Simulation of groundwater recharge from an aquifer storage recovery well under shallow water-table condition

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A finite-element groundwater flow model, HYDRUS 2D, was used to simulate drawup and drawdown of piezometric pressure heads in the aquifer storage recovery cycles of varying buffer storage volumes and residence times in a highly brackish, semi-confined aquifer under shallow water-table condition. Physical flow region implemented in HYDRUS 2D involved a soil profile of 500 m width and 69 m depth, with an exocentric elliptical cavity of 1 m radius at 54 m depth. No flux boundary was given at the soil surface, at the bottom and at the lateral sides of the flow region. Saturated hydraulic conductivity was estimated through inverse modelling technique using experimental pressure head time pairs during the first aquifer storage recovery cycle from a piezometer and an observation well. High regression coefficient (0.96), low sum of squared differences of predicted and experimental mean (1.12), and low root mean square error (RMSE; 0.81) between predicted and experimental pressure heads while calibrating the first ASR cycle indicate the high level of accuracy of estimating field-saturated hydraulic conductivity. Modelling efficiency was higher in the piezometer (99.86) than in the observation well (94.57). Overall, the HYDRUS 2D model performed well for simulating drawup and drawdown with RMSE values ranging from 0.26 to 1.29 and modelling efficiency ranging from 94.57 to 99.9 during validation in the second to sixth ASR cycles. Radial influencing zone increases with buffer storage volume with a mean value of 122 m during recharge, indicating that the next tube well should be installed at least 122 m away from the existing aquifer storage recovery well.

Keywords: Aquifer, cavity well, recovery efficiency, buffer storage volume, residence time.

AQUIFER storage recovery (ASR) well is a relatively new water-resource management technology, which is sequentially used both for excess water injection in the aquifer and the recovery of the same stored excess water during shortage. This technique is increasingly used for reducing saline brackish aquifers for irrigation[1–3] to prevent surface ponding in standing crops[4] and maintain the desired water levels in freshwater aquifers[5–7] at relatively lesser cost. In Haryana, water-shortage problems, directly or indirectly, arise due to over exploitation of good-quality groundwater in the northeastern zone and non-utilization of poor-quality groundwater coupled with introduction of canal irrigation. This has resulted either in the decline in water levels or waterlogging and soil salinization. This is seriously affecting the sustainability of irrigated agriculture. Improvement in water quality in the aquifer surrounding ASR prompts the farmers to extract more groundwater for irrigation[3].

Modelling water pressure heads around an ASR well would help in quantifying temporal and spatial rise or fall in water levels and also in assessing the impacts on the environment[5] on a long-term basis by the planners and researchers. Simulation models can integrate geological and hydrological information and help in quantifying the influencing zone for optimizing operational factors such as buffer storage volume (BSV) and residence time of the recharge water for success of ASR technology. Temporal and spatial water pressure responses near the ASR strainer wells were studied using analytical approaches[8–10] for saturated flow conditions in homogeneous areas. Numerical (two-/three-dimensional) approaches[11–15] were used for steady and transient saturated flow conditions for confined, unconfined and semi-confined aquifers in heterogeneous areas. These have been modelled with a fair degree of success. Farm-scale water-level responses are complicated by the problem of surface unsaturated flows and aerial horizontal and vertical heterogeneities. A few numerical modelling studies have been reported for cavity-type ASR wells. A scientifically documented and evaluated[16], HYDRUS 2D software package[17] 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 useful to predict water-level responses at farm with a cavity-type ASR well on both short-term and long-term basis. The main objective of the present study was to evaluate the applicability of HYDRUS 2D model for simulating

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drawup and drawdown of pressure heads during recharge and recovery cycles at different BSVs and storage time in a cavity-type ASR well.

Theory

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

$$\frac{\partial \theta}{\partial t}=\frac{\partial}{\partial x_i}\left[K\left(K_{ij}^{A}\frac{\partial h}{\partial x_j}+K_{iz}\right)\right]-S, \tag{1}$$

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

$$K(h, x, z) = K_s(x, z)K_r(h, x, z),$$

where K_r is the relative hydraulic conductivity and K_s the saturated hydraulic conductivity ($L\ s^{-1}$).

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

$$D=\frac{Q}{2\pi K r}, \tag{2}$$

where D is the drawdown or drawup of pressure head (m), Q the recharge or discharge rate (m^3/day), K the aquifer hydraulic conductivity (m/day) and r the radial distance from the cavity (m).

Materials and methods

Geo-hydrology of the experimental site

About 98% of Haryana is covered with plains of fluvial alluvium of Recent to sub-Recent age, blanketing almost the entire sub-surface geology[18]. There are, however, outcrops of the various rock-systems on the northeastern, southern, southwestern and the western boundaries of the state.

Semi-confined, shallow aquifers are found in sand and loamy sand layers above illite type of non-continuous clay layers. Depth to groundwater level varies from 2 to 10 m below ground level during pre-monsoon period, and quality of groundwater varies from 2 dS/m (2000 μmhos/cm) to more than 30.2 dS/m (30,200 μmhos/cm) at Soil Research Farm of Haryana Agricultural University (HAU). Range of water quality and depth of water level of Haryana are presented in Figure 1.

Field experiments

The field experiment was conducted at the Soil Research Farm of Chaudhary Charan Singh HAU, Hisar (28°59′–29°49′N lat. and 75°11′–76°18′E long. at an elevation of 215.2 m amsl) to study the effect of BSV and residence time on water-level responses. The site lithology and schematic diagram of ASR facility is shown in Figure 2. Canal water was injected into cavity-type ASR well to create BSV of 6000, 10,000 and 14,000 m^3, employing siphon system in July–August 2003. Details of the ASR cycle test programme adopted in the study are given in Table 1.

