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Groundwater modelling to assess the effect of interceptor drainage and lining

Example of model application in the Fordwah Eastern Sadiqia project, Pakistan

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Abstract. Recharge to the aquifer through seepage from irrigation canals is often quoted as one of the main causes for waterlogging in Pakistan. In the design of drainage systems to control this waterlogging, rules-of-thumb are often used to quantify the seepage from canals. This paper presents the option to use a groundwater model for a more detailed assessment. Groundwater models may assist in evaluating the effect of recharge reducing measures such as interceptor drains along irrigation canals and lining. These measures are commonly aimed at reducing the drainage requirement of adjacent agricultural lands.

In this paper an example is given of the application of a numerical groundwater model, aimed at assessing the effect of interceptor drainage and canal lining in the Fordwah Eastern Sadiqia project, being a typical and well-monitored location in Pakistan.

The paper also presents references to other conditions. The model was used to obtain a better insight in the key hydraulic parameters, such as the *infiltration resistance* of the bed and slopes of irrigation canals, the *drain entry resistance* of interceptor drains and the hydraulic conductivity of soil layers. The model was applied to assess the *effectiveness* and *efficiency* of interceptor drains under various conditions.

The results of the study show that the *net percentage of intercepted seepage* is too low to have a significant effect on the drainage requirement of the adjacent agricultural lands. Besides, the operation of the system, with pumping required, is often an added headache for the institution responsible for operation of the system. The marginal effect of interceptor drains and lining on the drainage requirement of adjacent agricultural land does not always justify the large investments involved. It can be concluded that:

- Use of rules-of-thumb to estimate components of the water balance of irrigation systems in designing drainage can be very misleading;
- Interceptor drainage may cause induced seepage from irrigation canals, which is often an order of magnitude more than the net intercepted seepage;
- Interceptor drains and canal lining do not significantly reduce the drainage requirements, or in other words, cannot prevent the need for the installation of a drainage system;
- A numerical model can aid to evaluate proposed measures and strategies to alleviate water losses and drainage problems.

Relevant hydrological concepts and modelling parameters with respect to leakage from irrigation canals and interception by interceptor drains are presented in a separate paper.

Key words: canal seepage, induced seepage, interceptor drainage, numerical modelling

1. Introduction

1.1. Waterlogging and salinization

In many countries, the introduction of irrigated agriculture has also resulted in negative side effects, such as increased water tables, waterlogging and salinization. These side effects are caused by a change in the local hydrology. Waterlogging and salinization are the result of altered water and salt balances in the root zone and subsoil.

Surface irrigation systems, generally, cause an increase of recharge to the subsoil. If this water is not adequately discharged by a natural or man-made drainage system, the water tables will rise and salts may accumulate. In irrigated areas, the following recharge sources require attention:

- (excess) precipitation;
- irrigation application surplus;
- leakage from irrigation canals;
- losses in the field distribution system and operational spills.

Obviously, the irrigation application should be narrowly matched with the climatic and crop requirements. The amount of excess irrigation water can be minimised, or rather optimised, through efficient irrigation methods, appropriate crop selection and -rotation, and good operational management. In the case of optimum irrigation practices, any occurring irrigation application surplus can be considered as an *intentional recharge source*, necessary for the leaching of salts. A man-made drainage system may be required to discharge the excess irrigation water (and salts).

The leakage from irrigation canals and losses in the field distribution system are an *unintentional recharge source*. They result in reduced irrigation efficiencies and increased operational costs, possibly with waterlogging in the irrigated areas and water shortages downstream.

The losses from the field distribution system and losses through spills can often be countered by using the appropriate irrigation equipment, and the proper installation and operation of the system. Leakage from canals involves – sometimes poorly understood – hydrological concepts, more complicated design aspects and, often, elevated cost for measures. This paper will, therefore, focus on leakage from irrigation canals.

1.2. Canal leakage

In Pakistan, the recharge to the aquifer through leakage from irrigation canals is often quoted as one of the main causes for waterlogging. Various measures to control canal leakage have been proposed or implemented. These measures are either aimed at the *prevention* of leakage or at the *mitigation* of the negative impacts of leakage.

The main *preventive measure* against water losses through canal leakage is the lining of irrigation canals, which is, however, a costly measure. A possible *mitigation measure* is the installation of interceptor drains.

In Pakistan, interceptor drains have been installed in various systems. In addition to mitigating seepage from the irrigation canals, they were also aimed at reducing the drainage requirement in the irrigated fields served by the canals. The effectiveness of interceptor drains has, however, been subject of discussion. The objective of this paper is to provide a more accurate (and more decisive) assessment method to evaluate interceptor drainage and canal lining.

1.3. Assessment methods

Several methods exist to assess the leakage from irrigation canals and the effectiveness of interceptor drains:

- Water balance studies;
- Field tests;
- Hydraulic calculations.

