64.80	1231.20	45.40	-0.20
87.17	64.80	11.02	51.05	0.05	87.43	64.80	27.86	49.90	-0.10	109.00	64.80	1425.60	45.20	-0.20
87.18	64.80	11.66	50.95	-0.10	87.45	64.80	29.16	49.80	-0.10	112.00	64.80	1620.00	45.30	0.10
87.20	64.80	12.96	50.90	-0.05	87.47	64.80	30.46	49.70	-0.10	115.00	64.80	1814.40	45.10	-0.20
87.22	64.80	14.26	50.80	-0.10	87.48	64.80	31.10	49.60	-0.10	118.00	64.80	2008.80	45.00	-0.10
87.23	64.80	14.90	50.70	-0.10	87.50	64.80	32.40	49.50	-0.10	121.00	64.80	2203.20	44.80	-0.20
87.25	64.80	16.20	50.60	-0.10	87.75	64.80	48.60	49.30	-0.20	126.00	0.00	0.00	44.80	0.00

Table C VI: Depth of water head in piezometer d_{hp} during recharge in second ASR cycle at Soil Reseach Farm, Hisar

Time (h)	qi (m^3/h)	V_i (m^3)	d_{ph}	Drawup in d_{ph}	Time (h)	qi (m^3/h)	V_i (m^3)	d_{ph}	Drawup in d_{ph}	Time (h)	qi (m^3/h)	V_i (m^3)	d_{ph}	Drawup in d_{ph}
1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
126.00	0.00	0.00	44.80	44.80	126.27	23.76	6.34	50.05	0.00	129.00	23.76	71.28	50.80	0.20
126.02	23.76	0.48	49.25	4.45	126.28	23.76	6.65	50.10	0.05	135.00	23.76	213.84	50.90	0.10
126.03	23.76	0.71	49.40	0.15	126.30	23.76	7.13	50.15	0.05	141.00	23.76	356.40	51.20	0.30
126.05	23.76	1.19	49.50	0.10	126.32	23.76	7.60	50.20	0.05	147.00	23.76	498.96	51.40	0.20
126.07	23.76	1.66	49.60	0.10	126.33	23.76	7.84	50.20	0.00	153.00	23.76	641.52	51.60	0.20
126.08	23.76	1.90	49.70	0.10	126.35	23.76	8.32	50.15	-0.05	159.00	22.32	736.56	51.80	0.20
126.10	23.76	2.38	49.75	0.05	126.37	23.76	8.79	50.30	0.15	165.00	22.32	870.48	51.70	-0.10
126.12	23.76	2.85	49.80	0.05	126.38	23.76	9.03	50.35	0.05	171.00	22.32	1004.40	51.80	0.10
126.13	23.76	3.09	49.80	0.00	126.40	23.76	9.50	50.40	0.05	177.00	22.32	1138.32	51.80	0.00
126.15	23.76	3.56	49.85	0.05	126.42	23.76	9.98	50.45	0.05	183.00	22.32	1272.24	51.90	0.10
126.17	23.76	4.04	49.80	-0.05	126.43	23.76	10.22	50.50	0.05	189.00	22.32	1406.16	51.90	0.00
126.18	23.76	4.28	49.85	0.05	126.45	23.76	10.69	50.55	0.05	195.00	23.76	1639.44	52.00	0.10
126.20	23.76	4.75	49.90	0.05	126.47	23.76	11.17	50.60	0.05	201.00	23.76	1782.00	52.10	0.10
126.22	23.76	5.23	49.95	0.05	126.48	23.76	11.40	50.55	-0.05	207.00	23.76	1924.56	52.20	0.10
126.23	23.76	5.46	50.00	0.05	126.50	23.76	11.88	50.60	0.05	213.00	0.00	2067.12	52.30	0.10
126.25	23.76	5.94	50.05	0.05	127.00	23.76	23.76	50.60	0.00					

Table D VII: Depth of water head in piezometer d_{hp} during recovery in second ASR cycle at Soil Reseach Farm, Hisar

Time (h)	qi (m^3/h)	V_i (m^3)	d_{ph}	Drawdown in d_{ph}	Time (h)	qi (m^3/h)	V_i (m^3)	d_{ph}	Drawdown in d_{ph}	Time (h)	qi (m^3/h)	V_i (m^3)	d_{ph}	Drawdown in d_{ph}
1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
213	0.00	0	52.30	0	213.27	64.80	17.50	49.10	-0.20	214.00	64.80	64.8	46.80	-0.20
213.02	64.80	1.30	51.65	-0.65	213.28	64.80	18.14	49.00	-0.10	214.50	64.80	97.20	46.50	-0.30
213.03	64.80	1.94	51.00	-0.65	213.30	64.80	19.44	48.90	-0.10	215	64.80	129.60	46.00	-0.50
213.05	64.80	3.24	50.80	-0.20	213.32	64.80	20.74	48.70	-0.20	216	64.80	194.40	45.80	-0.20
213.07	64.80	4.54	50.60	-0.20	213.33	64.80	21.38	48.60	-0.10	217	64.80	259.20	45.50	-0.30
213.08	64.80	5.18	50.40	-0.20	213.35	64.80	22.68	48.40	-0.20	220	64.80	453.60	45.30	-0.20
213.10	64.80	6.48	50.25	-0.15	213.37	64.80	23.98	48.30	-0.10	223	64.80	648.00	45.20	-0.10
213.12	64.80	7.78	50.10	-0.15	213.38	64.80	24.62	48.20	-0.10	226	64.80	842.40	45.10	-0.10
213.13	64.80	8.42	50.00	-0.10	213.40	64.80	25.92	48.10	-0.10	229	64.80	1036.80	45.00	-0.10
213.15	64.80	9.72	49.90	-0.10	213.42	64.80	27.22	48.00	-0.10	232	64.80	1231.20	44.80	-0.20
213.17	64.80	11.02	49.80	-0.10	213.43	64.80	27.86	47.90	-0.10	235	64.80	1425.60	44.70	-0.10
213.18	64.80	11.66	49.70	-0.10	213.45	64.80	29.16	47.80	-0.10	238	64.80	1620.00	44.60	-0.10
213.20	64.80	12.96	49.60	-0.10	213.47	64.80	30.46	47.60	-0.20	241	64.80	1814.40	44.50	-0.10
213.22	64.80	14.26	49.50	-0.10	213.48	64.80	31.10	47.40	-0.20	244	64.80	2008.80	44.50	0.00
213.23	64.80	14.90	49.40	-0.10	213.50	64.80	32.40	47.20	-0.20	255.00	64.80	2203.20	44.80	0.30
213.25	64.80	16.20	49.30	-0.10	213.75	49.20	48.60	47.00	-0.20					