Residence time of 70.83, 118.35 and 113.20 days was allowed at a BSV of 14,000 m^3 in the fourth, fifth and

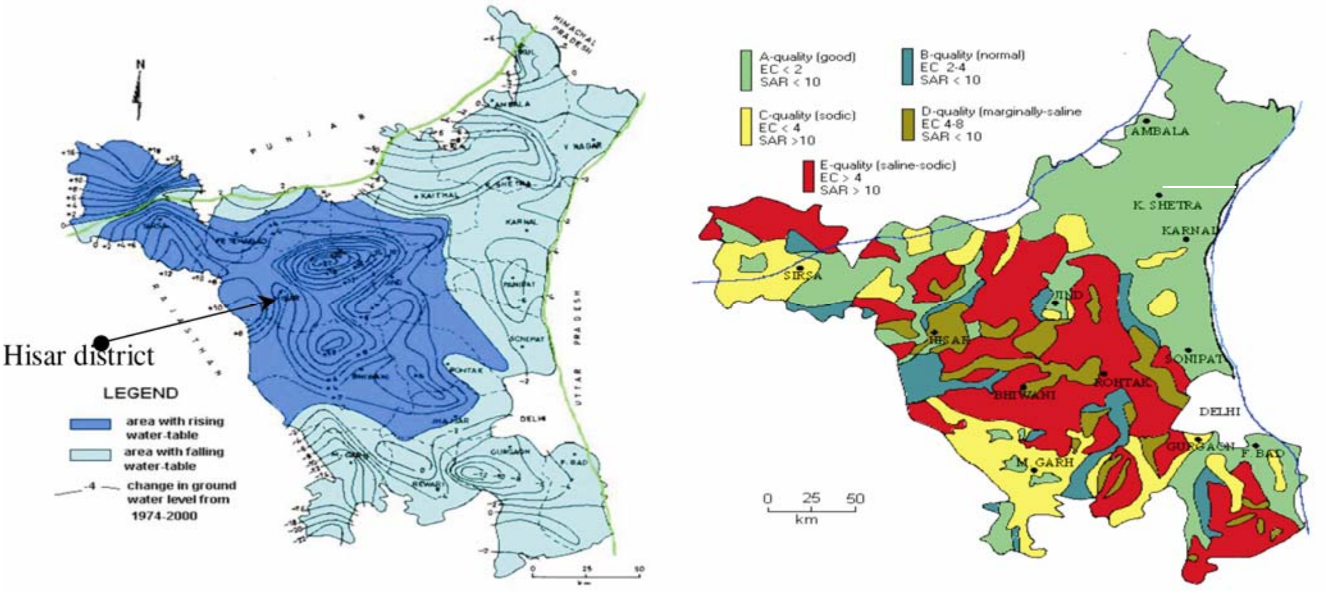

Figure 1. Fluctuation in groundwater levels and groundwater quality of Haryana.

Table 1. The aquifer storage recovery (ASR) cycle test programme at Hisar site to study the effect of storage volume and storage time on recovery efficiency

Cycle number j	BSV (m^3)	Vr_j (m^3)	Vi_j (m^3)	t_i (days)	$\bar{t}$ (days)	t_r (days)
1	6000	2000	6000	12.00	7.20	2.40
2	10,000	2000	6000	10.60	6.05	1.50
3	14,000	2000	6000	25.60	13.55	1.50
4	14,000	2000	2000	10.20	70.83	2.40
5	14,000	2000	2000	9.17	118.35	1.54
6	14,000	2000	2000	8.92	113.20	1.54

t_i, Time of injection; $\bar{t}$, Residence time; t_r, Recovery time; Vr_j, Volume recovered in the jth cycle; Vi_j, Total volume injected in the jth cycle, and BSV, Buffer storage volume.

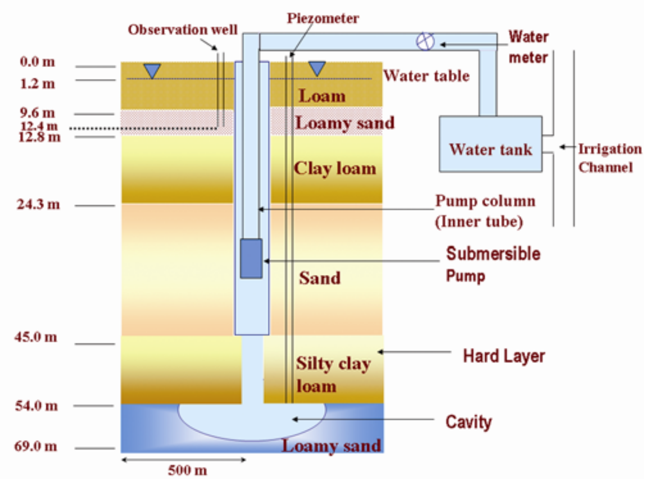

Figure 2. Schematic diagram of the aquifer storage recovery well.

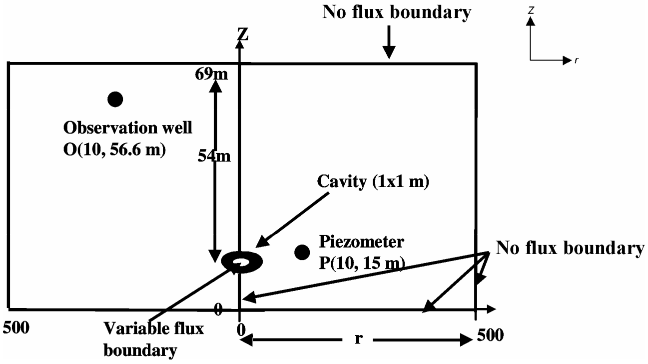

Figure 3. Schematic layout of the ASR system implemented in HYDRUS 2D.

sixth ASR cycles respectively. BSV of current cycle, BSV_j was measured by the difference between the volume injected, Vi and volume recovered Vr added to the buffer storage volume of the previous cycle $\mathrm{BSV}_{(j-1)}$ as:

$$\mathrm{BSV}_j = Vi_j^* - Vr_j + \mathrm{BSV}_{(j-1)}, \tag{3}$$

where j denotes the ASR cycle number (Table 1), Vi_j^* the total volume injected in the jth cycle and Vr_j the volume recovered in the jth cycle.