A constraint of canal leakage assessments through water balances is the (absolute) accuracy of the measuring devices. Measuring inaccuracies in the (relatively large) inflow and outflow terms often result in a large relative error in the canal leakage component (being the difference between inflow and outflow), although both the inflow and outflow may have been measured accurately.

Field tests mainly refer to infiltration tests, such as the ‘ponding test’, in which the decrease of the water level in a controlled section of the canal is measured. As the groundwater flow pattern during the test is different from the flow pattern during normal operation, this method is rather tentative. Constant level ponding tests are more reliable, but they have the same disadvantages as water balance studies.

Hydraulic calculations can provide good results, if they are based on reliable data. For simple cases (or as a first estimate), infiltration from irrigation canals and interception by interceptor drains can be calculated with *analytical methods*. However, *numerical methods* have become very popular, given the broad availability of easy-to-use numerical modelling packages and their capacity to assess more complicated situations (incorporating spatial and temporal variability of parameters, heterogeneity, etc.).

1.4. Numerical modelling

This paper presents the application of a numerical model to assess preventive and mitigating measures with respect to canal lining and interceptor drainage at the Interceptor Drainage Trial Site along the Malik Branch Canal in the Fordwah Eastern Sadiqia Project, Pakistan. Advantages of numerical modelling are the possibility to quickly evaluate various measures or water management options, under different physical and hydrological conditions, which enables the selection of the most feasible measures and strategies to alleviate water losses and drainage problems.

Section 2 (Methods and materials) presents a brief description of the area and a summary of the collected data. The most important details on the applied groundwater modelling package are given and, finally, the methodology to evaluate measures and scenarios is presented.

The model calculations have been conducted with the modelling package MODFLOW, being one of the most widely used groundwater modelling packages. The presented methodology is, however, in principle independent of the modelling software and can, therefore, also be applied with any other modelling packages.

Background information on the hydrological concepts involved and the conversion of these concepts to model parameters (parameterisation) are presented in a separate paper (Jansen, 2003).

Section 3 presents the model calculations, which includes the implementation and calibration of the model and the simulation of various measures. Additional model calculations were made for other physical conditions (soil properties).

A discussion of the results and conclusions follow in Section 4.

2. Methods and materials

2.1. Brief area characterisation

The Fordwah Eastern Sadiqia (South) Project was the third major project in Pakistan where interceptor drainage was installed. Pilot interceptor drains were installed along three main canals: Malik Branch, Hakra Branch and 3-R Khatan Distributary. Along with the interceptor drainage an extensive performance monitoring system was installed.

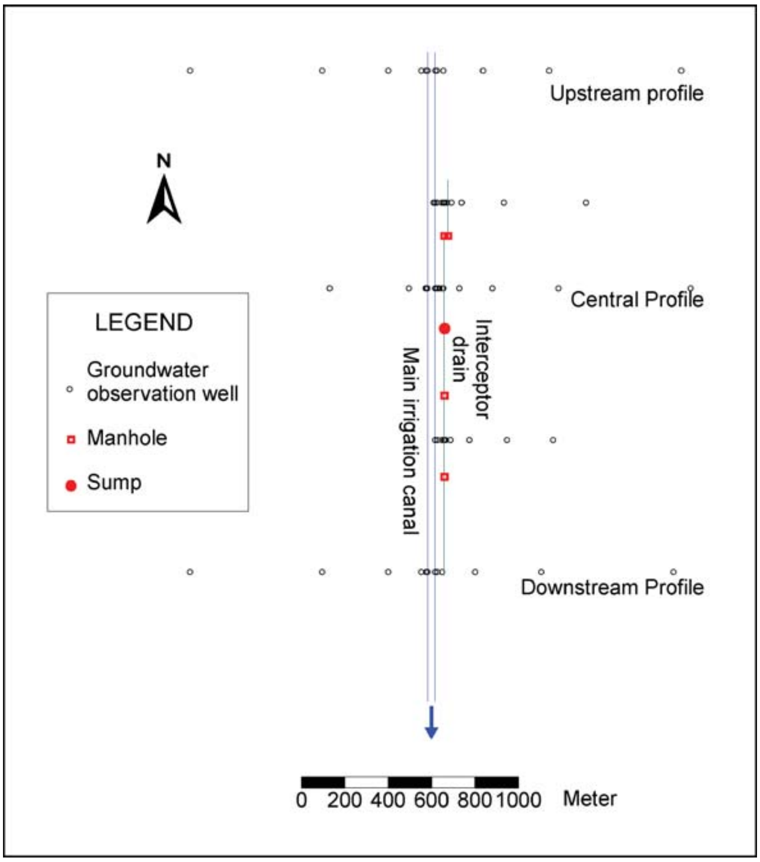

Figure 1. General location map with monitoring points.

The numerical model has been applied for a section along the Malik Branch where a pilot interceptor drain had been installed. The area is representative in terms of physical setting and drainage problems, while extensive monitoring data allow for the verification of calculation results.