Table E VIII: Depth of water head in piezometer d_{hp} during recharge in third ASR cycle at Soil Reseach Farm, Hisar

Time (h)	qi (m^3/h)	V_i (m^3)	d_{ph}	Drawup in d_{ph}	Time (h)	qi (m^3/h)	V_i (m^3)	d_{ph}	Drawup in d_{ph}	Time (h)	qi (m^3/h)	V_i (m^3)	d_{ph}	Drawup in d_{ph}
1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
255.00	0.00	0.00	44.80	44.80	255.27	23.76	6.34	50.05	0.00	256	23.76	71.28	50.80	0.20
255.02	23.76	0.48	49.25	4.45	255.28	23.76	6.65	50.10	0.05	258	23.76	213.84	50.90	0.10
255.03	23.76	0.71	49.40	0.15	255.30	23.76	7.13	50.15	0.05	264	23.76	356.40	51.20	0.30
255.05	23.76	1.19	49.50	0.10	255.32	23.76	7.60	50.20	0.05	270	23.76	498.96	51.40	0.20
255.07	23.76	1.66	49.60	0.10	255.33	23.76	7.84	50.20	0.00	276	23.76	641.52	51.60	0.20
255.08	23.76	1.90	49.70	0.10	255.35	23.76	8.32	50.15	-0.05	282	22.32	736.56	51.80	0.20
255.10	23.76	2.38	49.75	0.05	255.37	23.76	8.79	50.30	0.15	288	22.32	870.48	51.70	-0.10
255.12	23.76	2.85	49.80	0.05	255.38	23.76	9.03	50.35	0.05	294	22.32	1004.40	51.80	0.10
255.13	23.76	3.09	49.80	0.00	255.40	23.76	9.50	50.40	0.05	300	22.32	1138.32	51.90	0.10
255.15	23.76	3.56	49.85	0.05	255.42	23.76	9.98	50.45	0.05	306	22.32	1272.24	52.00	0.10
255.17	23.76	4.04	49.80	-0.05	255.43	23.76	10.22	50.50	0.05	312	22.32	1406.16	52.10	0.10
255.18	23.76	4.28	49.85	0.05	255.45	23.76	10.69	50.50	0.00	318	23.76	1639.44	52.20	0.10
255.20	23.76	4.75	49.90	0.05	255.47	23.76	11.17	50.55	0.05	324	23.76	1782.00	52.30	0.10
255.22	23.76	5.23	49.95	0.05	255.48	23.76	11.40	50.60	0.05	330	23.76	1924.56	52.40	0.10
255.23	23.76	5.46	50.00	0.05	255.50	23.76	11.88	50.70	0.10	336	23.76	2067.12	52.40	0.00
255.25	23.76	5.94	50.05	0.05	255.75	23.76	23.76	50.75	0.05	342	0.00	0.00	52.40	0.00

Table F IX: Depth of water head in piezometer d_{hp} during recovery in third ASR cycle at Soil Reseach Farm, Hisar

Time (h)	qi (m^3/h)	V_i (m^3)	d_{ph}	Drawdown in d_{ph}	Time (h)	qi (m^3/h)	V_i (m^3)	d_{ph}	Drawdown in d_{ph}	Time (h)	qi (m^3/h)	V_i (m^3)	d_{ph}	Drawdown in d_{ph}
1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
342	0.00	0	52.30	0	342.27	64.80	17.50	50.50	0.05	342.77	64.80	64.8	49.40	-0.20
342.02	64.80	1.30	52.40	0.10	342.28	64.80	18.14	50.45	-0.05	343.02	64.80	97.20	48.70	-0.70
342.03	64.80	1.94	51.70	-0.70	342.30	64.80	19.44	50.40	-0.05	343.52	64.80	129.60	48.00	-0.70
342.05	64.80	3.24	51.45	-0.25	342.32	64.80	20.74	50.35	-0.05	344	64.80	194.40	47.40	-0.60
342.07	64.80	4.54	51.30	-0.15	342.33	64.80	21.38	50.30	-0.05	345	64.80	259.20	46.70	-0.70
342.08	64.80	5.18	51.20	-0.10	342.35	64.80	22.68	50.25	-0.05	346	64.80	453.60	46.10	-0.60
342.10	64.80	6.48	51.10	-0.10	342.37	64.80	23.98	50.20	-0.05	349	64.80	648.00	45.80	-0.30
342.12	64.80	7.78	51.00	-0.10	342.38	64.80	24.62	50.15	-0.05	352	64.80	842.40	45.60	-0.20
342.13	64.80	8.42	50.90	-0.10	342.40	64.80	25.92	50.00	-0.15	355	64.80	1036.80	45.40	-0.20
342.15	64.80	9.72	50.80	-0.10	342.42	64.80	27.22	49.95	-0.05	358	64.80	1231.20	45.20	-0.20
342.17	64.80	11.02	50.70	-0.10	342.43	64.80	27.86	49.90	-0.05	361	64.80	1425.60	45.10	-0.10
342.18	64.80	11.66	50.60	-0.10	342.45	64.80	29.16	49.85	-0.05	364	64.80	1620.00	45.00	-0.10
342.20	64.80	12.96	50.50	-0.10	342.47	64.80	30.46	49.80	-0.05	367	64.80	1814.40	44.90	-0.10
342.22	64.80	14.26	50.55	0.05	342.48	64.80	31.10	49.75	-0.05	370	64.80	2008.80	44.70	-0.20
342.23	64.80	14.90	50.50	-0.05	342.50	64.80	32.40	49.70	-0.05	376	64.80	2203.20	44.60	-0.10
342.25	64.80	16.20	50.45	-0.05	342.52	49.20	48.60	49.60	-0.10	391	0.00	2203.20	44.60	0.00

Table G X: Depth of water head in piezometer d_{hp} during recharge in fourth ASR cycle at Soil Reseach Farm, Hisar