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

$$\bar{t} = 0.5(t_\mathrm{i} + t_\mathrm{r}) + t_\mathrm{s}, \tag{4}$$

where t_i is the injection time, t_r the recovering time and t_s the storage time between ti2 and tr1.

Numerical experiments

The HYDRUS 2D model was calibrated for simulating drawup and drawdown of pressure heads during recharge and recovery for the first ASR cycle with BSV of 6000 m^3. The remaining cycles with BSV 10,000 and 14,000 m^3 and three cycles of residence time $\bar{t} = 70.8$, 118.4 and 113.2 days at BSV of 14,000 m^3 were used for validation. In total, six HYDRUS 2D runs were carried out for simulating drawup and drawdown pressure heads during recharge and recovery (Table 1).

The physical flow region involved a soil profile of 500 m width and 69 m depth, and with an exocentric elliptical cavity of 1 m horizontal radius and 1 m vertical radius at 54 m depth (Figure 3). In fact, the z coordinate was taken as zero at the bottom of the flow region and increased positively upwards (Figure 3). No flux boundary was given at the soil surface, bottom and lateral sides of the flow regions (Figure 3). The piezometer (P) was installed at a radial distance of 10 m (r = 10 m) and at a soil depth of 54 m (z = 15 m). Observation well (O) was installed at a radial distance of 10 m from the cavity (r = 10 m) and at 12.4 m depth from the soil surface (z = 56.6 m; Figure 3). Experimentally observed recharge fluxes (negative) and recovery fluxes (positive) as a function of time served as a variable flux boundary condition for HYDRUS 2D (Figure 4).

Parameter estimation

Soil water retention functions were derived from pressure head and water content data from undisturbed soil samples, measured on pressure plate apparatus using Van Genuchten–Mualem equations[19] as:

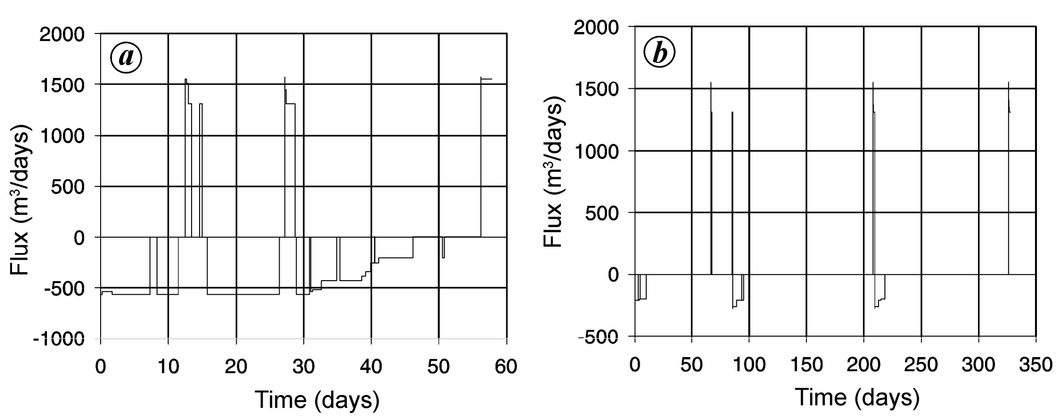

Figure 4. Recharge (negative) and recovery fluxes (positive) of (***a***) cycles having buffer storage volume (BSV) 6000, 10,000 and 14,000 m^3 and (***b***) residence time $\bar{t}$ = 70.8, 118.35 and 113.20 days.

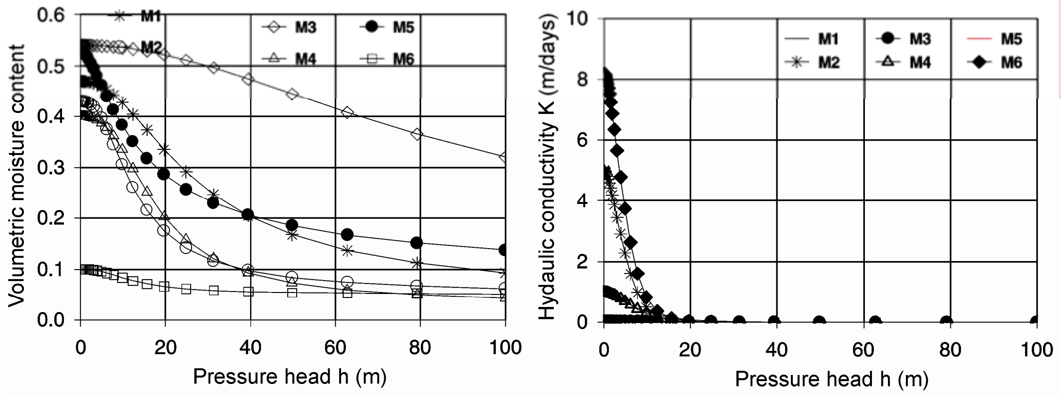

Figure 5. Volumetric pressure content θ vs pressure head (h), and hydraulic conductivity (K) vs h relationships as fitted from experimental data.

$$\theta(h) = \frac{\theta_s - \theta_r}{[1 + |\alpha h|^n]^m} \quad \text{for} \quad h < 0, \tag{5}$$

$$\theta(h) = \theta_s \quad \text{for} \quad h \geq 0, \tag{6}$$

$$K(h) = K_s S_e^k [1 - (1 - S_e^{k/m})^m], \tag{7}$$

where θ is the volumetric water content, h the pressure head, α, n, m (=1=1/n), and k (= 0.5) are empirical parameters, $S_e = (\theta - \theta_r)/(\theta_s - \theta_r)$ the degree of saturation θ_r, the residual water content and θ_s the saturated water content. Here θ_r was set equal to air dry water content and θ_s was set equal to total porosity as calculated from bulk density obtained in $h - \theta$ measuring cores, assuming particle density of 2.65 g/cm^3. The functional lines of $\theta(h)$ and $k(h)$ have been fitted to experimental data (Figure 5).

