Performance evaluation of aquifer storage recovery wells for conjunctive water management as influenced by buffer storage volume and storage time

V. Goyal[1,*], B. S. Jhorar[2], R. S. Malik[2] and T. Streck[3]

[1]Water Technology Centre, Indian Agricultural Research Institute, New Delhi 110 012, India
[2]Department of Soil Sciences, Chaudhary Charan Singh Haryana Agricultural University, Hisar 125 004, India
[3]Institute for Soil Science and Land Evaluation, Biogeophysics Section, University of Hohenheim, Stuttgart 70593, Germany

Field experiments were carried out in a cavity type of aquifer storage recovery (ASR) well installed in an aquifer having highly saline native groundwater (EC = 28.4 dS per m). Good quality canal water (EC = 0.46 dS per m) was injected to investigate the effect of buffer storage volume (varying from 2000 to 14,000 cubic m) and storage time (varying from 2.5 to 70 days) on the recovery efficiency in five ASR test cycles. Field experiments with different ASR cycles showed that the recovery efficiency increased with increasing buffer storage volume and decreased with increasing storage time. For buffer storage volume of 14,000 cubic m and storage time of 13 days, the observed instantaneous recovery efficiency (IRE) and integrated recovery efficiency (CRE) at the target water quality of 2 dS per m of the recovered water were 80.2 and 108% respectively. At the test site it was observed that a buffer storage volume of 14,000 cubic m was essential to create a buffer zone of good-quality water between native saline groundwater and reusable freshwater zone to achieve a good recovery efficiency of injected water after a storage time of 70 days. The ASR technique was found practically feasible and economically viable for reclamation of groundwater quality under shallow water-table condition.

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

THE objective of artificial groundwater recharge may greatly influence the choice of method of recharge[1]. In the past, majority of the artificial recharge operations were directed towards replenishing over-exploited aquifers. However, more recently, it is also used to improve groundwater quality and to store surplus surface water for subsequent withdrawal[2,3]. In areas underlain by poor quality of groundwater, if excess water of good quality is directly injected into the aquifer, subsequent withdrawal of a certain amount of water at the same location after a certain time span may be of better quality than the native groundwater. Improvement in quality, however, depends on the physical and chemical interactions occurring between the injected and the native groundwater and the aquifer material. Under actual field conditions, particularly after a certain period of time, mixing between the injected and the native groundwater does occur due to groundwater movement or salt diffusion. Therefore, the quality of recovered water may be different from the injected water.

The aquifer storage recovery (ASR) technique is a special form of artificial groundwater recharge through wells, in which the same well is used for both recharge and recovery[3]. ASR wells are used to store water in suitable aquifers during times when surface water is available in abundance and to recover the water during times when it is needed. An understanding of the effect of operational parameters such as volume of water injected and storage time on the recovered water quality is of paramount importance for successful application of the ASR technique. Recovery efficiency (RE), as related to ASR operations, represents the volume of water of usable quality (or target quality) that can be recovered relative to the volume of water injected. The hydro-geological and operational factors which affect the movement and mixing of injected water in aquifers, ultimately control the RE[4,5]. Hydrogeological factors include transmissivity, porosity, thickness, heterogeneity and dispersivity of aquifers, native groundwater quality and regional hydraulic gradient. Operational factors include the quality of injected water, critical target water quality, storage time, buffer storage volume (BSV) and ratio of recovery to injection rate. Quantification of RE is particularly important for conditions where there is a significant difference in the quality of the injected water and the native groundwater. An optimum BSV is required at each ASR site for attaining acceptable levels of RE[5]. BSV is the volume of injected water that is not recovered during the recovery cycle and is presumed to act as a buffer zone between the injected water and the native groundwater. Increasing storage time may decrease RE in aquifers having poor quality of

*For correspondence. (e-mail: vishal_goyal11@rediffmail.com)

groundwater[5,6], depending upon aquifer characteristics and BSV.

Thus the present investigation was aimed at studying the effect of storage time and BSV on RE. The study was carried out using a cavity-type tube well installed in a highly saline aquifer (EC = 28.4 dS per m). Cavity wells are special types of tube wells without the conventional screen. These are constructed by drilling a hole until a saturated sand layer is encountered below a hard layer, usually of stiff clay. After retracting the casing pipe into the clay layer, sand is pumped out until a stable cavity has been developed in the sand below the clay layer and the water clears of sand and silt particles. Accordingly, development of a cavity well means drawing out of sand from below the clay layer. In contrast to a screened well or gravel-packed well, where fine particles are selectively removed during well development, the development of an ordinary cavity well results in the removal of the aquifer material as a whole, thereby forming the cavity. Although the ASR technique will work well in screened wells also, clogging has been reported to be the major problem in most of the screened/filter wells. The study was carried out in cavity wells because most of the wells are cavity type in North India mainly because (i) pipe length and screening cost are lesser in cavity wells than those in screen wells and (ii) low technical input is required in constructing a cavity-type well. In addition to reasons of economical and practical feasibility, cavity wells were not found to clog when they were used to inject freshwater even of a large (900 mg per l), sedimentation load[7,8].