Figure 1 presents the layout of the Malik Branch Canal, the interceptor drain with the measuring points (manholes) and the groundwater observation wells. The Malik Branch Canal has a width of approximately 35 m and a (design) water depth of approximately 2.5 m. The average (long-term) water level in the canal out of the closure period ranges from (downstream) 163.4 to (upstream) 163.7 m + MSL (Mean Sea Level).

The interceptor drain was installed between October 1995 and March 1996. The drain has a total length of 1828 m, divided in a northern section (upstream portion of the canal) of 685 m, and a southern section of 1143 m. Both sections discharge into a sump. The distance to the canal edge varies from approximately 45 to 60 m (60 to 80 m to the canal axis). The drain diameter varies from 20 cm (8 inches) to 25 cm (10 inches) at the sump. The average installation depth is (approximately) 2.7 m (Niazi et al., 1999; IWASRI, 1998).

The area is characterised by a thick phreatic aquifer, consisting of fine sands and loams. The hydraulic conductivity is in the order of 1 m/day (IWASRI, 1998; Euroconsult, 1994).

2.2. *Performance monitoring*

From 1994 to 1997 an extensive monitoring programme was executed. During 4 years the following data were measured on a regular basis:

- water levels in the irrigation canal (upstream and downstream);
- groundwater levels in the observation wells and some piezometers;
- drain discharges and water quality (13 times after drain installation; from March 1996 to June 1997);

In addition, a seepage measurement was executed by means of a ponding test during the closure period of January 1998 (IWASRI, 1998).

The data were analysed to determine the interaction between the irrigation canal, the groundwater and the interceptor drain. Special attention was paid to temporal trends, particularly the situation before and after the installation of the interceptor drains.

The data analysis showed that

- The water level in the canal is very constant over the year (except for the closure period; see also Jansen, 2003);
- The response of the groundwater to changes in the water level of the canal is very direct;
- The average observed discharge of the interceptor drain is in the order 4.5 l/s. This is much less than the design discharge of 14 l/s (Euroconsult, 1994). The difference is explained in (Jansen, 2003).
- The installation of the interceptor drain did not cause significant changes in groundwater levels (see also Niazi et al., 1999).

Special attention was paid to investigate the temporal trends of the groundwater levels. For each East–West running profile and for each observation well both the monthly and the long-term averages were calculated for the periods before and after the drain installation (the data collected during the drain installation were not used for this assessment). No significant impact of the interceptor drain on the regional groundwater levels was observed. As an example, Figure 2 shows the average groundwater levels before and after drain installation at the central profile.

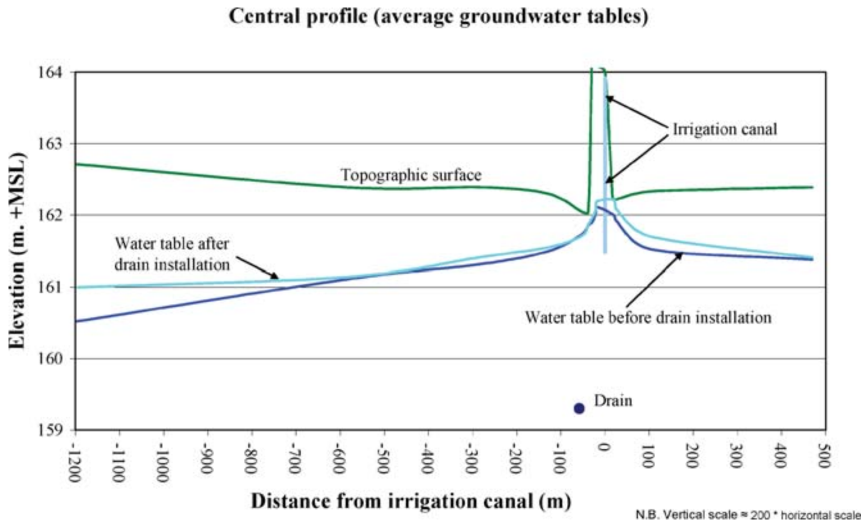

Figure 2. Impact of interceptor drain on long-term average groundwater table.

2.3. Numerical modelling

The model calculations have been conducted with the (pseudo-)3D groundwater modelling package MODFLOW.[1] MODFLOW was developed by the U.S. Geological Survey and is one of the most widely used packages. The model is based on the finite-difference calculation technique and is capable to simulate the effects of wells, rivers, drains, and other groundwater recharge (or discharge) functions.

To assess the situation at the interceptor drainage trial site along the Malik Branch Canal a simple model can serve. The modelling work included the following activities:

- Set-up of the model (schematisation, parameter definition);
- Calibration;
- Sensitivity analysis (emphasis on critical parameters);
- Evaluation of measures.

2.4. Measures and scenarios

A properly calibrated and validated model can be used to evaluate measures and scenarios. For this assessment the effect of interceptor drainage and canal lining at the trial site along the Malik Branch Canal were evaluated. In addition, an assessment was made for interceptor drainage in areas with different soil characteristics, as the soil hydraulic properties are one of the most determining factors in drain design.