The HYDRUS 2D code includes a Levenberg–Marquardt parameter optimization algorithm for inverse estimation of hydraulic conductivity parameter. We utilized this algorithm to estimate field-scale hydraulic conductivity using measured pressure heads (h) and time (t) pairs from a piezometer (z = 15 m and r = 10 m) and observation well (z = 56.6 m and r = 10 m) taking the observed θ_r, θ_s, α, n and m as fixed parameters. The algorithms express the error between observed and modeled data as:

$$SSQ = \sum_{i=1}^{m_q} [P_i^*(z,t) - P_i(z,t)]^2. \tag{8}$$

SSQ represents the sum of squared difference between measured and calculated values. The right-hand side represents the sum of squared difference between the measured and calculated space–time variables, e.g. time and pressure heads. Here m_q is the number of measurements, $P_i^*(z, t)$ represents specific measurements at time t and depth z and $P_i(z, t)$ are corresponding values simulated[20].

Statistical test

Statistical tests to assess simulation performance were as follows.

Table 2. Hydraulic parameters used in numerical experiments

Parameters	θ_r (m^{3}m^{-3})	θ_s (m^{3}m^{-3})	α (m^{-1})	n	K_s^* (m/d)
Loam (M1)	0.03	0.47	0.05	2.2	1.00
Loamy sand (M2)	0.05	0.43	0.10	2.5	5.00
Clay loam (M3)	0.07	0.54	0.015	2.1	0.05
Sand (M4)	0.03	0.40	0.07	2.7	1.00
Silty clay loam (M5)	0.06	0.50	0.13	1.7	0.20
Loamy sand (M6)	0.05	0.10	0.10	2.5	8.20
SSQ	–	–	–	–	1.13
R^2	–	–	–	–	0.98

θ_r, Residual moisture content; θ_s, Saturated moisture content; K_s^*, Estimated field-saturated hydraulic conductivity using inverse method of HYDRUS 2D; SSQ, Objective function which is the sum of squared differences between the measured and simulated data (eq. (8)), R^2, Coefficient of determination between measured and simulated data.

Table 3. Calibration and validation statistical tests of drawup and drawdown in pressure heads in piezometer during recharge and recovery

			n		RMSE		
Cycle no.	BSV (m^3)	$\bar{t}$ (days)	Recharge	Recovery	Recharge	Recovery	ME (%)
Calibration							
1	6000	7.20	142	226	0.32	1.29	99.82
Validation							
2	10,000	6.05	79	127	0.45	1.21	99.84
3	14,000	13.55	161	209	0.67	0.89	99.91
4	14,000	70.83	77	128	0.26	0.90	99.90
5	14,000	118.35	70	120	0.32	1.00	99.88
6	14,000	113.20	72	120	0.29	1.29	99.80
Mean					0.39	1.10	99.86

RMSE, Root mean square error; ME, Modelling efficiency; n, Number of observations.

$$\text{Modelling efficiency (ME)} = =1-\frac{\sum_{i=1}^{n}(O_i-S_i)^2}{\sum(O_i-\bar{O})^2}, \qquad (9)$$

where O_i and S_i represent the observed and simulated values, n represents the number of observed and simulated values used in the comparison, and $\bar{O}$ the observed average:

$$\bar{O}=\sum_{i=1}^{n}\frac{O_i}{n}. \qquad (10)$$

Negative values of ME are considered as unacceptable[11].

The root mean square error,

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

Paired t-test was applied to compare pressure heads generated numerically and analytically at radial distances as follows:

$$t_{\text{cal}}=\frac{d}{\sqrt{S^2\left[\frac{1}{n_1}+\frac{1}{n_2}\right]}}, \quad d=X_1-X_2, \qquad (12)$$

$$\text{s.d.}=\sqrt{\frac{n_1xS_1^2+n_2xS_2^2}{(n_1+n_2-2)}}, \qquad (13)$$

where n and S are the number of comparable paired points and standard deviation and their subscripts are indicative of their respective experimental and predicted values, s.d. is standard deviation of mean and t_{cal} is the calculated t value.

Results and discussion

Calibration

Optimized, field-saturated hydraulic conductivity was obtained from pressure heads and time data pairs during the first ASR cycle from inverse modelling technique of HYDRUS 2D using θ_r, θ_s, α, n and m (derived

Table 4. Calibration and validation statistical tests of drawup and drawdown in pressure heads in observation well

Cycle no.	BSV (m^3)	$\bar{t}$ (days)	n Recharge	n Recovery	RMSE Recharge	RMSE Recovery	ME (%)
Calibration							
1	6000	7.20	30	51	1.25	1.93	91.52
Validation							
2	10,000	6.05	45	64	1.16	1.56	94.58
3	14,000	13.55	75	105	0.83	0.91	97.81
Mean					1.08	1.47	94.57