Study area

The ASR field site is at Hisar, Haryana, which is located in the northwestern part of India. Haryana is one of the most progressive states of India, which has seen full success of the green revolution. Recent years, however, have seen a number of problems related to water resources development and management. Non-utilization of the poor quality of groundwater in some of the canal-irrigated areas of the state threatens the sustainability of irrigated agriculture with the potential problem of waterlogging and soil salinization. Also the quality of groundwater had not shown major improvement as a result of additional recharge from canal seepage[9]. Apparently, excessive salt in the soil profile leached down to the deeper layers. Therefore, it is particularly attractive if the excess water is directly injected at the well sites to take the advantage of improvement in the water quality locally. Mishra and Tyagi[10] analysed the irrigation water-delivery system in the study area and observed that for the months of April, May, July, August and November, average supply values were more than the corresponding average demand. On the other hand, during other periods of year, average supply values were less than the corresponding demand. Therefore, with proper selection of recharge timing (e.g. August and November) during excess supply periods, it is possible to achieve an acceptable RE to meet the water demands during periods of deficit supply (e.g. September, October, December and January). Improved groundwater quality in the marginal to saline groundwater zone will encourage farmers to conjunctively use the groundwater for crop production.

Experimental set-up

The site lithology is made up of different layers of sand, loamy sand and clay loam with a relatively hard silt loam layer of 9.0 m thickness at depth of 45.0 m from the soil surface. A cavity-type ASR tubewell fitted with a submersible pump was installed at the site (Figure 1). At the start of the experiment, groundwater depth at the ASR well site was 1.2 m from the soil surface.

Good-quality canal water (EC = 0.46 dS per m) was injected to investigate the effect of BSV and storage time on RE. Water samples of recovered water as a function of recovery time and that of injected water and native water were analysed for EC using portable conductivity meter. Injection and recovery rates were continuously monitored with mechanical water meters.

Performance evaluation criteria

Different parameters (recovery percentage, BSV and mixing fraction) are required to quantify RE as a function of BSV and storage time.

Recovery percentage

Recovery percentage, I, denotes the volume of the water recovered V_r as a per cent of the total volume of water injected V_i. It is expressed as

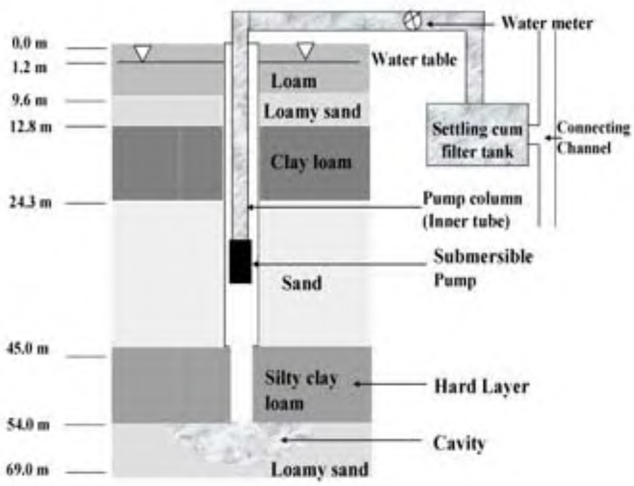

Figure 1. Schematic diagram of the aquifer storage recovery well.

$$I = 100\left[\frac{\int_{tr1}^{tr2} qr(t)\mathrm{d}t}{\int_{tr1}^{ti2} qi(t)\mathrm{d}t}\right] = 100\left[\frac{V_\mathrm{r}}{V_i}\right], \quad (1)$$

where $qr(t)$ is the recovery rate as a function of time, $qi(t)$ the injection rate as a function of time, $tr1$ the time when recovery starts, $tr2$ the time when recovery ends, $ti1$ the time when injection starts and $ti2$ the time when injection ends.

Recovery efficiency

RE is that recovery percentage (I) at which the quality of the recovered water becomes equal to the desired water quality. It may be expressed as:

$$\mathrm{RE} = 100\left[\frac{\int_{tr1}^{trt} qr(t)\mathrm{d}t}{\int_{ti1}^{ti2} qi(t)\mathrm{d}t}\right] = 100\left[\frac{V_\mathrm{r}^{**}}{V_i}\right], \quad (2)$$

where V_r** is the total volume of the water recovered at which target water quality was achieved in target time *trt*. Here the desired (target) water quality (electrical conductivity, EC) of the recovered water for irrigation purpose was taken as 2 dS per m.

RE is often described as instantaneous or integrated. The instantaneous recovery efficiency (IRE) is that recovery percentage (I) at which the quality of a small sample of the recovered water at any instant of recovery time becomes equal to the desired water quality. The integrated recovery efficiency (CRE) is that recovery percentage at which the quality of composite recovered water collected so far during the whole recovery time becomes equal to desired water quality (2 dS per m). IRE is useful when the recovered water is put to direct use such as for drinking or irrigation. CRE is useful when the recovered water may be stored in storage tanks till the composite quality reaches the target criteria.