Time (h)	qi (m^3/h)	V_i (m^3)	d_{ph}	Drawup in d_{ph}	Time (h)	qi (m^3/h)	V_i (m^3)	d_{ph}	Drawup in d_{ph}	Time (h)	qi (m^3/h)	V_i (m^3)	d_{ph}	Drawup in d_{ph}
1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
391.00	0.00	0.00	44.80	44.80	391.27	23.76	6.34	50.10	0.00	392	23.76	71.28	50.70	0.20
391.02	23.76	0.48	44.50	-0.30	391.28	23.76	6.65	50.15	0.05	394	23.76	213.84	50.90	0.20
391.03	23.76	0.71	44.40	-0.10	391.30	23.76	7.13	50.20	0.05	400	23.76	356.40	51.10	0.20
391.05	23.76	1.19	49.40	5.00	391.32	23.76	7.60	50.20	0.00	406	23.76	498.96	51.30	0.20
391.07	23.76	1.66	49.55	0.15	391.33	23.76	7.84	50.25	0.05	412	23.76	641.52	51.50	0.20
391.08	23.76	1.90	49.65	0.10	391.35	23.76	8.32	50.20	-0.05	418	22.32	736.56	51.60	0.10
391.10	23.76	2.38	49.70	0.05	391.37	23.76	8.79	50.30	0.10	424	22.32	870.48	51.80	0.20
391.12	23.76	2.85	49.75	0.05	391.38	23.76	9.03	50.25	-0.05	430	22.32	1004.40	51.90	0.10
391.13	23.76	3.09	49.80	0.05	391.40	23.76	9.50	50.30	0.05	436	22.32	1138.32	52.00	0.10
391.15	23.76	3.56	49.85	0.05	391.42	23.76	9.98	50.35	0.05	442	22.32	1272.24	52.10	0.10
391.17	23.76	4.04	49.90	0.05	391.43	23.76	10.22	50.40	0.05	448	22.32	1406.16	52.20	0.10
391.18	23.76	4.28	49.85	-0.05	391.45	23.76	10.69	50.45	0.05	454	23.76	1639.44	52.30	0.10
391.20	23.76	4.75	49.90	0.05	391.47	23.76	11.17	50.50	0.05	460	23.76	1782.00	52.30	0.00
391.22	23.76	5.23	50.00	0.10	391.48	23.76	11.40	50.55	0.05	466	23.76	1924.56	52.30	0.00
391.23	23.76	5.46	50.05	0.05	391.50	23.76	11.88	50.60	0.05	472	23.76	2067.12	52.40	0.10
391.25	23.76	5.94	50.10	0.05	391.52	23.76	23.76	50.65	0.05	478	0.00	0.00	52.40	0.00

Table H XI: Depth of water head in piezometer d_{hp} during recovery in fourth ASR cycle at Soil Reseach Farm, Hisar

Time (h)	qi (m^3/h)	V_i (m^3)	d_{ph}	Drawdown in d_{ph}	Time (h)	qi (m^3/h)	V_i (m^3)	d_{ph}	Drawdown in d_{ph}	Time (h)	qi (m^3/h)	V_i (m^3)	d_{ph}	Drawdown in d_{ph}
1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
478	0.00	0	52.40	0	478.27	64.80	17.50	49.70	0.05	479	64.80	64.8	50.70	1.60
478.02	64.80	1.30	51.70	-0.70	478.28	64.80	18.14	49.80	0.10	480	64.80	97.20	50.90	0.20
478.03	64.80	1.94	51.40	-0.30	478.30	64.80	19.44	49.75	-0.05	480	64.80	129.60	51.10	0.20
478.05	64.80	3.24	51.20	-0.20	478.32	64.80	20.74	49.80	0.05	480	64.80	194.40	51.30	0.20
478.07	64.80	4.54	51.10	-0.10	478.33	64.80	21.38	49.75	-0.05	481	64.80	259.20	51.50	0.20
478.08	64.80	5.18	51.00	-0.10	478.35	64.80	22.68	49.70	-0.05	482	64.80	453.60	51.60	0.10
478.10	64.80	6.48	49.90	-1.10	478.37	64.80	23.98	49.60	-0.10	485	64.80	648.00	51.80	0.20
478.12	64.80	7.78	49.80	-0.10	478.38	64.80	24.62	49.65	0.05	488	64.80	842.40	51.90	0.10
478.13	64.80	8.42	49.85	0.05	478.40	64.80	25.92	49.60	-0.05	491	64.80	1036.80	52.00	0.10
478.15	64.80	9.72	49.80	-0.05	478.42	64.80	27.22	49.50	-0.10	494	64.80	1231.20	52.10	0.10
478.17	64.80	11.02	49.75	-0.05	478.43	64.80	27.86	49.40	-0.10	497	64.80	1425.60	52.20	0.10
478.18	64.80	11.66	49.70	-0.05	478.45	64.80	29.16	49.30	-0.10	500	64.80	1620.00	52.30	0.10
478.20	64.80	12.96	49.65	-0.05	478.47	64.80	30.46	49.35	0.05	503	64.80	1814.40	52.30	0.00
478.22	64.80	14.26	49.70	0.05	478.48	64.80	31.10	49.30	-0.05	506	64.80	2008.80	52.30	0.00
478.23	64.80	14.90	49.70	0.00	478.50	64.80	32.40	49.20	-0.10	509	64.80	2203.20	52.30	0.00
478.25	64.80	16.20	49.65	-0.05	478.75	49.20	48.60	49.10	-0.10					

Appendix - V

Table A V : Electrical Conductivity EC and pH of the recovered water in different ASR cycles at Balsamand ASR

ASR cycle 1

$V_r = 450$ m^3 $EC_n = 28.4$ dS m^{-1}

$V_i = 300$ m^3 $EC_i = 0.350$ dS m^{-1}

Time (h)	qr (m^3 h^{-1})	Vr (m^3)	del Vr (m^3)	I (%)	EC (dS m^{-1})		pH	
					Cr	Crw	Cr	Crw
1	2	3	4	5	6	7	8	9
0.25	3.26	0.78	0.78	0.26	0.35	0.35	7.45	7.45
0.50	3.26	1.56	0.78	0.52	0.38	0.37	7.45	7.45
0.75	3.26	2.34	0.78	0.78	0.45	0.39	7.45	7.45
1.00	3.26	3.12	0.78	1.04	0.46	0.41	7.45	7.45
2.00	3.26	6.24	3.12	2.08	0.55	0.48	7.45	7.45
3.00	3.26	9.36	3.12	3.12	0.68	0.55	7.45	7.45
4.00	3.26	12.48	3.12	4.16	0.96	0.65	7.45	7.45
5.00	3.26	15.60	3.12	5.20	1.30	0.78	7.50	7.46
9.00	3.26	28.08	12.48	9.36	1.50	1.10	7.52	7.47
13.00	3.26	40.56	12.48	13.52	1.80	1.32	7.55	7.49
17.00	3.26	53.04	12.48	17.68	2.20	1.52	7.60	7.49