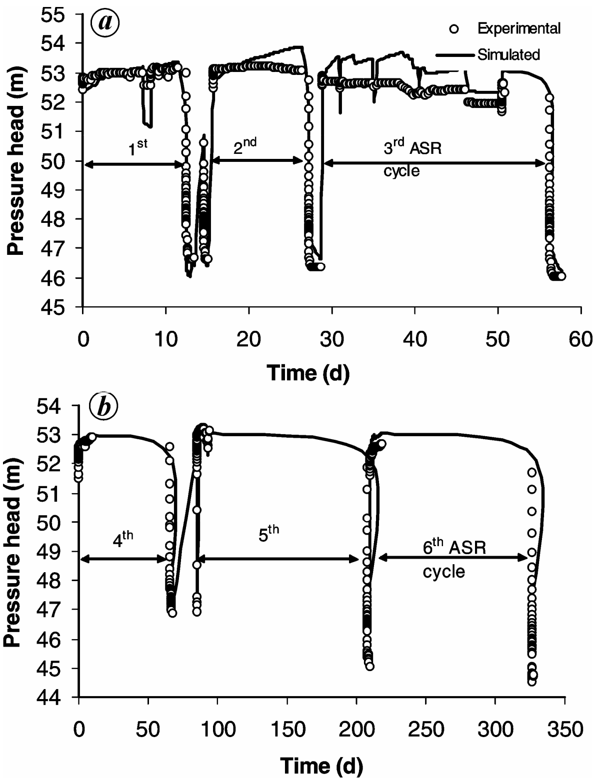

Figure 6. Simulated vs experimental drawup and drawdown of piezometric head at (***a***) first, second and third ASR cycles of BSV = 6000, 10,000 and 14,000 m^3, (***b***) fourth, fifth and sixth ASR cycles of residence time $\bar{t}$ = 70.8, 118.6 and 113.2 days.

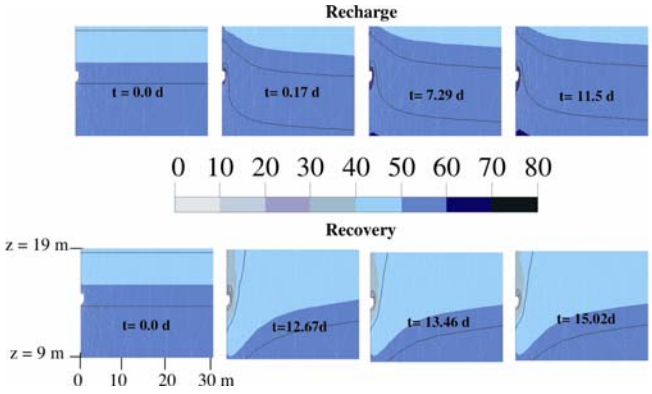

Figure 7. Development of two-dimensional pressure isolines of a sectioned (partial) flow region (r = 0–30 m and z = 9–19 m) at increasing time of recharge and recovery in the first ASR cycle.

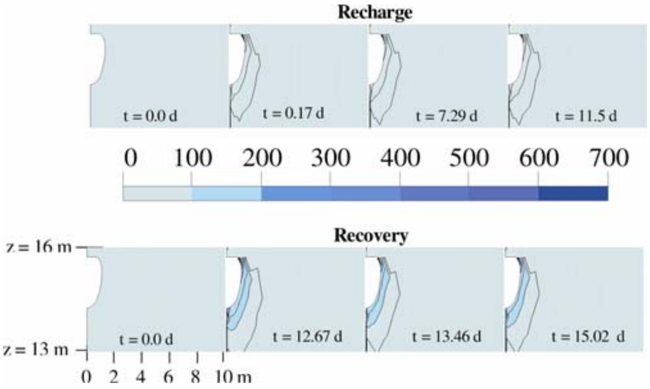

Figure 8. Development of velocity isolines at increasing time of recharge and recovery in the first ASR cycle as a function of time.

experimentally) as fixed parameters, according to eq. (8) and Table 2. Simulated and observed pressure heads during the first ASR cycle are compared in Figure 6*a*, and their statistical comparison is given in Table 3. The high regression coefficient R^2 (0.96), low value of sum of squared difference of predicted and experimental means SSQ (1.12), and low mean RMSE of 0.81 for piezometeric pressure head (Table 3) and 1.59 for observation well pressure head (Table 4) calibrated the model, indicating the high degree of accuracy of obtaining field-saturated hydraulic conductivity from inverse modelling for the first ASR cycle.

The rising isopressure lines with time of recharge (Figure 7) indicate increase in drawup ($ht - hi$, where ht is the pressure head at any time t and hi is that at the initial time) with recharge time. This is because of increase in groundwater with time during recharge. The falling isopressure lines with time of recovery (Figure 7) showed decrease in drawdown ($ht - hi$) with recovery time due to depletion of groundwater. The negative slope of pressure isolines at any particular time (Figure 7) showed that pressure decreased with radial distance during recharge, as recharge is done in cavity.

Positive slope of pressure isolines at any particular time (Figure 7) showed increase in pressure with radial distance during recovery. Figure 6 shows only a part of the flow region, i.e. z from 9 to 19 m and r from 0 to 30 m, to highlight the main pressure isoline of the aquifer. The