Three situations have been simulated:

A. The existing situation. The phenomenon of *induced seepage* and the effect of interceptor drainage on the drainage requirement of the adjacent agricultural lands were also assessed.
B. Canal lining. It was investigated whether canal lining would significantly reduce the drainage requirement of the adjacent agricultural lands.
C. The existing layout of interceptor drainage with other hydraulic properties of the soil.

2.5. Evaluation of measures

In order to evaluate and compare the preventive and mitigating measures (canal lining and interceptor drainage), it is required that logic, unambiguous evaluation criteria (*indicators*) be defined. Both the *effectiveness* and *efficiency* were addressed.

The *effectiveness* of a measure refers to the degree that the objectives are met. The effectiveness is, therefore, mostly an engineering criterion: desired impacts of a measure should be maximised.

The *efficiency* of a measure refers to the ratio between the desired impacts of the measure and the required input (i.e. impact per cost unit). Efficiency, therefore, involves both engineering and financial criteria.

In this paper the effectiveness of measures will be assessed through the '*net intercepted seepage*'. Figures 3 and 4 show details on this concept (Bhutta and Wolters, 2000). The *relative effectiveness* is the net intercepted seepage as a percentage of the initial seepage.

It is noted that the drain discharge is not a suitable indicator, as a huge drain discharge does not necessarily imply that the seepage from the canal to the land decreases significantly. The introduction of interceptor drains will, generally, cause induced seepage from the canal (see also Bhutta and Wolters, 2000; Jansen, 2003). This induced seepage should be subtracted from the drain discharge to obtain the net intercepted seepage (Figure 4).

The efficiency of the measure can be expressed as the ratio between the net intercepted seepage and the total canal seepage. This indicator thus account for the most important (unwanted) side effect of the measure (induced seepage).

Hence, an efficiency (and effectiveness) of 0% would mean that all intercepted water is induced seepage and that the net seepage rates do not decrease. An efficiency of 100% would mean that all initial seepage is intercepted. To illustrate the concepts effectiveness and efficiency, some hypothetical examples are given in Table 1.

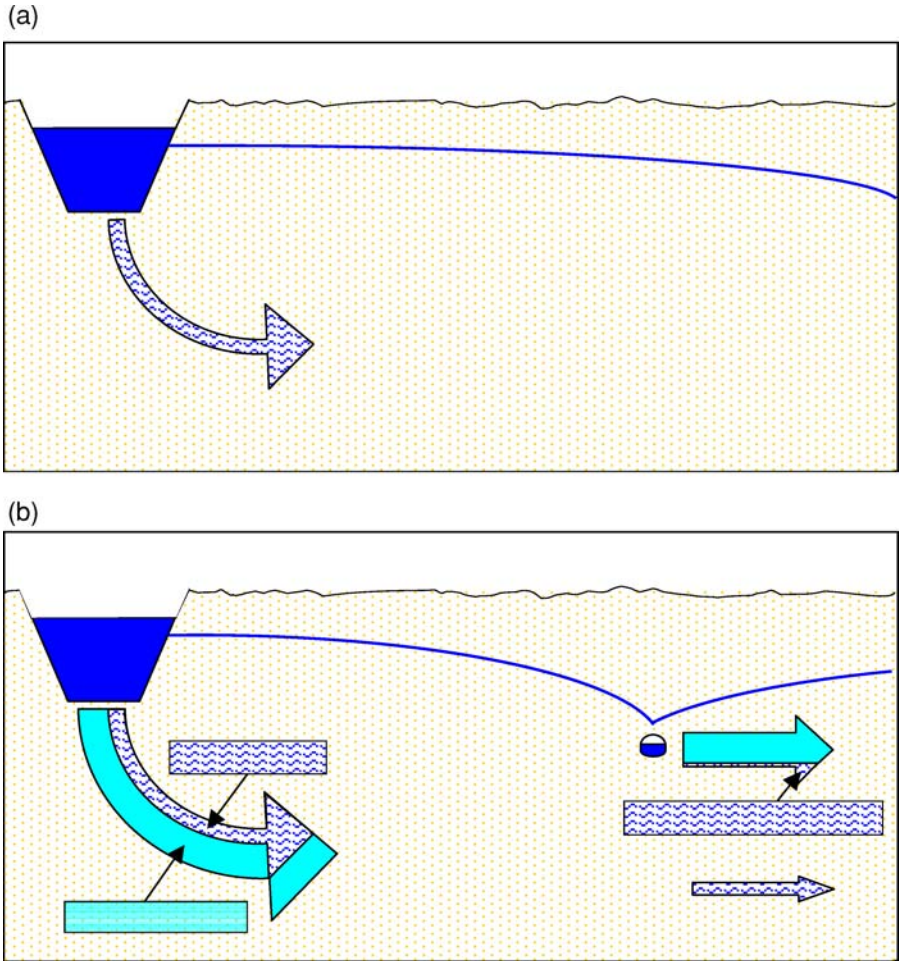

Figure 3. Concepts of induced and net intercepted seepage. (a) Situation before drain installation; (b) Situation after drain installation.