21.00	3.26	65.52	12.48	21.84	2.40	1.69	7.60	7.50
22.00	3.26	68.64	3.12	22.88	2.80	1.74	7.62	7.51
34.00	3.26	106.08	37.44	35.36	4.50	2.71	7.65	7.51
40.00	3.26	124.80	18.72	41.60	5.80	3.18	7.65	7.52
46.00	3.26	143.52	18.72	47.84	6.20	3.57	7.70	7.53
52.00	3.26	162.24	18.72	54.08	7.80	4.06	7.70	7.54
58.00	3.26	180.96	18.72	60.32	8.40	4.51	7.75	7.60
70.00	3.26	218.40	37.44	72.80	10.20	5.48	7.75	7.60
76.00	3.26	237.12	18.72	79.04	15.60	6.28	7.80	7.64
82.00	3.26	255.84	18.72	85.28	18.20	7.15	7.82	7.68
88.00	3.26	274.56	18.72	91.52	20.80	8.09	7.90	7.74
94.00	3.26	293.28	18.72	97.76	24.70	9.15	7.90	7.74
100.00	3.26	312.00	18.72	104.00	24.70	10.08	7.90	7.74
106.00	3.26	330.72	18.72	110.24	24.70	10.91	7.90	7.74
112.00	3.26	349.44	18.72	116.48	24.70	11.65	7.90	7.74
118.00	3.26	368.16	18.72	122.72	24.70	12.31	7.90	7.74
124.00	3.26	386.88	18.72	128.96	24.70	12.91	7.90	7.74
130.00	3.26	405.60	18.72	135.20	24.70	13.45	7.90	7.74
136.00	3.26	424.32	18.72	141.44	24.70	13.95	7.90	7.74
145.00	3.26	452.40	9.36	150.80	24.70	14.62	7.90	7.74

ASR cycle 2

$V_r = 150\ m^3$ $V_i = 300\ m^3$

Time (h)	qr ($m^3\ h^{-1}$)	Vr (m^3)	del Vr (m^3)	I (%)	EC ($dS\ m^{-1}$)		pH	
					Cr	Crw	Cr	Crw
1	2	3	4	5	6	7	8	9
0.25	3.26	0.78	0.78	0.26	0.35	0.35	7.45	7.45
0.50	3.26	1.56	0.78	0.52	0.36	0.36	7.45	7.45
0.75	3.26	2.34	0.78	0.78	0.39	0.37	7.45	7.45
1.00	3.26	3.12	0.78	1.04	0.42	0.38	7.45	7.45
2.00	3.26	6.24	3.12	2.08	0.46	0.42	7.45	7.45
3.00	3.26	9.36	3.12	3.12	0.54	0.46	7.45	7.45
7.00	3.26	21.84	12.48	7.28	1.20	0.88	7.45	7.45
12.00	3.26	37.44	15.60	12.48	2.00	1.35	7.50	7.46
17.00	3.26	53.04	15.60	17.68	2.80	1.78	7.55	7.47
21.00	3.26	65.52	12.48	21.84	3.50	2.10	7.55	7.49
34.00	3.26	106.08	40.56	35.36	4.20	2.91	7.60	7.50
39.00	3.26	121.68	15.60	40.56	6.20	3.33	7.60	7.50
44.00	3.26	137.28	15.60	45.76	7.60	3.81	7.60	7.52
49.00	3.26	152.88	15.60	50.96	9.40	4.38	7.60	7.52

ASR cycle 3

$V_r = 150\ m^3$ $V_i = 300\ m^3$

Time	qr	Vr	del Vr	I	EC		pH	
(h)	($m^3\ h^{-1}$)	(m^3)	(m^3)	(%)	($dS\ m^{-1}$)			
					Cr	Crw	Cr	Crw
1	2	3	4	5	6	7	8	9
0.25	3.26	0.78	0.78	0.26	0.35	0.35	7.45	7.45
0.50	3.26	1.56	0.78	0.52	0.36	0.36	7.45	7.45
0.75	3.26	2.34	0.78	0.78	0.38	0.36	7.45	7.45
1.00	3.26	3.12	0.78	1.04	0.40	0.37	7.45	7.45
2.00	3.26	6.24	3.12	2.08	0.42	0.40	7.45	7.45
3.00	3.26	9.36	3.12	3.12	0.50	0.43	7.45	7.45
7.00	3.26	21.84	12.48	7.28	0.86	0.68	7.45	7.45
12.00	3.26	37.44	15.60	12.48	1.82	1.15	7.50	7.46
17.00	3.26	53.04	15.60	17.68	2.25	1.48	7.55	7.47
21.00	3.26	65.52	12.48	21.84	3.27	1.82	7.55	7.49
34.00	3.26	106.08	40.56	35.36	3.94	2.63	7.60	7.50
39.00	3.26	121.68	15.60	40.56	5.60	3.01	7.60	7.50
44.00	3.26	137.28	15.60	45.76	7.40	3.51	7.65	7.55
49.00	3.26	152.88	15.60	50.96	8.80	4.05	7.65	7.55

Appendix - VI

Table A VI: Water quality parameter of native, recharged and recovered water at Balsamand site as a function of recovery percentage in different cycles

