GROUNDWATER MODELLING TO ASSESS THE EFFECT OF INTERCEPTOR DRAINAGE AND LINING

HYDROLOGICAL AND MODELLING CONCEPTS[1]

H.C. Jansen[2]

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 can 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 the hydrological concepts with respect to leakage from irrigation canals and interception by interceptor drains are presented. A good understanding of these concepts is critical for the proper application of numerical groundwater models and for the correct quantification of model parameters. Key hydraulic parameters are the *infiltration resistance* of the bed and slopes of irrigation canals, the *drain entry resistance* of interceptor drains, *hydraulic conductivity* and *hydraulic resistance* of soil layers and *equivalent depth of groundwater flow.*

The paper shows how the hydrological concepts can be transferred into model parameters for the widely used groundwater modelling package MODFLOW. Most concepts, however, can also be applied in other modelling packages.

The presented hydrological and modelling concepts have been applied in a numerical model for the Fordwah Eastern Sadiqia project, Pakistan. This model application is reported in a separate paper.

1 INTRODUCTION

1.1 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. A possible *mitigation measure* is the installation of interceptor drains. Interceptor drains have been installed in various projects. 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 many discussions. In the design of these drainage systems, rules-of-thumb are often used to quantify the seepage from canals. In previous studies it was recommended that a groundwater model be used for a more detailed assessment (Saleem Bashir et al., 1995). Groundwater models can assist in evaluating the effect of recharge reducing measures such as interceptor drains along irrigation canals and lining.

1.2 Groundwater model

In this paper the hydrological and modelling concepts with respect to leakage from irrigation canals and interception by interceptor drains are presented. A good understanding of these concepts is critical for the proper application of numerical groundwater flow models and for the correct quantification of model parameters.

Reference is made to the use of MODFLOW, however, the presented hydrological and modelling concepts are also applicable for other modelling packages.

The *application* of a numerical model to assess preventive and mitigating measures with respect to canal lining and interceptor drainage in a selected (pilot) area in Pakistan is presented in a separate paper (Jansen et al, 2003).

In this paper, interceptor drainage in *flat areas* with *phreatic aquifers* is addressed, which are common in the Indo Gangetic Plain (Pakistan and Northern India). Section 2 deals with some theoretical concepts on the hydrology of interceptor drains and canal lining. The application of these concepts in a numerical model (i.e. the *parameterisation* = conversion of concepts to model parameters) is presented in Section 3.

An example of the application of the theoretical concepts and field data to obtain model parameters is presented in Section 4. Conclusions follow in Section 5.

2 HYDROLOGICAL CONCEPTS OF CANAL LEAKAGE AND INTERCEPTOR DRAINS

2.1 Hydraulic Resistance

Water leaking from an irrigation canal into the aquifer, from where it subsequently flows to an interceptor drain, which eventually discharges the water, encounters *hydraulic resistance* on its way. The hydraulic resistance results in a loss of hydraulic head between the water level in the canal and the water level inside the drain.

The total hydraulic resistance between the canal and the drain can be subdivided in:

- canal infiltration resistance (aquifer entry resistance) (resulting in head loss D_1);
- aquifer resistance (resulting in D_2);
- drain entry resistance (resulting in D_3).

These three components together determine the canal leakage and the flow of groundwater to the interceptor drain. This is schematically shown in Figure 1. Note that this scheme assumes direct hydraulic contact between the canal and the saturated aquifer. The case of an (easier to assess) unsaturated zone below the canal bed is discussed below.

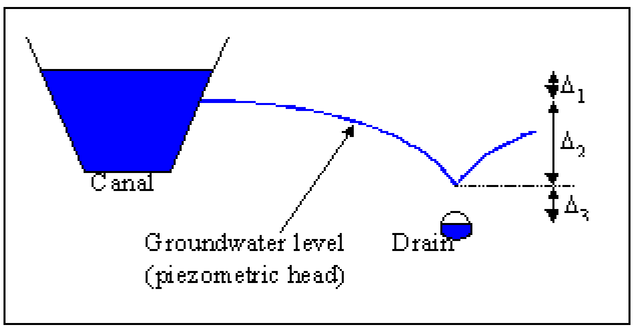


Figure 1 Hydraulic resistance groundwater flow.