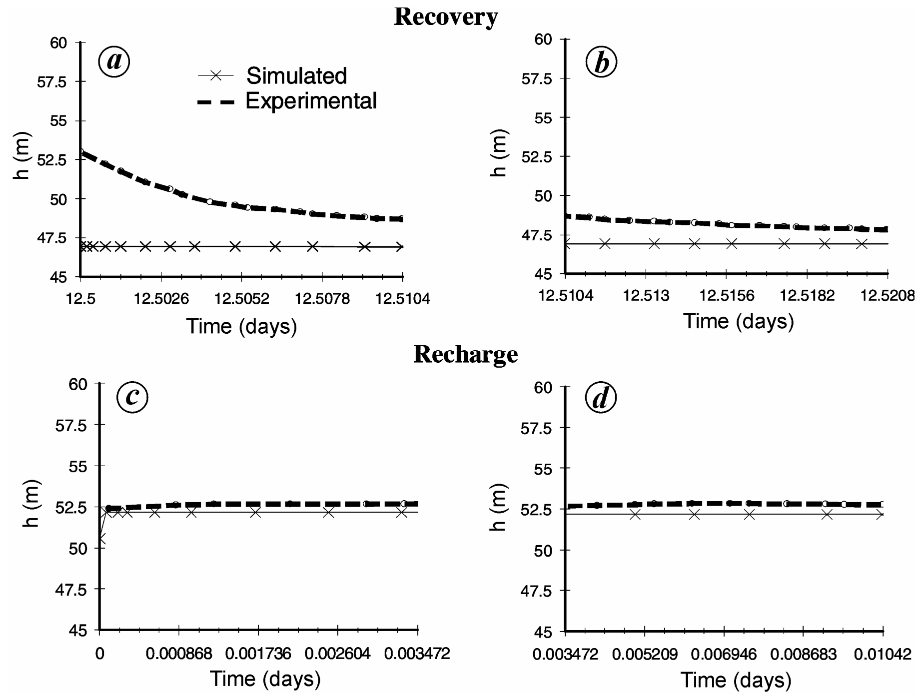

Figure 9. Simulated versus experimental piezometric pressure heads of (***a***) initial 12.5 to 12.5104 d (15 min), (***b***) 12.5104–12.5208 d (15–30 min) during drawdown, (***c***) initial 0.0034 (5 min) during drawup, and (***d***) 0.0034–0.0104d (5–15 min) during drawup in the first ASR cycle.

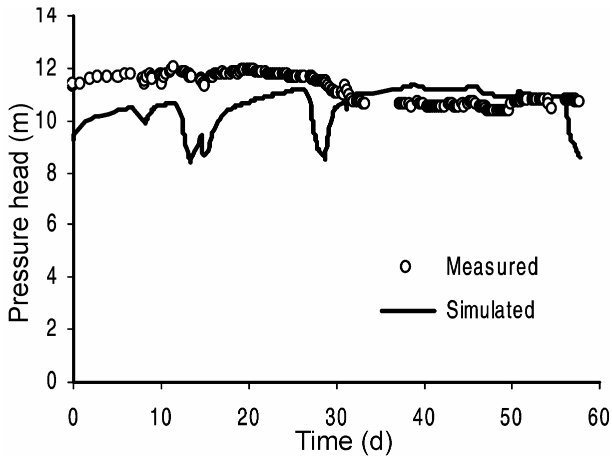

Figure 10. Simulated vs experimental rise and fall in pressure head (m) in observation well at BSV = 6000, 10,000 and 14,000 m^3.

unsaturated zone in fact had appeared near the soil surface, and this explained the necessity of using HYDRUS 2D for this variably saturated flow region. For simulating temporal pressures for a longer period of time of 1–10 years, this model has to take into account naturally occurring recharge (rainfall, irrigation, seepage from canal) and recovery (evapo-transpiration, rainfall) processes. Hence the use of HYDRUS 2D model in this study is justified for groundwater recharge.

Shifting velocity isolines towards cavity with time (Figure 8) suggests that water velocity at any radial distance decreases with time during recharge and recovery due to decrease in potential gradients with time.

Validation

Saturated hydraulic conductivity values obtained in the calibration of the model in the first ASR cycle were used for validating the model in the second to sixth ASR cycles. There was good match between experimental and simulated drawups and drawdowns in piezometric pressure heads in the second and third ASR cycles of BSV of 10,000 and 14,000 m^3 (Figure 6*a*) and in the fourth, fifth and sixth ASR cycles of residence time $\bar{t} = 70.8$, 118.4 and 113.2 days (Figure 6*b*). Successful calibration in the first and validation in the second to sixth ASR cycles implied that HYDRUS 2D model may be used for simulating spatial and temporal groundwater responses to recharge and recovery in an ASR well. It may be further seen that the method of estimating saturated field hydraulic conductivity from inverse modelling through HYDRUS 2D was satisfactory for simulating drawup and drawdown in the ASR cycle even up to a longer time of 300 days.

A deviation between experimental and simulated pressure heads was observed in the initial recovery time from 12.5 to 12.5104 days (0–15 min), which decreased to some extent from 12.5104 to 12.5208 days (15–30 min). Thereafter there was minimal deviation (Figure 9*a* and *b*).

These deviations near the cavity centre during recovery may have been due to the following: (1) that HYDRUS 2D model does not take into account the storage coefficient in the aquifer and/or (2) the entry point resistances of the piezometer might have delayed their response to drawdown pressure heads under actual field conditions. However, simulated drawup pressure heads had a good match when compared for longer times (Figure 9 *c* and *d*). These initial, short, time deviations between simulated and experimental values were not observed during recharge. It may be because of the low magnitude of recharge rates that allowed slow rise of pressure heads so as to match model datapoints.

The matching of experimental and simulated pressure head datapoints of the observation well were not as satisfactory as those of the piezometer during the first two cycles of BSV 6000 and 10,000 m^3 (Figure 10). Under prediction of observation well pressure head observed in the first and second ASR cycle was due to seepage from canal and water courses flowing near the experimental area. During the third ASR cycle of BSV = 14,000 m^3, the matching of experimental and simulated datapoints was satisfactory, as the experiment was conducted during the canal dry period.

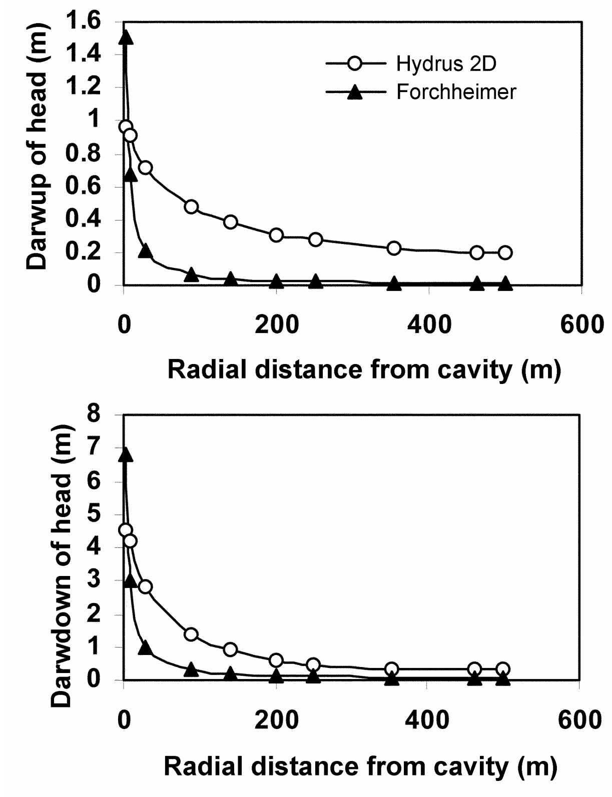

Figure 11. Drawdown and drawup in the pressure head as a function of radial distance from cavity (m) as given numerically by HYDRUS 2D model and analytically by Forchheimer.