ASR cycle 1

$V_r = 450\ m^3$ $V_i = 300\ m^3$

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
0.26	0.35	0.35	0.10	0.10	1.25	1.25	1.95	1.95	1.75	1.75	1.50	1.50	0.02	0.02	0.02	0.02	0.05	0.05	-9.32	-1.45	0.28
0.52	0.35	0.35	0.10	0.10	1.25	1.25	1.95	1.95	1.75	1.75	1.50	1.50	0.02	0.02	0.02	0.02	0.05	0.05	-9.20	-1.45	0.28
0.78	0.38	0.36	0.12	0.11	1.30	1.27	2.00	1.97	1.80	1.77	1.50	1.50	0.02	0.02	0.02	0.02	0.05	0.05	-7.80	-1.50	0.30
1.04	0.40	0.37	0.13	0.11	1.40	1.30	1.95	1.96	1.90	1.80	1.70	1.55	0.02	0.02	0.02	0.02	0.05	0.05	-8.14	-1.45	0.31
2.08	0.80	0.59	0.10	0.11	1.65	1.48	2.30	2.13	2.00	1.90	2.30	1.93	0.02	0.02	0.02	0.02	0.09	0.07	-9.05	-1.95	0.57
3.12	1.20	0.79	0.15	0.12	2.10	1.68	2.50	2.25	2.10	1.97	3.10	2.32	0.02	0.02	0.03	0.02	0.16	0.10	-9.67	-2.50	0.79
4.16	1.90	1.07	0.16	0.13	2.30	1.84	2.80	2.39	2.20	2.03	4.20	2.79	0.02	0.02	0.03	0.02	0.24	0.13	-6.80	-2.90	1.19
5.20	2.50	1.35	0.18	0.14	2.40	1.95	2.70	2.45	2.30	2.08	5.50	3.33	0.03	0.02	0.03	0.02	0.37	0.18	5.62	-2.80	1.57
9.36	3.20	2.17	0.20	0.17	2.50	2.19	3.10	2.74	2.40	2.22	6.90	4.92	0.05	0.03	0.04	0.03	0.42	0.29	8.57	-3.20	1.91
13.52	5.80	3.29	0.25	0.19	2.70	2.35	3.40	2.94	2.60	2.34	7.80	5.80	0.03	0.03	0.04	0.03	0.54	0.37	-9.83	-3.50	3.32
17.68	7.20	4.21	0.28	0.21	2.90	2.48	6.00	3.66	2.70	2.42	12.40	7.36	0.04	0.03	0.06	0.04	0.62	0.43	-3.49	-6.20	3.41
21.84	10.40	5.39	0.30	0.23	3.10	2.60	9.20	4.72	2.80	2.50	17.40	9.27	0.06	0.04	0.07	0.05	0.76	0.49	-8.65	-9.50	4.19

XXXV

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	-8.6	21	22
22.88	21.4	11.0	0.4	0.3	3.3	2.6	24.6	12.2	3.2	2.8	48.6	22.3	0.2	0.1	0.13	0.08	1.09	0.73	-5.8	-24.7	5.73
35.36	26.4	13.0	0.4	0.3	3.4	2.901	29.4	14.5	3.3	2.8	54.7	26.6	0.4	0.1	0.14	0.08	1.15	0.78	6.1	-29.5	6.52
41.60	31.4	15.1	0.4	0.3	3.7	3.0	35.5	16.9	3.5	2.9	62.4	30.7	0.4	0.1	0.15	0.09	1.21	0.83	-2.0	-35.7	7.09
47.84	38.4	17.5	0.6	0.3	4.7	3.2	42.8	19.6	3.9	3.0	76.2	35.4	0.5	0.2	0.17	0.10	1.35	0.89	-8.2	-43.6	7.88
54.08	42.2	21.8	0.7	0.4	6.1	3.6	50.4	24.9	4.2	3.2	88.8	44.6	0.6	0.2	0.20	0.12	1.45	0.98	-9.2	-52.3	7.94
60.32	46.1	23.7	0.7	0.4	8.2	4.0	55.0	27.2	4.4	3.3	98.7	48.8	0.7	0.3	0.22	0.13	1.38	1.01	-8.4	-58.8	8.20
72.80	52.4	25.8	0.9	0.4	10.3	5.1	62.4	29.8	4.6	3.4	114.2	53.6	0.8	0.3	0.24	0.13	1.52	1.05	-8.5	-68.1	8.69
79.04	66.4	28.6	0.92	0.48	12.9	5.7	70.4	32.6	4.9	3.5	142.2	59.7	0.93	0.36	0.260	0.14	1.67	1.093	-7.9	-78.4	10.29
85.28	98.6	33	1	0.51	15.7	6.5	82.4	35.8	5.0	3.6	180	67.4	0.98	0.4	0.280	0.15	1.88	1.143	-4.79	-93.1	14.08
91.52	132.6	39	1.1	0.55	19.6	7.36	92.2	39.1	5	3.7	231	77.1	1.02	0.44	0.3	0.16	1.92	1.19	-8.85	-106.8	17.74
97.76	136.4	44.5	1.1	0.58	23.8	8.409	115	43.4	5	3.8	254	87.2	1.12	0.48	0.31	0.17	1.98	1.235	-6.56	-133.8	16.37
104	144.2	49.9	1.2	0.61	29.2	9.657	123	47.7	5	3.8	269	96.9	1.19	0.52	0.32	0.18	2.05	1.278	-8.08	-147.2	16.53
110.2	148.6	54.9	1.2	0.64	32.4	10.94	124	51.6	5	3.9	270	106	1.28	0.55	0.33	0.18	2.14	1.322	-8.5	-151.4	16.8
116.5	150	59.5	1.3	0.67	33.6	12.16	123	55	5	3.9	270	114	1.25	0.59	0.35	0.19	2.1	1.36	-9.92	-151.6	16.95
122.7	150	63.7	1.3	0.7	34	13.27	124	58.2	5	4	270	121	1.24	0.62	0.35	0.2	2.1	1.394	-9.76	-153	16.88
129	150	67.5	1.3	0.73	33	14.22	123	61.1	5	4	270	127	1.24	0.65	0.35	0.21	2.04	1.423	-8.22	-151	16.98
135.2	148.6	70.9	1.3	0.75	33.4	15.11	122	63.7	5	4.1	270	133	1.25	0.67	0.35	0.21	2.1	1.451	-8.11	-150.4	16.86
150.8	150	72.5	1.3	0.76	34	17.06	124	64.9	5	4.1	270	136	1.24	0.68	0.35	0.22	2.1	1.465	-9.31	-153	16.88