Not only the hydraulic resistances and head losses determine the groundwater flow, but also the "wetted surfaces". This can be represented by the following equations (assuming 2-dimensional groundwater flow, i.e. the flow direction is perpendicular to the canal and drain):

$$q = P_{CANAL} * D_1 / c_{CANAL} \quad (1)$$

$$q = D_{AQ} * D_2 / c_{AQ} \quad (2)$$

$$q = P_{DRAIN} * D_3 / c_{DRAIN} \quad (3)$$

where: q = Groundwater flow [L^2T^{-1}];
P_{CANAL} = Wetted perimeter of the canal (portion that causes flow to the drain) [L];
P_{DRAIN} = Wetted perimeter of the drain [L];
D_{AQ} = Average thickness of the aquifer, which contributes to groundwater flow to the drain [L] (further details will be given below);
D_1 = Loss of hydraulic head in the canal bed [L];
D_2 = Loss of hydraulic head in the aquifer [L];
D_3 = Loss of hydraulic head in (and near) the drain [L];
c_{CANAL} = Canal infiltration resistance [T];
c_{AQ} = Hydraulic resistance aquifer [T];
c_{DRAIN} = Drain entry resistance [T].

The canal infiltration resistance is caused by a thin layer of fines accumulated on the canal bed and by any soil compaction, for example due to reed growth. The aquifer resistance is dependent on the hydraulic conductivity (permeability) of the aquifer material and the distance between the canal and the drain. The drain entry resistance is caused by various factors, which will be addressed in the following section.

2.2 Drain entry Resistance

Groundwater approaching a drain will encounter hydraulic resistance before entering the pipe (or open drain). The drain entry resistance, c_{DRAIN}, can be considered as the cumulative effect of various hydraulic losses, being the result of:

- Flowline contraction (as pipe drains have limited open area to ensure sufficient structural strength. Flowline contraction can be aggravated by clogging);
- Drain envelope resistance;
- Soil compaction occurred during installation;
- Turbulent flow in and near the drain openings;
- Friction in drain openings;
- Limited discharge capacity.

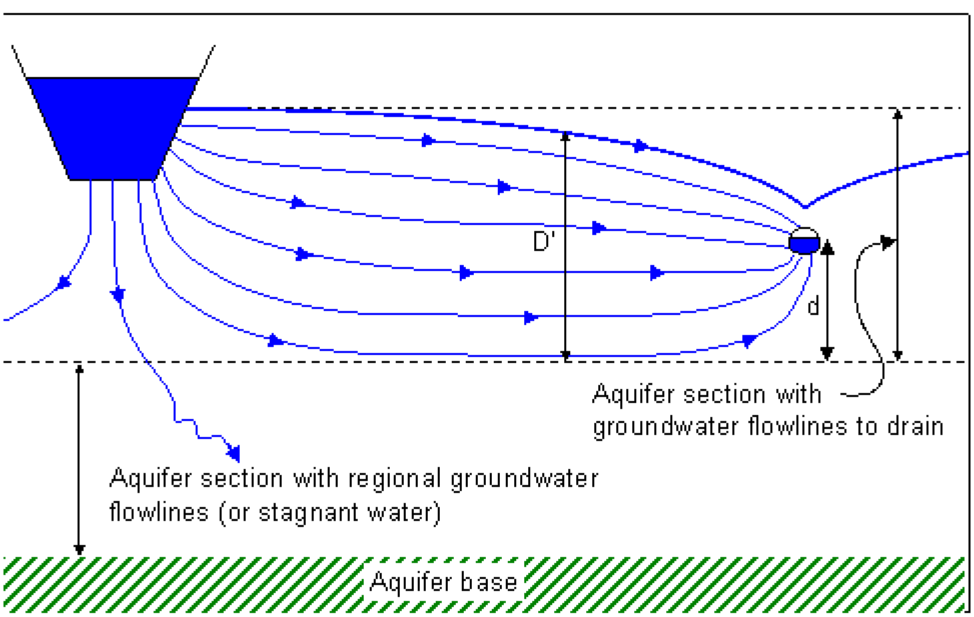
In addition, the drain entry resistance may account for reduced groundwater flow to the drain due to *partial penetration*, i.e. if the drains are installed well above the base of the aquifer. The partial penetration of drains results that the groundwater flow to the drains is confined to a limited portion of the aquifer (further details are given below). It may be argued whether the partial penetration of drains should be accounted for by the drain entry resistance or by the aquifer resistance, as the partial penetration losses are both determined by the drain design and the aquifer properties (see below). For modelling purposes it is, however, more practical to consider the partial penetration losses as drain hydraulic losses.