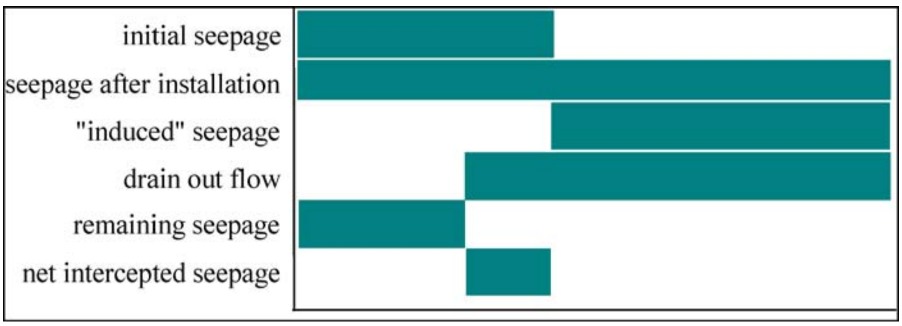

Figure 4. Determination of induced and net intercepted seepage.

Table 1. Calculation examples effectiveness and efficiency.

Initial canal seepage (m^2/day) A	Canal seepage after drain installation (m^2/day) B	Drain discharge (m^2/day) C	Effectiveness (%) 100 × {C − (B − A)/A}	Efficiency (%) 100 × {C − (B − A)/B}
0.1	0.1	0.1	100	100
0.1	0.2	0.2	100	50
0.1	1.0	1.0	100	10
0.1	0.5	0.45	50	10
0.1	0.2	0.1	0	0

3. Application of numerical model in Fordwah Eastern Sadiqia (Pakistan)

3.1. Set-up and parameters

3.1.1. *Geometry and schematisation*
A regional numerical model was constructed, which included the entire area with the interceptor drain and the observation wells, shown in Figure 1. Figure 5 presents the (lateral) boundaries.

The numerical model is a one-layer, phreatic model, covering an area of 18 km^2 (4.5 × 4.0 km) with 90,000 grid elements. The size of the grid elements varies from 5 × 20 m along the canal and drain (where steep hydraulic gradients can be expected, perpendicular to the canal) to 20 × 20 m near the eastern and western edges of the model (Figure 5).

The impermeable base is assumed at approximately 12 m below the ground surface, which is the bottom boundary of the model. As phreatic conditions were simulated, the upper boundary of the model consists of the (calculated) phreatic water table. The northern and southern boundaries are closed (no-flow); the groundwater flow is mostly parallel to these boundaries. The eastern and western boundaries are constant head boundaries.

3.1.2. *Hydraulic conductivity aquifer*
In the model, a constant value of 1.0 m/day was used for the hydraulic conductivity of the aquifer. No spatial trend was observed (see also IWASRI, 1998).

3.1.3. *Canal hydraulic conductance (C_{CANAL})*
On the basis of the data from the monitoring programme, it could be concluded that the canal infiltration resistance, c_{CANAL}, is very low: probably less than 1 day. The model calculations were made with $c_{\mathrm{CANAL}} = 0.1$ days, which