ASR cycle 2

$V_r = 150\ m^3$ $V_i = 300\ m^3$

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
0.26	0.4	0.4	0.1	0.1	1.25	1.25	2.0	2.0	1.8	1.8	1.5	1.5	0.015	0.02	0.02	0.02	0.05	0.05	-9.32	-1.45	0.277
0.52	0.4	0.4	0.1	0.1	1.25	1.25	2.0	2.0	1.8	1.8	1.5	1.5	0.016	0.02	0.02	0.02	0.05	0.05	-9.74	-1.45	0.285
0.78	0.4	0.4	0.1	0.1	1.25	1.25	2.0	2.0	1.8	1.8	1.6	1.5	0.015	0.02	0.02	0.02	0.05	0.05	-7.77	-1.50	0.275
1.04	0.4	0.4	0.1	0.1	1.3	1.263	2.0	2.0	1.9	1.8	1.6	1.5	0.017	0.02	0.02	0.02	0.07	0.05	-11.8	-1.40	0.298
2.08	0.5	0.4	0.1	0.1	1.5	1.381	2.0	2.0	2.0	1.9	2.1	1.8	0.018	0.02	0.02	0.02	0.08	0.07	1.158	-1.55	0.378
3.12	0.9	0.6	0.1	0.1	1.8	1.521	2.2	2.1	2.0	1.9	2.8	2.1	0.018	0.02	0.02	0.02	0.09	0.07	-1.99	-2.00	0.636
7.28	1.2	0.9	0.2	0.1	2.1	1.852	2.4	2.3	2.1	2.0	3.0	2.6	0.019	0.02	0.03	0.02	0.15	0.12	-9.98	-2.40	0.8
12.48	2.2	1.5	0.2	0.1	2.2	1.997	2.6	2.4	2.2	2.1	3.9	3.2	0.02	0.02	0.03	0.02	0.28	0.19	-6.77	-2.60	1.42
17.68	3.0	1.9	0.2	0.2	2.3	2.086	2.9	2.5	2.3	2.2	5.2	3.8	0.04	0.03	0.03	0.03	0.32	0.22	-6	-2.90	1.861
21.84	4.6	2.4	0.2	0.2	2.5	2.165	3.4	2.7	2.5	2.2	6.8	4.3	0.05	0.03	0.04	0.03	0.54	0.28	-7.56	-3.40	2.678
35.36	6.8	4.1	0.3	0.2	2.6	2.331	5.6	3.8	2.7	2.4	11.4	7.0	0.06	0.04	0.05	0.04	0.60	0.41	-2.91	-5.50	3.358
40.56	10.4	4.9	0.3	0.2	2.8	2.391	10.5	4.7	2.9	2.5	17.2	8.3	0.08	0.05	0.08	0.04	0.80	0.46	-13	-10.40	4.033
45.76	12.3	5.7	0.3	0.2	3.4	2.506	15.4	5.9	4.0	2.6	24.5	10.2	0.1	0.05	0.09	0.05	0.90	0.51	-9.04	-14.80	4.012
50.96	18.6	7.1	0.3	0.4	4	2.658	18.4	7.2	4.6	2.8	33.6	12.6	0.2	0.07	0.10	0.05	1.00	0.56	-8.13	-17.80	5.558

ASR cycle 3

$V_r = 150\ m^3$ $V_i = 300\ m^3$

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
0.26	0.4	0.4	0.1	0.1	1.3	1.3	2.0	2.0	1.8	1.8	1.5	1.5	0.015	0.02	0.02	0.02	0.05	0.05	-9.32	-1.45	0.277
0.52	0.4	0.4	0.1	0.1	1.3	1.3	2.0	2.0	1.8	1.8	1.5	1.5	0.016	0.02	0.02	0.02	0.05	0.05	-9.83	-1.45	0.285
0.78	0.4	0.4	0.1	0.1	1.3	1.3	2.0	2.0	1.8	1.8	1.6	1.5	0.015	0.02	0.02	0.02	0.05	0.05	-7.83	-1.45	0.277
1.04	0.4	0.4	0.1	0.1	1.3	1.3	2.0	2.0	1.8	1.8	1.6	1.5	0.015	0.02	0.02	0.02	0.05	0.05	-13.8	-1.45	0.282
2.08	0.4	0.4	0.1	0.1	1.4	1.3	2.1	2.0	1.9	1.8	1.8	1.7	0.016	0.02	0.02	0.02	0.07	0.06	-6.87	-1.65	0.302
3.12	0.5	0.4	0.1	0.1	1.5	1.4	2.2	2.1	1.9	1.8	2.2	1.8	0.017	0.02	0.02	0.02	0.07	0.06	-2.58	-1.80	0.368
7.28	0.8	0.7	0.1	0.1	1.8	1.6	2.5	2.3	2.0	1.9	2.7	2.3	0.018	0.02	0.02	0.02	0.09	0.08	-8.65	-2.30	0.573
12.48	1.6	1.1	0.1	0.1	2.0	1.8	2.6	2.4	2.1	2.0	3.5	2.8	0.019	0.02	0.03	0.02	0.15	0.11	-8.93	-2.50	1.055
17.68	2.4	1.4	0.2	0.1	2.1	1.9	2.8	2.5	2.2	2.1	4.7	3.4	0.024	0.02	0.03	0.03	0.23	0.14	-3.64	-2.70	1.533
21.84	3.7	1.9	0.2	0.1	2.2	1.9	3.2	2.7	2.4	2.1	5.6	3.8	0.034	0.02	0.04	0.03	0.45	0.20	-8.48	-3.00	2.252
35.36	5.8	3.4	0.2	0.2	2.4	2.1	4.8	3.5	2.7	2.3	9.2	5.9	0.056	0.04	0.05	0.04	0.52	0.32	-5.33	-4.50	3.057
40.56	8.7	4.1	0.2	0.2	2.6	2.2	8.7	4.2	2.8	2.4	14.6	7.0	0.07	0.04	0.06	0.04	0.71	0.37	-10.4	-8.50	3.66
45.76	11.2	4.9	0.3	0.2	2.9	2.3	12.5	5.1	2.9	2.5	21.4	8.6	0.12	0.05	0.08	0.04	0.91	0.43	-5.61	-12.50	4.036
50.96	17.4	6.1	0.3	0.4	3.8	2.4	16.2	6.2	4.2	2.6	32.2	11.0	0.025	0.05	0.12	0.05	1.02	0.49	-3.66	-15.80	5.502

Appendix - VII

Table A VII : Depth of water head in piezometer d_{hp} during recharge in first ASR cycle at RRS, Balsamand