The instantaneous electrical conductivity $\mathrm{EC_r}$ of the recovered water was obtained from direct measurements during the recovery cycles. The integrated electrical conductivity $\mathrm{EC_{rw}}$ of recovered water was estimated as

$$\mathrm{EC_{rw}}(t) = \left[\frac{\int_{tr1}^{tr2} \mathrm{EC_r}(t)qr(t)\mathrm{d}t}{\int_{ti1}^{ti2} qr(t)\mathrm{d}t}\right] = \frac{\sum \mathrm{EC_r}(r)\Delta V_\mathrm{r}}{\sum \Delta V_\mathrm{r}}, \quad (3)$$

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

Mixing of injected and native water

Mixing fraction $f(t)$ of the injectant present in the recovered water as a function of recovery time t depends on operational factors as well as aquifer properties. Important factors influencing $f(t)$ include volume of water injected (V_i) and recovered (V_r), longitudinal dispersivity α and groundwater flow at the ASR site. In case of negligible regional hydraulic gradient, $f(t)$ can be quantified using the analytical solution of the problem given by Gelhar and Collins[11] as:

$$f(t) = \frac{1}{2}\mathrm{erfc}\left[\frac{\left(\frac{V_\mathrm{r}(t)}{V_\mathrm{i}} - 1\right)}{\sqrt{\frac{16\alpha}{3r_m}\left(2 - \sqrt{\left(1 - \frac{V_\mathrm{r}(t)}{V_\mathrm{i}}\right)}\left(1 - \frac{V_\mathrm{r}(t)}{V_\mathrm{i}}\right)\right)}}\right], \quad (4)$$

where r_m is the radius of the injected water bubble around the ASR well and can be approximated from the volume of pore space occupied by the injectant (assuming a cylindrical bubble):

$$r_\mathrm{m} = \sqrt{\frac{V_i}{\pi n_\mathrm{e} b}}, \quad (5)$$

where n_e is the effective porosity of the aquifer, and b is the thickness of the aquifer.

The relative dispersivity (α_rd), a factor of mixing of injected water with native water, is described as the ratio of the longitudinal dispersivity (α) to the radius of the injected water bubble r_m (ref. 5) as

$$\alpha_\mathrm{rd} = \frac{\alpha}{r_\mathrm{m}}. \quad (6)$$

Mixing fraction $f(t)$ is defined as:

$$f(t) = \frac{C_\mathrm{rw}(t) - C_\mathrm{n}}{C_\mathrm{i} - C_\mathrm{n}}, \quad (7)$$

where $C_\mathrm{rw}(t)$ is the integrated solute concentration in the recovered water at any recovery time, C_n is solute concentration in the native water and C_i is solute concentration in the injected water. C is a conservative solute, and $C_\mathrm{i} \neq C_\mathrm{n}$ and $f^* = f(t_\mathrm{r}^*)$. Chloride, fluoride, EC and deuterium are commonly used to determine f. However f^*, the minimum f for an acceptable quality of recovered water, is reached when any solute species in the recovered water exceeds its maximum permissible value at target time t_r^* for its beneficial use in crop production. The $f(t)$ prediction may be helpful in predicting RE at any desired water quality and estimation of α helps characterize to the aquifer dispersion parameters.

Buffer storage volume and storage time

The BSV acts as a buffer zone in the aquifer between the injected water and the native groundwater. The buffer zone has historically been formed over several operating cycles by leaving a certain portion of injected water in the aquifer as unrecovered in each successive cycle. The volume of the water to be injected in the jth cycle was estimated from the equation:

$$V_{ij} = (\mathrm{BSV}_j + V_{rj}) - \mathrm{BSV}_{j-1}, \quad (8)$$

where BSV_j is the buffer storage volume to be maintained in the jth cycle, BSV_{j-1} is the buffer storage volume maintained in the previous $j - 1$ cycle and V_{rj} is the volume to be recovered in the jth cycle.

Storage time t_s was estimated as:

$$t_s = 0.5\ (t_i + t_r) + t_R, \quad (9)$$

where t_i is the injection time, t_r the recoverable time, and t_R the time of residence of the water bubble, excluding that of t_i and t_r.

Results and discussion

Injection rates decreased from 23.23 to 13.29 cubic m per h with increasing volume of injected water because of increasing pressure head and water-table mounds around the ASR well under shallow water-table condition in the 1st to 5th ASR cycle. However, the recovery rates remained fairly constant at an average value of 60.21 cubic m per h. Thus the study showed that injection could be done in a cavity-type ASR well under shallow water-table condition even when water table depth was 0.54–2.08 m. At other sites in Haryana where the water table was deep, injection and recovery rates remained almost equal[8].

Effect of buffer storage volume on recovery efficiency

In order to study the effect of BSV on RE, five ASR cycle test programmes were implemented (Table 1). In each cycle, the recoverable volume of water was kept as 2000 cubic m.