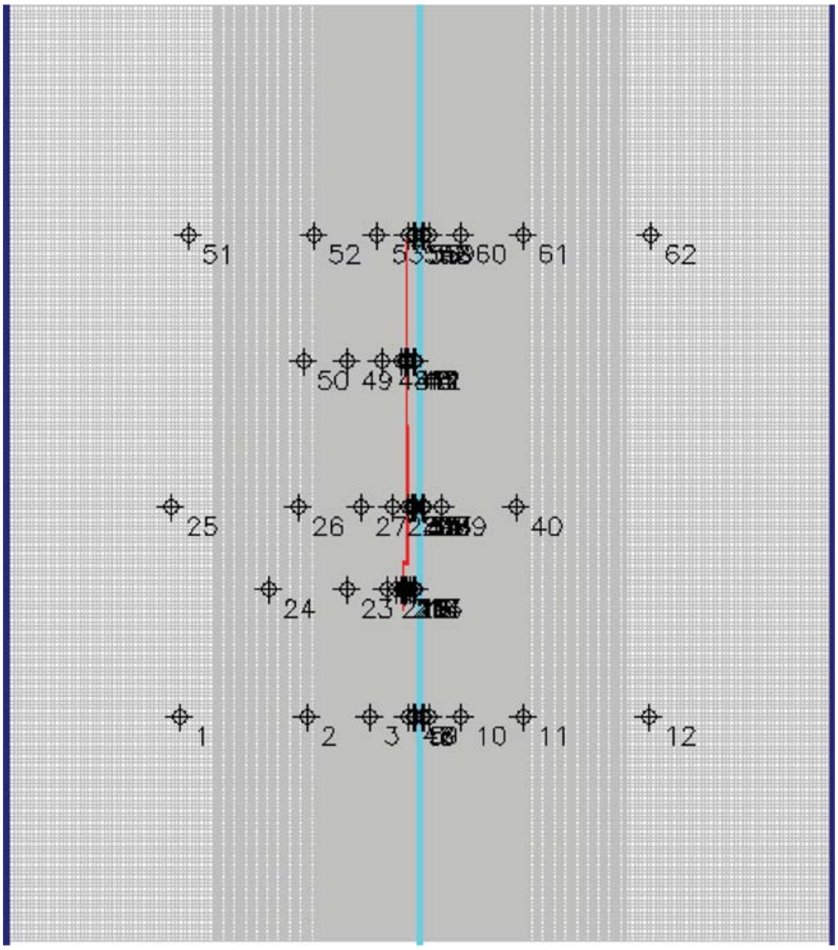

Figure 5. Model lay-out (180° rotated).

means that the canal hydraulic conductance, C_{CANAL}, would be 1000 m^2/day (see also Jansen, 2003). Rather than trying to determine the exact value, a sensitivity analysis was executed, which showed that the calculation results are not sensitive for the canal infiltration resistance, if this parameter is less than approximately 10 days (see also Section 3.2.1).

Both the canal leakage rate and the interceptor drain discharge are not very much influenced by (uncertainties in) the canal infiltration resistance (below 10 days), hence further quantification of this parameter was not necessary.

3.1.4. *Drain hydraulic conductance* (C_{DRAIN})

The hydraulic losses due to partial penetration of the drains were incorporated in the drain entry resistance. This means that the drain entry resistance is at least (see Jansen, 2003):

$$c_{\text{DRAIN}} \geq 2 \times (h - H_{\text{DRAIN}}) \times P_{\text{DRAIN}} \times L/\{K\times, (H_{\text{CANAL}} - H_{\text{DRAIN}})^2 + 2 \times K \times d\times(H_{\text{CANAL}} - H_{\text{DRAIN}})\}$$

The drain hydraulic conductance is then (Jansen, 2003):

$$C_{\text{DRAIN}} \leq L_{\text{DRAIN}} \times P_{\text{DRAIN}}/c_{\text{DRAIN}}$$

where

c_{DRAIN}: Drain entry resistance [T];
h: Piezometric level in the aquifer [L];
H_{DRAIN}: Drain level (elevation of the drain) [L];
H_{CANAL}: Hydraulic head (water level) in the canal [L];
P_{DRAIN}: Wetted perimeter of drain [L];
L: Distance between the canal and drain [L];
K: Hydraulic conductivity of the aquifer [LT^{-1}];
d: Equivalent depth of groundwater flow [L];
C_{DRAIN}: Drain hydraulic conductance [L^2T^{-1}];
L_{DRAIN}: Length of the drain segment (in model node) [L].

The drain entry resistance and drain hydraulic conductance (considering partial penetration) can be estimated from the layout of the canal and drain system, the monitoring data, and the model geometry, which are summarised in Table 2.

Substitution of these values in the equations gives:

$$c_{\text{DRAIN}} \geq 7 \times P_{\text{DRAIN}} \text{ days.}$$
$$C_{\text{DRAIN}} \leq 2.9\,\text{m}^2/\text{day.}$$

These values are first estimates. As other hydraulic losses than partial penetration losses occur in and near the interceptor drain, the actual value of C_{DRAIN} will be less than 2.9 m^2/day.

Table 2. Parameters for estimation of drain entry resistance.

Parameter:	Value:
$h - H_{\text{DRAIN}}$	≈2 m (on average)
L	≈45 m
K	≈1 m/day
$H_{\text{CANAL}} - H_{\text{DRAIN}}$	≈2.7 m
d	≈3.4 m (calculated)
L_{DRAIN}	20 m (model grid length)

3.2. *Calibration and sensitivity analysis*

The objective of the model calibration was to quantify the parameters that were not well known, yet having significant impact on the modelling results. During the calibration procedure, also the sensitivity of parameters was investigated.

3.2.1. *Calibration method and parameters*

Given the low sensitivity of the canal hydraulic conductance, not much attention was paid to this parameter (see also Section 3.1.3). The hydraulic conductivity of the aquifer was much better known than the drain hydraulic conductance and the groundwater recharge. Moreover, the role of the hydraulic conductivity of the aquifer was further investigated during the scenario calculations.

The calibration, therefore, focussed on:

- Drain entry resistance (inclding the effect of partial penetration);
- Net groundwater recharge from irrigated areas.