Time (h)	qi (m^3/h)	V_i (m^3)	d_{ph}	Drawup in d_{ph}	Time (h)	qi (m^3/h)	V_i (m^3)	d_{ph}	Drawup in d_{ph}
1	2	3	4	5	1	2	3	4	5
0.08	3.12	0.26	21.00	0.00	10.00	3.12	31.20	21.97	0.01
0.17	3.12	0.52	21.23	0.23	16.00	3.12	49.92	21.98	0.01
0.25	3.12	0.78	21.45	0.22	22.00	3.12	68.64	21.99	0.01
0.33	3.12	1.04	21.57	0.12	28.00	3.12	87.36	22.00	0.01
0.42	3.12	1.30	21.58	0.01	34.00	3.12	106.08	22.01	0.01
0.50	3.12	1.56	21.64	0.06	40.00	3.12	124.80	22.02	0.01
0.58	3.12	1.82	21.66	0.02	46.00	3.12	143.52	22.03	0.01
0.67	3.12	2.08	21.67	0.01	52.00	3.12	162.24	22.03	0.00
0.75	3.12	2.34	21.69	0.02	58.00	3.12	180.96	22.04	0.01
0.83	3.12	2.60	21.71	0.02	64.00	3.12	199.68	22.04	0.00
0.92	3.12	2.86	21.72	0.01	70.00	3.12	218.40	22.05	0.01
1.00	3.12	3.12	21.73	0.01	76.00	3.12	237.12	22.05	0.00
2.00	3.12	6.24	21.85	0.12	82.00	3.12	255.84	22.06	0.01
3.00	3.12	9.36	21.92	0.07	88.00	3.12	274.56	22.07	0.01
4.00	3.12	12.48	21.93	0.01	94.00	3.12	293.28	22.08	0.01
7.00	3.12	21.84	21.96	0.03	100.00	3.12	312.00	22.08	0.00

Table B VII : Depth of water head in piezometer d_{hp} during recovery in first ASR cycle at RRS, Balsamand

Time (h)	qi (m^3/h)	V_i (m^3)	d_{ph}	Drawdown in d_{ph}	Time (h)	qi (m^3/h)	V_i (m^3)	d_{ph}	Drawdown in d_{ph}	Time (h)	qi (m^3/h)	V_i (m^3)	d_{ph}	Drawdown in d_{ph}
1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
100.08	3.12	0.259	20.25	0.00	110.00	3.12	31.20	18.33	-0.09	206.00	3.12	330.72	17.64	-0.01
100.17	3.12	0.52	19.83	-0.42	116.00	3.12	49.92	18.30	-0.03	212.00	3.12	349.44	17.60	-0.04
100.25	3.12	0.78	19.58	-0.25	122.00	3.12	68.64	18.28	-0.02	218.00	3.12	368.16	17.57	-0.03
100.33	3.12	1.04	19.48	-0.10	128.00	3.12	87.36	18.12	-0.16	224.00	3.12	386.88	17.54	-0.03
100.42	3.12	1.30	19.36	-0.12	134.00	3.12	106.08	17.93	-0.19	230.00	3.12	405.60	17.53	-0.01
100.50	3.12	1.56	19.28	-0.08	140.00	3.12	124.80	17.92	-0.01	236.00	3.12	424.32	17.52	-0.01
100.58	3.12	1.82	19.21	-0.07	146.00	3.12	143.52	17.90	-0.02	242.00	3.12	443.04	17.51	-0.01
100.67	3.12	2.08	19.13	-0.08	152.00	3.12	162.24	17.88	-0.02					
100.75	3.12	2.34	19.06	-0.07	158.00	3.12	180.96	17.86	-0.02					
100.83	3.12	2.60	18.98	-0.08	164.00	3.12	199.68	17.85	-0.01					
100.92	3.12	2.86	18.90	-0.08	170.00	3.12	218.40	17.84	-0.01					
101.00	3.12	3.12	18.83	-0.07	176.00	3.12	237.12	17.77	-0.07					
102.00	3.12	6.24	18.70	-0.13	182.00	3.12	255.84	17.72	-0.05					
103.00	3.12	9.36	18.65	-0.05	188.00	3.12	274.56	17.69	-0.03					
104.00	3.12	12.48	18.58	-0.07	194.00	3.12	293.28	17.67	-0.02					
107.00	3.12	21.84	18.42	-0.16	200.00	3.12	312.00	17.65	-0.02					

Table C VII : Depth of water head in piezometer d_{hp} during recharge in second ASR cycle at RRS, Balsamand

Time (h)	qi (m^3/h)	V_i (m^3)	d_{ph}	Drawup in d_{ph}	Time (h)	qi (m^3/h)	V_i (m^3)	d_{ph}	Drawup in d_{ph}
1	2	3	4	5	1	2	3	4	5
242.08	3.12	0.26	20.65	0.00	252.00	3.12	31.20	21.72	0.01
242.17	3.12	0.52	20.90	0.25	258.00	3.12	49.92	21.73	0.01
242.25	3.12	0.78	21.14	0.24	264.00	3.12	68.64	21.82	0.09
242.33	3.12	1.04	21.36	0.22	270.00	3.12	87.36	21.85	0.03
242.42	3.12	1.30	21.48	0.12	276.00	3.12	106.08	21.86	0.01
242.50	3.12	1.56	21.51	0.04	282.00	3.12	124.80	21.87	0.01
242.58	3.12	1.82	21.56	0.05	288.00	3.12	143.52	21.88	0.01
242.67	3.12	2.08	21.59	0.03	294.00	3.12	162.24	21.88	0.00
242.75	3.12	2.34	21.61	0.02	300.00	3.12	180.96	21.88	0.00
242.83	3.12	2.60	21.64	0.03	306.00	3.12	199.68	21.88	0.00
242.92	3.12	2.86	21.66	0.02	312.00	3.12	218.40	21.89	0.01
243.00	3.12	3.12	21.67	0.02	318.00	3.12	237.12	21.89	0.00
244.00	3.12	6.24	21.68	0.01	324.00	3.12	255.84	21.89	0.00
245.00	3.12	9.36	21.69	0.01	330.00	3.12	274.56	21.90	0.01
246.00	3.12	12.48	21.70	0.01	336.00	3.12	293.28	21.91	0.01
249.00	3.12	21.84	21.71	0.01	342.00	3.12	312.00	21.91	0.00