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

ASR cycle number	Volume of water (cubic m)			Storage time (days)
	Injected	Recovered	Buffer storage	
1	4000	2000	2000	2.50
2	6000	2000	6000	7.20
3	6000	2000	10000	6.05
4	6000	2000	14000	13.55
5	2000	2000	14000	70.00

EC_r and EC_{rw} (eq. (3)) as a function of I (eq. (1)) is presented in Figure 2 *a* and *b*. Both EC_r and EC_{rw} of the recovered water increased consistently with increasing volume of the latter. The increase was gradual until the recovery percentage was about 70. Thereafter, the increase in both EC_r and EC_{rw} was relatively at a faster rate with increasing levels of recovery percentage. It can also be noted from Figure 2 *a* and *b* that EC_{rw} increased at a relatively slower rate compared to EC_r, signifying increasing rate of mixing between the native and injected water with increasing recovery volume.

For a recovery percentage of up to about 70, not much difference was observed among EC_r (or EC_{rw}) values for different BSV values . However, thereafter, the increase in EC_r (or EC_{rw}) was at much faster rate for small values of BSV (e.g. BSV = 2000 cubic m) compared to larger values of BSV (e.g. BSV = 14,000 cubic m). Noting that the recovered volume was the same (equal to 2000 cubic m) for all the ASR cycles, it clearly shows the effectiveness of an increasing BSV in reducing the mixing between the native and injected water. This suggests that the increasing value of BSV is expected to increase the RE.

RE (eq. (2)), IRE and CRE at target water quality of 2 dS per m of the recovered water was estimated using recovery percentage as observed from Figure 2 *a* and *b*. The RE as a function of BSV is shown in Figure 3. CRE is higher than IRE at each BSV. Both IRE and CRE increased linearly with BSV as:

$$\mathrm{IRE} = 41.53 + 0.0028\ \mathrm{BSV}, \quad r^2 = 0.9845, \quad (10)$$

$$\mathrm{CRE} = 60.205 + 0.0033\ \mathrm{BSV}, \quad r^2 = 0.986. \quad (11)$$

The strong linear relationship, as indicated by the r^2 value, verifies the fact that increasing value of BSV is expected to increase RE at this site. Moreover, for the target water quality of 2 dS per m at the test site, CRE is expected to be at least 20% higher than IRE (see the value of constants in eqs (10) and (11)) with increasing difference between CRE and IRE as BSV is increased. During the fourth ASR cycle (Table 2), the observed IRE and CRE at the target water quality of 2 dS per m of the recovered water was 80.2 and 108% respectively, at BSV of 14,000 cubic m. It suggested that at the test site, the minimum BSV required to maintain the acceptable CRE of 100% is 14,000 cubic m. Pyne[12] has reported RE varying from 25 to 100% at different sites in Florida depending upon BSV, aquifer water quality and aquifer hydraulic characteristics.

It is common to assume the safe maximum limit (target value) of EC of irrigation water as 2 dS cubic per m. However, with suitable management practices (such as choice of salt-tolerant crops and planned leaching), groundwater of EC up to 6 dS cubic per m can be used

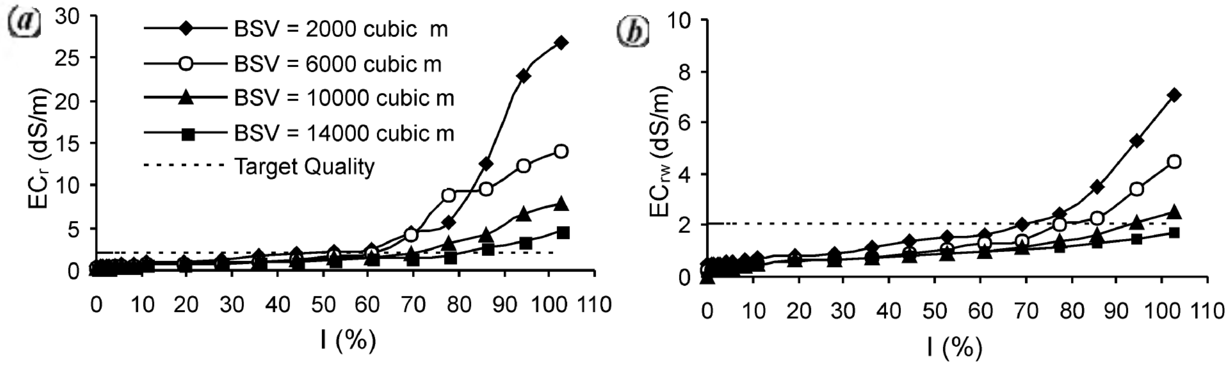

Figure 2. Instantaneous electrical conductivity EC_r (***a***) and integrated electrical conductivity EC_{rw} (***b***) of the recovered water as a function of recovery percentage (I) at indicated buffer storage volume (BSV). Dotted line shows that EC = 2 dS per m was taken as the target water quality.