Given the constant water level in the canal (the closure period excepted) and the direct relation between the canal water level and the groundwater level, the groundwater system can be considered in steady-state (see also Jansen, 2003). The model was, therefore, calibrated for a steady-state situation, based on the following historical data:

- Drain discharge measurements (the average discharge being 4.445 l/s = 384 m^3/day; see Section 2.2);
- Groundwater levels of 38 observation wells. Only the data recorded after the installation of the interceptor drain were used (i.e. weekly groundwater measurements from April 1996 to November 1997).

3.2.2. *Calibration results*

The main results are:

- The drain hydraulic conductance is approximately 1.5 m^2/day;
- The net groundwater recharge from irrigated fields is very low (in the order of only 0.02 mm/day, hence almost nil);
- Calculation results are very much influenced by the *hydraulic conductivity* of the aquifer, *the drain hydraulic conductance* and the *groundwater recharge* from irrigated areas;

- In the expected range of magnitude, the canal *hydraulic conductance* is not a sensitive parameter (See also Section 3.1.3).

The very low value of the (average) net groundwater recharge was also reported by (Saleem Bashir et al., 1995), who found that the recharge to groundwater did more or less equal the capillary rise.

The drain discharge simulated by the calibrated model was 387 m^3/day.

3.3. *Simulation of measures and scenarios*

Once a groundwater model is properly calibrated, a further analysis of the hydrological system can be made, while also all kind of management scenarios can be evaluated. In this section, a few examples are given.

3.3.1. *Assessment of the existing situation ("Reference situation")*

To allow for an easy evaluation of measures, the *reference situation* was defined, being the calibrated situation without any groundwater recharge from the adjacent fields.

Net intercepted seepage

In the reference situation, the simulated infiltration from the irrigation canal amounted to 413 m^3/day (the section along the interceptor drain). Without interceptor drain, the (calculated) leakage from the canal would be 60 m^3/day. This means that the net intercepted seepage is 34 m^3/day (namely: 60 − [413 − 387]), which is 57% of the initial seepage. This means that the *effectiveness* of the drain is 57%.

However, the efficiency of the system is only 8%. This implies that for each cubic meter seepage reduction, also more than 10 cubic meter of induced seepage need to be discharged (pumped). This is also shown in Figure 6.

Use of interceptor drain for field drainage

The idea to use the interceptor drains to both intercept the canal leakage and to drain the adjacent irrigated land can easily be assessed by investigating the impact of increased groundwater recharge from irrigated fields (irrigation water excess). Table 3 presents the simulated relation between the irrigation water excess from the cultivated lands, the discharge by the interceptor drain and the canal leakage.

The drain discharge does not increase proportionally with the groundwater recharge. In addition, the reduced canal leakage indicates that the drain cannot discharge all water originating from the irrigated lands. Water tables between the canal and drain are also influenced. This indicates that the capacity of the aquifer is too small to discharge all excess irrigation water to the drain.

Table 3. Relation between the irrigation water excess, drain discharge and canal leakage.

Irrigation water excess (recharge)[a] (mm/day)	Canal infiltration (m^2/day)[b]	Drain discharge (m^2/day)[b]
0 (≈ present situation)	0.29	0.22
0.1	0.16	0.24
0.2	0.10	0.27
0.3	0.03	0.30

[a]Only applied on (cultivated) east bank of the canal, east of the interceptor drain.
[b]Volumes per stretching meter of drain/canal (specific volumes).

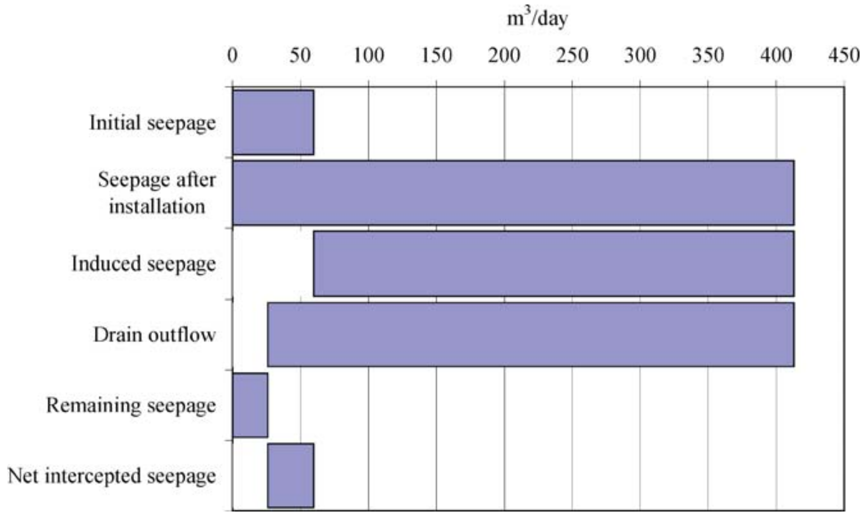

Figure 6. Simulated induced and net intercepted seepage; reference situation. The volumes refer to the canal section adjacent to the interceptor drain (1828 m).

The model indeed simulates elevated water tables, if the recharge increases to 0.1 mm/day or more.