Table D VII : Depth of water head in piezometer d_{hp} during recovery in second ASR cycle at RRS, Balsamand

Time (h)	qi (m^3/h)	V_i (m^3)	d_{ph}	Drawdown in d_{ph}
1	2	3	4	5
342.08	3.12	0.259	20.25	0.00
342.17	3.12	0.52	19.83	-0.42
342.25	3.12	0.78	19.58	-0.25
342.33	3.12	1.04	19.48	-0.10
342.42	3.12	1.30	19.36	-0.12
342.50	3.12	1.56	19.28	-0.08
342.58	3.12	1.82	19.21	-0.07
342.67	3.12	2.08	19.13	-0.08
342.75	3.12	2.34	19.06	-0.07
342.83	3.12	2.60	18.98	-0.08
342.92	3.12	2.86	18.9	-0.08
343.00	3.12	3.12	18.83	-0.07
344.00	3.12	6.24	18.76	-0.07
345.00	3.12	9.36	18.7	-0.06
346.00	3.12	12.48	18.65	-0.05
349.00	3.12	21.84	18.58	-0.07
352.00	3.12	31.20	18.42	-0.16
358.00	3.12	49.92	18.38	-0.04
364.00	3.12	68.64	18.14	-0.24
370.00	3.12	87.36	18.00	-0.14
376.00	3.12	106.08	17.92	-0.08
382.00	3.12	124.80	17.83	-0.09
388.00	3.12	143.52	17.72	-0.11
390.00	3.12	152.60	17.67	-0.05

Table E VII : Depth of water head in piezometer d_{hp} during recharge in third ASR cycle at RRS, Balsamand

Time (h)	qi (m^3/h)	V_i (m^3)	d_{ph}	Drawup in d_{ph}	Time (h)	qi (m^3/h)	V_i (m^3)	d_{ph}	Drawup in d_{ph}
1	2	3	4	5	1	2	3	4	5
390.08	3.12	0.26	20.65	0.00	400.00	3.12	31.20	21.73	0.02
390.17	3.12	0.52	20.9	0.25	406.00	3.12	49.92	21.74	0.01
390.25	3.12	0.78	21.14	0.24	412.00	3.12	68.64	21.75	0.01
390.33	3.12	1.04	21.36	0.22	418.00	3.12	87.36	21.76	0.01
390.42	3.12	1.30	21.48	0.12	424.00	3.12	106.08	21.77	0.01
390.50	3.12	1.56	21.51	0.04	430.00	3.12	124.80	21.79	0.02
390.58	3.12	1.82	21.56	0.05	436.00	3.12	143.52	21.81	0.02
390.67	3.12	2.08	21.59	0.03	442.00	3.12	162.24	21.82	0.01
390.75	3.12	2.34	21.61	0.02	448.00	3.12	180.96	21.83	0.01
390.83	3.12	2.60	21.64	0.03	454.00	3.12	199.68	21.84	0.01
390.92	3.12	2.86	21.66	0.02	460.00	3.12	218.40	21.85	0.01
391.00	3.12	3.12	21.67	0.02	466.00	3.12	237.12	21.86	0.01
392.00	3.12	6.24	21.68	0.01	472.00	3.12	255.84	21.87	0.01
393.00	3.12	9.36	21.7	0.02	478.00	3.12	274.56	21.88	0.01
394.00	3.12	12.48	21.71	0.01	484.00	3.12	293.28	21.89	0.01
397.00	3.12	21.84	21.72	0.01	490.00	3.12	312.00	21.89	0.00

Table F VII : Depth of water head in piezometer d_{hp} during recovery in third ASR cycle at RRS, Balsamand

Time (h)	qi (m^3/h)	V_i (m^3)	d_{ph}	Drawdown in d_{ph}
1	2	3	4	5
490.08	3.12	0.259	20.25	0.00
490.17	3.12	0.52	19.83	-0.42
490.25	3.12	0.78	19.58	-0.25
490.33	3.12	1.04	19.48	-0.10
490.42	3.12	1.30	19.36	-0.12
490.50	3.12	1.56	19.28	-0.08
490.58	3.12	1.82	19.21	-0.07
490.67	3.12	2.08	19.13	-0.08
490.75	3.12	2.34	19.06	-0.07
490.83	3.12	2.60	18.83	-0.23
490.92	3.12	2.86	18.76	-0.07
491.00	3.12	3.12	18.7	-0.06
492.00	3.12	6.24	18.65	-0.05
493.00	3.12	9.36	18.58	-0.07
494.00	3.12	12.48	18.52	-0.06
497.00	3.12	21.84	18.46	-0.06
500.00	3.12	31.20	18.42	-0.04
503.00	3.12	49.92	18.36	-0.06
506.00	3.12	68.64	18.21	-0.15
509.00	3.12	87.36	18.14	-0.07
512.00	3.12	106.08	18.07	-0.07
515.00	3.12	124.80	17.94	-0.13
518.00	3.12	143.52	17.90	-0.04
521.00	3.12	152.60	17.85	-0.05

ABSTRACT

Title of Thesis : **Modelling of groundwater recharge in brackish aquifer storage and recovery wells**

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Canal water was gravity recharged in successive ASR cycles at two ASR sites by employing siphon system under varying water table depths. Recharge and recovery rates were constant in successive cycles and both ASR sites. The instantaneous IRE and cumulative recovery efficiency CRE increased with successive ASR cycles linearly. The CRE was 74 and 44 % with successive ASR cycles at Hisar and Balsamand ASR sites, respectively.

Simple mixing M*(Cl^-) increased with recovery percentage (I) for all the quality parameters. It decreased linearly with successive ASR cycles. Calcite dissolution decreased with successive ASR cycles at both sites. With one irrigation of 0.06 m, 14 and 6 kg of potassium could be added through irrigation from last successive cyles at Hisar and Balsamand, respectively.

The HYDRUS-2D and PMWIN simulated the drawup and drawdown in piezometric pressure heads successfully during recharge and recovery in Aquifer Storage and recovery (ASR) cycles. HYDRUS-2D and PMWIN were fairly well calibrated and validated for solute transport studies in brackish ASR wells. Both models predicted similar radial influencing zone at both ASR sites. Radial influencing zone increased with successive ASR cycles. 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 and PMWIN may be adopted for simulations in ground water recharge and solute transport studies in ASR wells. Filters reduced more than 90% of the sedimentation load in the water channel.

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