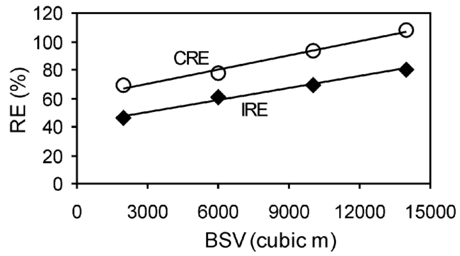

Figure 3. Instantaneous recovery efficiency (IRE) and integrated recovery efficiency (CRE) as a function of buffer storage volume (BSV).

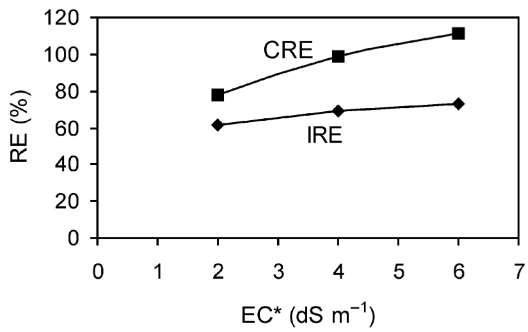

Figure 4. Instantaneous recovery efficiency (IRE) and integrated recovery efficiency (CRE) as a function of target EC* (dS per m).

safely in the study area[13,14]. The RE at different target values of EC (2, 4 and 6 dS per m) of the recovered water was estimated using Figure 2 *a* and *b*. IRE and CRE as functions of the target water quality are shown in Figure 4. Regression analysis showed that RE increased linearly with the increasing target EC* of the recovered water as

$$\text{IRE} = 55.833 + 3\ \text{EC}^*,\ r^2 = 0.9453, \quad (12)$$

$$\text{CRE} = 62.33 + 8.375\ \text{EC}^*,\ r^2 = 0.9739. \quad (13)$$

A strong linear relationship between RE and target EC* implies that higher RE can be achieved for a given ASR cycle for salt-tolerant crops. Moreover, the difference in the coefficients of EC in eqs (12) and (13) suggests that a much higher value of CRE compared to IRE would be achieved for larger values of target EC*.

Effect of storage time on recovery efficiency

In order to study the effect of storage time on RE, two storage times of 13 and 70 days were allowed at BSV of 14,000 cubic m during the fourth and fifth ASR cycle (Table 1). Recovery curves representing EC_r and EC_{rw} of the recovered water as a function of recovery percentage at different storage times are shown in Figure 5 *a* and *b*. RE at the target water quality of 2 dS per m, as estimated using Figure 5 *a* and *b* is given in Table 2.

The results showed that both IRE and CRE decreased with increasing storage time. Pavelic *et al.*[5] and Pyne[12] had also reported a decrease in RE with increasing storage time in brackish aquifer depending upon aquifer characteristics and BSV. For the aquifer conditions at the experimental site and under the prevailing hydraulic gradient, it is safe to assume that a BSV of 14,000 cubic m will be sufficient to achieve RE of more that 75%, at the target water quality of 2 dS per m for a storage time of up to 2 months at V_r of 2000 cubic m.

Dispersivity parameters

Longitudinal dispersivity α as estimated as a fitting parameter in eq. (4) at $I = 0.5$ and relative dispersivity α_{rd} as estimated from eqs (5) and (6) are given in Table 2 for different values of BSV and t_s. It showed good matching of experimental with predicted $f(t)$ points up to $I = 0.6$ (Figure 6).

Nevertheless, the RMSE values (0.11–0.12) for the whole range of I up to 1 in each cycle as given in Table 2, were also satisfactory. Lower matching of experimental and predicted $f(t)$ at $I > 0.6$, however, indicated that there

Table 2. Recovery efficiency and dispersivity parameters at different values of buffer storage volume (BSV) and storage time (t_s)

Cycle no.	BSV (cubic m)	t_s (days)	IRE (%)	CRE (%)	α (m)	α_{rd}	RMSE
1	2000	2.50	45.5	68.8	0.360	0.017	0.10
2	6000	7.20	61.0	77.5	0.291	0.004	0.10
3	10000	6.05	69.5	93.0	0.245	0.011	0.13
4	14000	13.60	80.2	108.0	0.235	0.011	0.14
5	14000	70.00	50.1	76.6	0.360	0.170	0.12

IRE, Instantaneous recovery efficiency; CRE, Integrated recovery efficiency; α, Longitudinal dispersivity; α_{rd}, Relative dispersivity; RMSE, Root mean square error.