If the drains have been properly designed and installed, the drain hydraulic losses should be small, except for the partial penetration losses, which are to a large extent determined by the physical environment. Especially in the case of a thick aquifer, the effect of partial penetration can be considerable.

2.3 Partial Penetrating Drains (Thick Aquifers)

In the case that an interceptor drain is installed in a thick aquifer, it should be realised that the (average) thickness of the aquifer contributing to groundwater flow to the drain (D_{AQ} in Equation (2)) can significantly differ from the aquifer thickness (see Figure 2). In such a situation, the Dupuit-Forchheimer Equation for groundwater flow in phreatic aquifers (often applied in numerical models!) is not valid.

Figure 2 Groundwater flow to interceptor drain in thick aquifer.



The groundwater flow should be calculated considering only the aquifer thickness that contributes to the groundwater flow to the drain (in Figure 2 indicated by *D'*, being the difference between the lower dotted line – = bottom limit of flow- and the phreatic groundwater level – = upper limit of flow-).

In the case of negligible canal infiltration and drain entry resistances, the following equation may be used:

$$q = \{K * (H_{CANAL} - H_{DRAIN})^2 + 2 * K * d * (H_{CANAL} - H_{DRAIN})\} / 2 * L \qquad (4)$$

where q = Specific groundwater flow $[L^2T^{-1}]$
K = Hydraulic conductivity of the aquifer $[LT^{-1}]$
H_{CANAL} = Hydraulic head (water level) in the canal [L]
H_{DRAIN} = Drain level (elevation of the drain) [L]
d = Equivalent depth of groundwater flow [L]
L = Distance between the canal and drain [L]

This equation adds the phreatic groundwater flow *above* the drain (according to the Dupuit-Forchheimer Equation) to confined groundwater flow *below* the drain down to the equivalent depth of groundwater flow (Darcy Equation). This equation is similar to the Hooghoudt Equation for parallel, partial penetrating drains (drains well above the base of the aquifer) with an infinite extension.

The equivalent depth according to Hooghoudt can be calculated as (Ritzema et al, 1994):

$$d = \frac{\pi L}{8\ln\left(\frac{L}{\pi r_0}\right) + 16\sum_{n=1}^{\infty}\ln\left[\coth\left(\frac{2\pi n D}{L}\right)\right]} \approx \frac{\pi L}{8\ln\left(\frac{L}{\pi r_0}\right) + 8\sum_{n=1,3,5,\ldots}^{\infty}\frac{4e^{-\frac{4\pi n D}{L}}}{n\left(1-e^{-\frac{4\pi n D}{L}}\right)}} \qquad (5)$$

where r_0 = Drain radius [L]
D = Thickness of aquifer below drain level [L]

This Hooghoudt Equation is valid for groundwater flow to drains with recharge from the top (precipitation or irrigation) or bottom (deep upward seepage) over a distance L. Given the analogous phreatic surface and groundwater flow pattern, it is assumed that the same equivalent depth can be used for groundwater flow with lateral recharge from leaking canals. The distance L may not be the exact physical distance between the canal and drain, but should rather be referred to as "hydraulic distance". The canal infiltration resistance c_{CANAL} can be accounted for by simply increasing the hydraulic distance L between the canal and drain.