High mean ME (99.86% in piezometer and 94.57% in observation well) and low RMSE (0.26–0.67 of piezometer and 0.83–1.25 m of observation well in drawup, and 0.89–1.29 of piezometer and 0.91–1.93 m of observation well in drawdown) of predicted and experimental pressure head values for the second to the sixth ASR cycle indicate that HYDRUS 2D model can be used for groundwater recharge in the ASR well. The RMSE and ME did not vary with the ASR cycle, BSV and $\bar{t}$, which further confirmed the validity of the model over long periods of time. The higher RMSE values for the observation well (Table 4) compared to that of the piezometer might have been due to seepage of water through the canal and water courses near the experimental area, which account for higher observed water pressure in the observation well. Therefore, HYDRUS 2D may be used for projecting and optimizing the operational factors as BSV and $\bar{t}$ of recharge water for the success of ASR technology. So far, the model has been used for predicting water, salt and heat balance studies, and pressure distributions in soil profiles mostly in unconsolidated zone[17,21,22]. Only few applications to simulate groundwater recharge have been reported[23].

Radial influencing zone

Radial influencing zone r_{iz} is taken as a radial distance r up to which there is 5% of maximum drawup and drawdown during recharge and recovery of each cycle. It means that r_{iz} would vary with recharge, recovery, BSV and $\bar{t}$ of the ASR cycle. It increased with BSV, with a mean value of 122 m during recharge. This may be due to the buffer zone that restricts direct mixing of injected water with native water. It is more for recharge than for recovery (Table 5), because more time is available (Table 1)

Table 5. Radial influence zone r_{iz} (m) at different BSVs and $\bar{t}$ for recharge and discharge in ASR well

			r_{iz} (m)	
Cycle no.	BSV (m^3)	$\bar{t}$ (days)	Recharge	Recovery
1	6000	7.20	111	57
2	10,000	6.05	127	46
3	14,000	13.55	129	25
4	14,000	70.83	16	16
5	14,000	118.35	15	15
6	14,000	113.20	24	24

Table 6. Paired *t*-test for drawup and drawdown as given by HYDRUS 2D and Forchheimer model

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

for spatial movement of the water during recharge. Mean radial influencing zone of 122 m (Table 5), at the experimental ASR site suggests that the next tube well should be installed at least 122 m away from the existing ASR well.

Numerical vs analytical solutions

The Forchheimer model under-predicts piezometric drawup and drawdown at all radial distances (Figure 11). The difference of the mean was significant at 5% probability level and non-significant at 10% probability (Table 6). The radial influencing zones were also not identical (111 and 87 m for HYDRUS 2D and Forchheimer model respectively). The significant difference at 5% could have been due to slightly higher optimized *K* values being used for HYDRUS 2D compared to analytical Forchheimer model (eq. (2)). Indeed, *K* values for analytical Forchheimer model are relatively difficult to determine, as it requires large number of pump tests under actual field conditions, which sometimes become difficult and costly for practical purposes. Furthermore, the Forchheimer model is a steady-state analytical groundwater model and does not take into account unsaturated water-flow processes occurring during recharge and recovery cycles.

Conclusion

1. HYDRUS 2D simulated the drawup and drawdown of pressure heads quite well during the whole period of time of recharge and recovery in all six ASR cycles.
2. The method of estimating saturated field hydraulic conductivity from inverse modelling through HYDRUS 2D was satisfactory for simulating drawup ad drawdown in ASR cycles even up to a longer time of 300 days.
3. ME did not vary with the number of cycles, BSV and residence time.
4. The radial influencing zone of the ASR well increased with increasing BSV from 6000 to 14,000 m^3, with a mean value of 122 m.
5. There was a deviation between predicted and experimental drawup and drawdown during the initial 15 min of recovery in the piezometer.
6. Forchheimer analytical model under-predicted the piezometric drawup and drawdown at all radial distances compared to the numerical HYDRUS 2D model.
7. Thus the HYDRUS 2D can be used for groundwater studies.