Interceptor drains, therefore, do not significantly reduce the drainage requirements, or in other words, cannot prevent the need for the installation of a drainage system.

3.3.2. *Lining of irrigation canal*

For the investigated Fordwah Eastern Sadiqia (South) Project, the model calculations showed that the lining of the irrigation canal obviously reduces the leakage, but does not eliminate the need of a field drainage system.

It was investigated whether a single drain along the edge of the cultivated land would suffice. Table 4 shows that the discharge by such a drain

Table 4. Simulated drain discharge with canal lining and significant irrigation water excess.

Lining:	Irrigation water excess (recharge) (mm/day)	Canal infiltration (m^2/day)	Drain discharge (m^2/day)
No canal lining	0 (≈ present situation)	0.29	0.22
Canal lining	0.1	0	0.14
	0.2	0	0.27
	0.3	0	0.41

corresponds to the drainage requirements of a strip of cultivated land of approximately 1400 m (along the drain). However, the model calculations also show that elevated water tables can be expected in the cultivated lands, away from the drain, if the recharge increases to 0.1 mm/day or more. It can, therefore be concluded, that neither canal lining alone, nor canal lining with a single drain along the fields will significantly reduce the drainage requirement of the agricultural lands.

3.3.3. *Effect of aquifer hydraulic properties*

The simulation of the impact of the hydraulic conductivity of the aquifer requires some attention, as the hydraulic resistance due to partial penetration is dependent of this parameter. The correct approach would be to divide the value of the drain hydraulic resistance into a portion that accounts for the partial penetration losses and a portion that accounts for all other drain hydraulic losses. The latter are (in principle) not depending on the aquifer properties, but merely on the drain properties, whereas the hydraulic resistance due to partial penetration is inversely proportional to the hydraulic conductivity of the aquifer (Jansen, 2003).

For the assessment of the impact of the aquifer properties it was assumed that the drain entry resistance was entirely due to the partial penetration losses (hence the drain design and installation were assumed optimum).

Table 5 presents the simulated relation between the hydraulic properties of the aquifer, the effectiveness and the efficiency of the interceptor drainage system.

It can be concluded that for the applied drain design (in terms of depth, diameter and distance from the canal), the effectiveness is in the order of 60%, almost irrespective of the aquifer properties. This means that the net intercepted seepage is approximately 60% of the original seepage.

The efficiency of the interceptor drain is, however, low for all situations. Less than 10% of the discharged water is net intercepted seepage water, the rest is induced seepage.

Table 5. Relation between aquifer hydraulic conductivity, effectiveness and efficiency of interceptor drains.

K (m/day)	Canal infiltration (m^2/day)	Induced seepage canal (m^2/day)	Net intercepted seepage (m^2/day)	Drain discharge (m^2/day)	Effectiveness (%)	Efficiency (%)
0.04	0.009	0.001	0.001	0.009	60	8.2
0.1	0.023	0.002	0.002	0.021	55	7.8
0.2	0.046	0.004	0.004	0.043	55	7.9
0.5	0.115	0.009	0.009	0.108	56	8.1
1	0.229	0.019	0.019	0.215	57	8.2
2	0.458	0.036	0.036	0.428	55	7.9
5	1.143	0.091	0.091	1.069	55	8.0
10	2.276	0.184	0.184	2.129	56	8.1
25	5.636	0.467	0.467	5.277	57	8.3

4. Discussion and conclusions

A numerical model can aid to evaluate the effectiveness and efficiency of measures and strategies to alleviate water losses and drainage problems. A numerical model can also be used to better quantify the components of the water balance, as the use of rules-of-thumb can be very misleading.

The effectiveness of a system of interceptor drains can be improved by an optimum design, in terms of distance to the irrigation canal, drain depth and diameter. The depth and distance to the canal are the most critical design parameters (see also Jansen, 2003).

The costs to achieve increased effectiveness are, however, often elevated. For the Fordwah Eastern Sadiqia (South) Project, more than 10 cubic meter of induced seepage need to be pumped for each cubic meter of net intercepted seepage. An optimum design may improve the efficiency, however interceptor drains in thick phreatic aquifers (with direct hydraulic contact between the irrigation canals and the aquifers) will always cause large volumes of induced seepage from the irrigation canals, up to an order of magnitude more than the net intercepted seepage. Under such conditions, it will be very difficult to achieve more acceptable efficiencies.

In flat areas pumping is often required, which is an added headache for the institution responsible for operation of the system. In the flat areas of the Gangetic Plain (Pakistan and Northern India) a system with pumps and sumps (that needs to be operated 24 h per day) is unavoidable.

It can finally, be concluded that interceptor drains and canal lining do not significantly reduce the drainage requirements, or in other words, cannot prevent the need for the installation of a drainage system.

Note

1. In a pseudo-3-dimensional model, the groundwater flow is strictly horizontal in aquifers, while the exchange of groundwater between aquifers at various depths occurs by (strictly) vertical flow through semi-confined layers.

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