2.4 Unsaturated flow

If there is no direct hydraulic contact between the canal and aquifer, i.e. in the case of an unsaturated zone below the canal bed, Equation (1) can still be applied, but the meaning of the symbol D_1 changes slightly (see Figure 3):

$$q = P_{CANAL} * D_1 / c_{CANAL} \qquad (1a)$$

where D_1 = Water level in the canal above the canal bed [L].

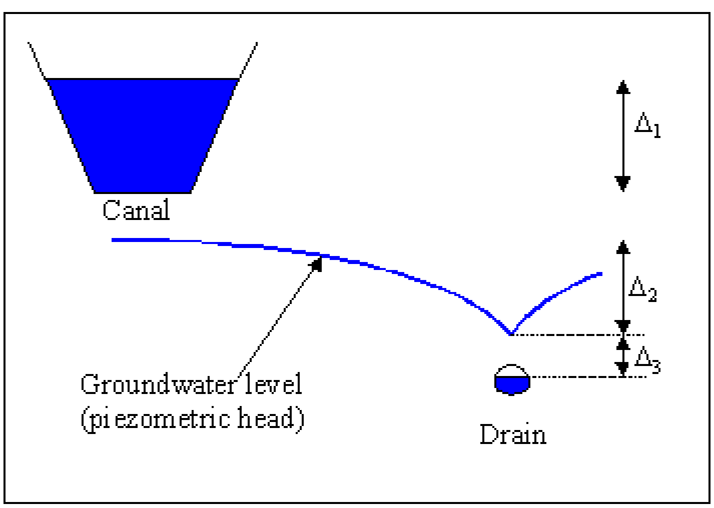


Figure 3   Hydraulic resistance groundwater flow with unsaturated zone

It is also noted that the canal infiltration resistance c_{CANAL} is calculated in a different way:

Saturated zone below canal bed: $c_{CANAL} = D_{CANAL} / K_{CANAL}$ (6)

Unsaturated zone below canal bed: $c_{CANAL} = D_1 / K_{CANAL}$ (7)

where: D_{CANAL} = Thickness of confining layer on the canal bed [L];

K_{CANAL} = Hydraulic conductivity of confining layer on the canal bed [LT^{-1}].

In the case of an unsaturated zone under the canal bed, the infiltration from the canal is a process that is *hydraulically isolated* from the groundwater flow towards the drain. This implies that the impact of canal lining is independent of the aquifer characteristics. For the same reason, the installation of an interceptor drain will not cause an increase of canal leakage.

The existence of an unsaturated zone under the canal bed does not impose restrictions to the application of most numerical groundwater models, including MODFLOW. Obviously, a modelling package that cannot simulate an unsaturated zone under the canal should be avoided.

2.5 Impact of Canal Lining and Interceptor Drains

It is obvious that the maximum flow to the interceptor drain occurs if the canal infiltration resistance and the drain entry resistance are both minimal. The groundwater gradient is then maximal and the volume of groundwater flow is principally determined by the hydraulic conductivity and thickness of the aquifer, the distance between the canal and drain and the water levels in the canal and drain (according to Equation (4)).

The lining of the canal will result in a large canal infiltration resistance (c_{CANAL}) and, therefore, a decrease of groundwater flow through canal leakage. However, whether or not the lining of the canal will indeed have the desired impact, depends on the *relative contributions* of the distinctive hydraulic resistances c_{CANAL} and c_{AQ} (together with the "wetted surfaces" P_{CANAL} and D_{AQ}) to the total hydraulic resistance between the canal and the drain. For example, in the case that the aquifer is composed of material with a relatively low hydraulic conductivity, c_{AQ} is large and canal lining may not have much effect, as in such a situation the aquifer will be the limiting factor for groundwater flow, not the canal bed.

Another implication is that the installation of an interceptor drain will *always induce additional canal leakage*, as the hydraulic gradients between the canal and drain increase. Whether this induced canal leakage is significant or not, also depends on the relative contributions of the distinctive hydraulic resistances to the total hydraulic resistance. Especially in the case of a permeable aquifer, the induced leakage may be large. In such a situation the canal infiltration resistance is, often, also low.