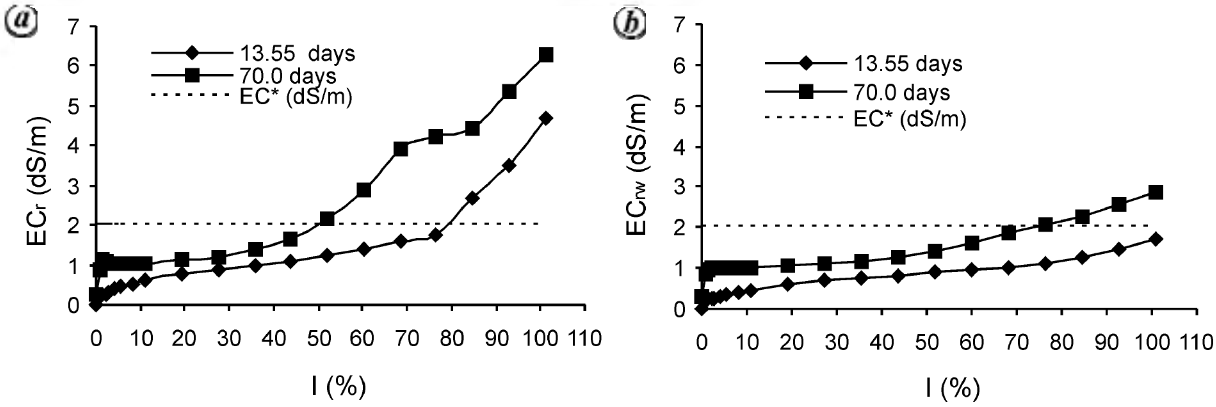

Figure 5. (***a***) Instantaneous electrical conductivity (EC_r) and (***b***) integrated electrical conductivity (EC_{rw}) of the recovered water as a function of recovery percentage (I) at indicated storage time (t_s).

was some deviation from the principal assumption of the model. The major limitations are that the regional hydraulic gradient and t_s have been neglected and aquifer homogeneity is assumed. Data on the regional hydraulic gradient (0.0007 in the eastern direction away from the ASR well) of the experimental site were also not negligible. Pavelic *et al.*[5] observed that the analytical model fits well in six of the total nine sites in Australia and USA. α and α_{rd} for different BSV and t_s values (Table 2) were in the same order of magnitude as reported by Pavelic *et al.*[5].

It may be seen from Figure 7 that α decreased linearly with BSV. α_{rd} also decreased with BSV and increased with t_s (Table 2).

This showed that α and α_{rd} were the main factors to affect RE. The decrease in dispersivity parameters (α, α_{rd}) with BSV and their increase with t_s may explain the above trend of increasing and decreasing RE with BSV and t_s (Table 2). Pyne[3,4] and Pavelic *et al.*[5] also reported that dispersivity was the main process to affect RE.

Summary and conclusion

Field experiments were carried out in a cavity-type ASR well installed in an aquifer having highly saline native groundwater (EC = 28.4 dS per m). In sequence, five ASR test cycles were carried out by injecting good-quality canal water. The major objective of the study was to predict attainable RE as a function of BSV and storage time. Accordingly, the variables studied included different values of BSV (varying from 2000 to 14,000 cubic m) and storage time (varying from 2.5 to 70 days). The effect of target water quality was also studied.

Injection rates (23.23 to 13.29 cubic m per h) were lower than recovery rates (60.21 cubic m per h) in all ASR cycles. Injection in the ASR well is possible even in shallow water-table condition (<1 m), though at much reduced rates. RE increased with increasing BSV and decreased with increasing storage time. CRE observed was 68.8, 77.5, 93.0 and 108.0% at BSV of 2000, 6000, 10,000 and 14,000 cubic m at storage time of 2.5, 7.2, 6.05 and 13.60 days; however it decreased to 76.6% at BSV of 14,000 cubic m when a storage time of 70 days was given. RE increased with increasing target EC* of the recovered water. CRE was always greater than IRE.

An analytical model described the mixing fraction $f(t)$ vs recovery percentage (I) successfully up to $I > 0.6$. Longitudinal dispersivity decreased with BSV. The study showed that the ASR well technique can be successfully used for reclamation of groundwater quality under shallow water-table conditions, if good-quality water is available for injection.

Economics of ASR well

The ASR well is practically feasible as it requires low technical inputs. The existing cavity wells can be con-