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1. Gerges, N. Z., Dillon, P. J., Sibenaler, X. P., Martin, R. R., Pavelic, P., Howles, S. R. and Dennis, K., South Australian experience in aquifer storage and recovery. In *Management of Aquifer Recharge for Sustainability* (ed. Dillon, P. J.), Proceedings of the International Symposium on Artificial Recharge 4, Adelaide, A.A. Balkema Publishers, Tokyo, 22–26 September 2002, pp. 453–458.
2. Gerges, N. Z., Howles, S. R. and Dillon, P. J., Town water supply purification using aquifer storage and recovery in a saline aquifer. In *Management of Aquifer Recharge for Sustainability* (ed. Dillon, P. J.), Proceedings of the International Symposium on Artificial Recharge 4, Adelaide, A.A. Balkema Publishers, Tokyo, 22–26 September 2002, pp. 459–464.
3. Malik, R. S., Jhorar, B. S., Jhorar, R. K., Streck, T. and Richter, J., Long-term successful operation of existing brackish cavity wells from ASR to improve quality for irrigation by Indian farmers. In *Management of Aquifer Recharge for Sustainability* (ed. Dillon, P. J.), Proceedings of the International Symposium on Artificial Recharge 4, Adelaide, A.A. Balkema Publishers, Tokyo, 22–26 September 2002, pp. 465–468.
4. Malik, R. S., Jhorar, B. S., Jhorar, R. K. and Streck, T., Retrofittings in cavity type irrigation tubewells for artificial ground water recharge for sustaining rice ecosystem, In Proceedings of the National Workshop on Rainwater and Ground Water Management for Rice Ecosystem, Kharagpur, 2000, pp. 1–21.
5. Gale, I. N., Williams, A. T., Gaus, I. and Jones, H. K., ASR-UK: Elucidating the hydrological issues associated with aquifer storage and recovery in the UK. UKWIR report ref. no. 02/WR/09/2, BGS Report no. CR/02/156/N, UK Water Industry Research Limited, London, 2002, p. 10; www.nwl.ac.uk/gwf/asr/asr_intro.htm
6. Pavelic, P., Dillon, P. J. and Simmons, C. T., Lumped parameter estimation of initial recovery efficiency during aquifer storage and recovery. In *Management of Aquifer Recharge for Sustainability* (ed. Dillon, P. J.), Proceedings of the International Symposium on Artificial Recharge 4, Adelaide, A.A. Balkema Publishers, Tokyo, 22–26 September 2002, pp. 285–290.
7. Pyne, R. D. G., *Ground Water Recharge and Wells – A Guide to Aquifer Storage Recovery*, CRC Press, Florida, USA, 1995, pp. 6–320.
8. Anon., Progress report of ICAR coordinated research schemes on optimization of ground water utilization through wells and pumps. Department of Soil and Water Engineering, College of Agriculture Engineering PAU, Ludhiana, 1993, pp. 4–26.
9. Forcchheimer, Ph., Groundwasserspiegel bei Brunnenalagen. *Z. Osterreichiscen Ingenieur Architekten Vereins*, 1898, **50**, 45–85.
10. Simpson, M. J., Prabhakar, C. T. and Yeomans, F. E., Analytical model for computing residence times near a pumping well. *Ground Water*, 2003, **41**, 351–354.
11. Chiang, W. H. and Kinzelbach, W., Processing Modflow. 3D-Groundwater Modelling with PMWIN: A simulation system for modeling ground water flow and pollution, Springer, 1998, 1st edn, p. 325.
12. Williams, A. T., Using an aquifer storage and recovery (ASR) trial as a large scale tracer test. In Tracers and Modelling in Hydrogeology. Proceedings of the TraM’ 2000 Conference, IAHS Publ. No. 262.
13. Kohfahl, C., Hamann, E. and Pekdger, A., Modelling of artificial water oscillations in a flooded lignite mine. In *Management of Aquifer Recharge for Sustainability* (ed. Dillon, P. J.), Proceedings of the International Symposium on Artificial Recharge 4, Adelaide, A.A. Balkema Publishers, Tokyo, 22–26 September 2002, pp. 261–264.
14. Jorgensen, N. O. and Helleberg, B. B., Stable isotopes (2H and 18O) and chloride as environmental tracers in a study of artificial recharge in Denmark. In *Management of Aquifer Recharge for Sustainability* (ed. Dillon, P. J.), A.A. Balkema Publishers, Tokyo, 22–26 September 2002, pp. 245–250.
15. Bogdanov, I. I., Mourzenko, V. V., Thovert, J. F. and Adler, P. M., Pressure drawdown well tests in fractured porous media. *Water Resour. Res.*, 2003, **39**, 1021–1029.
16. Diodato, D. M., Review: Hydrus-D. *Ground Water*, 2000, **38**, 10–11.

17. Manglik, A., Rai, S. N. and Singh, V. S., Modelling of aquifer response to time varying recharge and pumping from multiple basins and wells. *J. Hydrol*., 2004, **292**, 23–29.
18. Goyal, V. P., Gorlapuri, V. N. and Singh, M., Distribution of clay minerals in the semi arid region soils of a part of southern Haryana. *Int. J. Trop. Agric*., 1990, **8**, 154–165.
19. Van Dam, J. C. and Malik, R. S., Integration of remote sensing, crop and soil models and geographical information systems. Final project report of water productivity of irrigated crops in Sirsa district, India, IWMI, Wageningen UR, water watch and CCS HAU, Hisar, 2003.
20. Marquardt, D. W., An algorithms for least squares estimation of non-linear parameters. *SIAM J. Appl. Math*., 1963, **11**, 431–441.
21. Bristow, K. L., Hopmans, J. W., Cote, C. M., Charlesworth, P. B., Thorburn, P. J. and Cook, F. J., Development of improved water and nutrient management strategies through strategic modelling. In Proceeding of the 17th WCSS, Thailand, 2002, pp. 14–21.
22. Malik, R. S., Jhorar, B. S. and Jhorar, R. K., Modelling groundwater recharge from an ASR well. In *Groundwater Recharge and Management Through ASR Technology* (eds Jhorar, R. K. *et al.*), Proceedings of the Workshop on Groundwater Recharge and Management through ASR Technology, CCS Haryana Agricultural University, Hisar, 15–17 April 2004.
23. Van Genuchten, M. Th., A closed form equation for predicting the hydraulic conductivity of unsaturated soil. *Soil Sci. Soc. Am. Proc. J.*, 1980, **44**, 692–698.

ACKNOWLEDGEMENTS. We thank Volkswagen Foundation, Germany for providing ASR facilities created under Indo-German collaborative project on ‘Artificial recharge of ground water through integrated sand filter – injection well technique’ at Hisar. The project was jointly implemented by Chaudhary Charan Singh Haryana Agricultural University, Hisar, India, and the University of Hohenheim, Institute for Soil Science and Land Evaluation (Biogeophysics Section), Stuttgart, Germany.

Received 1 April 2008; revised accepted 18 December 2008

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