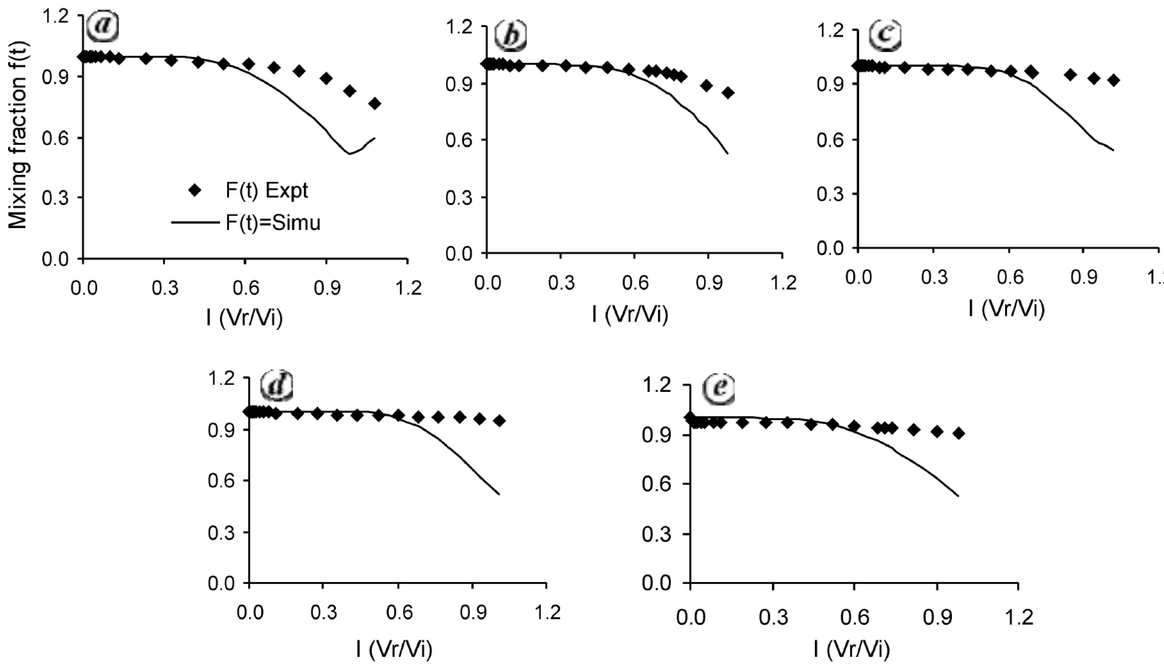

Figure 6. Fraction of injectant present in the recovered water $f(t)$ vs recovery percentage (I) at (***a***) BSV = 2000 cubic m and t_s = 2.5 d, (***b***) BSV = 6000 cubic m and t_s = 7.2 d, (***c***) BSV = 10000 cubic m and t_s = 6.5 d, (***d***) BSV = 14,000 cubic m and t_s = 13.5 d and (***e***) BSV = 14,000 cubic m and t_s = 70 d.

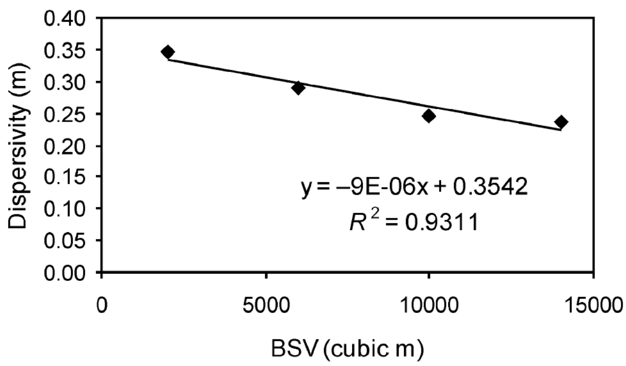

Figure 7. Dispersivity (α) as a function of buffer storage volume (BSV).

verted into ASR wells by (i) opening the reflex valve of the pump during injection, (ii) providing freshwater-collecting channels and (iii) making settling-cum-filter tank. The economics of using the ASR technique for conjunctive use of groundwater of high salinity (8 dS per m) with fresh surface water for a 4 ha farm may be estimated from total volume of injectable freshwater and the extra cost involved in installation and operation of the ASR facility in the existing cavity well.

The groundwater irrigation needed for cotton–wheat rotation in a canal command area was 0.4265 m per annum[15]. The conjunctive use in the ratio of 1 : 3; of groundwater (0.1064 m) : injected water (0.3201 m) would inject 12,804,000 l of freshwater through the ASR well. The extra cost for connecting channels was Rs 20,000 and for constructing settling-cum-filter tank was Rs 10,000. The extra cost of wear and tear of the ASR pump would be Rs 2000 per year. Contribution of initial cost towards operation of the ASR well at a depreciation rate of 10% would be Rs 3000 per annum. Thus the total cost of injecting 12,804,000 l of water through the ASR well for reclamation of groundwater quality from 8 to 2 dS per m would be Rs 5000 which is Rs 0.00039 per l. This shows that the ASR technique is economically affordable and viable.

Perspective for utilizing the ASR well for conjunctive use purposes

The ASR technique has good scope for conjunctive use of groundwater and canal water for irrigation purposes. Canal, river and storm waters collected in a suitable storage tank combined with the ASR well may provide dependable irrigation supplies to the surrounding farmers and for improving the quality of groundwater. It not only improves the productivity and total food production, but also helps in maintaining the water table at any desired depth, especially in the brackish groundwater zones. The ASR technique will not work in dug wells because the aquifers of dug wells are of lesser thickness and specific yield compared to those of cavity wells, leading to lesser recharge and discharge rates in dug wells even if they are of larger diameter.

The results obtained in this study suggest that the ASR technique has considerable potential to improve the quality of groundwater in different parts of Haryana and elsewhere, characterized by inland drainage basin conditions and poor groundwater quality. With suitably designed ASR operations (e.g. BSV), an acceptable level of RE can be achieved. There may be objections to the idea that artificial recharge is resorted to in areas facing rising water levels. However, considering the fact that the excess canal water/rainwater adds to the rise in the water table, the ASR technique needs special attention, particularly due to its positive impact on the quality of water in the aquifers surrounding the ASR wells. This technique will serve the twin purposes of checking the rising trend of groundwater levels and also partly meeting the widening gap between demand and supply. In practice, suitable levels of BSV may be maintained by injecting sufficient quantity of water compared to the amount of water to be recovered. For instance, at the test site it was observed that a BSV of 14,000 cubic m is sufficient to achieve a RE of 70% for storage time of two months. In this study, RE was based on the electrical conductivity of the recovered water. On the other hand, there could be other water quality parameters which may limit the use of recovered water. In regions, where geochemical issues are of concern, a detailed analysis of physical and chemical interactions between the injected and native water may be required for planning effective operational strategies for the ASR systems.

1. Jhorar, R. K., Malik, R. S., Jhorar, B. S., Goyal, V., Seharawat, Y. S. and Streck, T., Recovery efficiency of ASR operations under saline groundwater regions. In Invited papers. Fourth NATP Workshop on Technologies for Skimming and Recharging Fresh Water in Saline Groundwater Regions, CSSRI, Karnal, 24–25 November 2004, pp. 105–115.
2. Malik, R. S., Jhorar, B. S., Jhorar, R. K. and Streck, T., Towards improved groundwater availability in Haryana State, India. Final report of Indo-German project on artificial groundwater recharge, 2004, pp. 1–93.
3. Pyne, R. D. G., Water quality changes during aquifer storage recovery (ASR). In Proceedings of the International Symposium on Artificial Recharge 4, Adelaide. *Management of Aquifer Recharge for Sustainability* (ed. Dillon, P. J.), A.A. Balkema Publishers, Tokyo, 22–26 September 2002, pp. 65–68.
4. Pyne, R. D. G., *Groundwater Recharge and Wells: A Guide to Aquifer Storage Recovery*, Lewis Publishers, Boca Raton, Florida, 1995, p. 376.
5. Pavelic, P., Dillon, P. J. and Simmons, C. T., Lumped parameter estimation of initial recovery efficiency during aquifer storage and recovery. In Proceedings of the International Symposium on Artificial Recharge 4, Adelaide. *Management of Aquifer Recharge for Sustainability* (ed. Dillon, P. J.), A.A. Balkema Publishers, Tokyo, 22–26 September 2002, pp. 285–290.
6. Harpaz, Y., Artificial groundwater recharge by means of wells in Israel. *J. Hydraul. Div.*, 1971, **97**, 1947–1964.
7. Anon., Progress report of ICAR coordinated research schemes on optimization of groundwater utilization through wells and pumps. Department of Soil and Water Engineering, College of Agriculture Engineering, Punjab Agricultural University, Ludhiana, 1993, p. 4–26.
8. 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 Proceedings of the International Symposium on Artificial Recharge 4, Adelaide. *Management of Aquifer Recharge for Sustainability* (ed. Dillon, P. J.), A.A. Balkema Publishers, Tokyo, 22–26 September 2002, pp. 465–468.
9. Agarwal, M. C. and Roest, C. W. J., Towards improved water management in Haryana state. Final report of the Indo-Dutch operational research project on hydrological studies, Chaudhary Charan Singh Haryana Agricultural University (CCSHAU), Hisar, International Institute for Land Reclamation and Improvement, Wageningen and DLO Winand Staring Centre for Integrated Land, Soil and Water Research, new Alterra, Wageningen, The Netherlands, 1996, p. 80.
10. Mishra, A. and Tyagi, N. K., Improving canal water deliveries with auxiliary storage. *J. Irrig. Drain. Eng.*, 1988, **114**, 534–546.
11. Gelhar, L. W. and Collins, M. A., General analysis of longitudinal dispersion in non-uniform flow. *Water Resour. Res.*, 1971, **7**, 1511–1521.
12. Pyne, R. D. G., Aquifer storage recovery: Recent developments in the United States. In *Artificial Recharge of Groundwater* (ed. Peters, J. H.), A.A. Balkema, Rotterdam, 1998, pp. 257–261.
13. Kumar, S., Jhorar, R. K. and Agarwal, M. C., *Reuse of Saline Irrigation Water for Cereal Crops*, Department of Soil Science, CCSHAU, Hisar, 1996, p. 96.
14. Minhas, P. S. and Tyagi, N. K., Guidelines for irrigation with saline and alkali waters. Bull. No. 1/98, Central Soil Salinity Research Institute, Karnal, 1998, p. 36.
15. Malik, R. S. *et al.*, Final report of Indo-Dutch project on Water productivity of irrigated crops in Sirsa district, India (eds Van dam, J. C. and Malik, R. S.), 2003, pp. 29–39.

ACKNOWLEDGEMENTS. We acknowledge with thanks and gratitude the Volkswagen Foundation, Germany for providing ASR facilities under the Indo-German collaborative project on 'Artificial recharge of groundwater through integrated sand filter–injection well technique' between the Chaudhary Charan Singh Haryana Agricultural University, Hisar, India and the University of Hohenheim, Institute for Soil Science and Land Evaluation (Biogeophysics Section), Stuttgart.

Received 22 May 2007; revised accepted 28 December 2007