Finally, it can be seen that a poor-functioning drain (large c_{DRAIN}) may result that infiltrated groundwater moves across the drain (if the groundwater gradient expands further land inward), causing waterlogging inland.

It can be concluded that *all three components of the hydraulic resistance between the canal and the drain have to be assessed* before the most feasible solution for waterlogging problems can be identified. A numerical model can aid in this assessment. The numerical model should be able to incorporate the canal infiltration resistance, the drain entry resistance and the aquifer. In Section 3 further details are presented on the well-known MODFLOW modelling package.

3 THE USE OF A NUMERICAL MODEL

For the assessment of canal leakage and interceptor drainage, the MODFLOW-based (finite difference) groundwater modelling package PMWIN can be used. Advantages of this package are the relatively easy applicability and its common use (MODFLOW is used world-wide). The MODFLOW calculation routine is public domain. PMWIN (and other MODFLOW based packages) can simulate canals and drains, although some *conversion* is needed to transfer the hydrological concepts (presented in Section 2) into the model parameters. This parameterisation process is shown in the following.

3.1 Simulation of canal infiltration resistance

Most groundwater modelling packages are provided with tools to simulate the interaction between the aquifer and surface water. This interaction can be simulated through individual watercourses or by "lumped (infiltration or drainage) systems", which principally simulate q-h relations for a certain area (relations between the piezometric level and the aquifer discharge to the surface water system). The lumped approach is not suitable for interceptor drains and will, therefore, not be discussed.

The infiltration and drainage by individual surface watercourses can be simulated by applying the principles laid down in Equations (1) and / or (3). However, various methods exist to convert these equations into the model parameters. A correct and easy-to-use method would be to prescribe the wetted perimeters and the infiltration and drainage resistances in the model. In MODFLOW, however, these parameters have been lumped to the "*hydraulic conductance of the canal bed*" and the "*drain hydraulic conductance*". These parameters have no clear, explicit physical meaning and cannot be measured or determined in the field. To obtain the proper model parameter values, a conversion from (quantifiable) hydraulic parameters is, therefore, required.

In MODFLOW, the canal leakage is simulated as:

$Q_{CANAL} = C_{CANAL} * (H_{CANAL} - h)$ $\qquad$ $h > H_{BOT}$
$Q_{CANAL} = C_{CANAL} * (H_{CANAL} - H_{BOT})$ $\qquad$ h £ H_{BOT}

where: Q_{CANAL} = Canal leakage (can also be negative) $[L^3T^{-1}]$
C_{CANAL} = Hydraulic conductance of canal bed $[L^2T^{-1}]$
H_{CANAL} = Hydraulic head (water level) in the canal [L]
h = Piezometric level in the aquifer [L]
H_{BOT} = Elevation of canal bed [L]

With the aid of Equation (1), the hydraulic conductance of the canal bed can be determined as follows:

$$C_{CANAL} = L_{CANAL} * P_{CANAL} / c_{CANAL} = L_{CANAL} * P_{CANAL} * K_{CANAL} / D_{CANAL} \qquad (8)$$

where L_{CANAL} = Length of the canal segment [L]
P_{CANAL} = Wetted perimeter of canal [L]
c_{CANAL} = Canal infiltration resistance [T]
K_{CANAL} = Hydraulic conductivity (permeability) of the river bed $[LT^{-1}]$
D_{CANAL} = Thickness of the river bed [L]

Generally, the hydraulic conductance of the canal bed has to be further quantified through *model calibration*, as not all the involved parameters may be known in detail.

3.2 Simulation of drain entry resistance

If 2-dimensional groundwater models (or pseudo-3-dimensional[3] models such as MODFLOW) are used, one must take care that groundwater flow to drains can only occur in the aquifer section above the equivalent depth (see Figure 2). This may be achieved by reducing the depth of the aquifer (with the drain), or by introducing an additional drain entry resistance to account for the impacts of partial penetration, the latter option being more practical (see Section 2).

The conversion of (quantifiable) drain parameters to the drain hydraulic conductance is similar to the conversion of the above-described canal parameters. Analogously to canal leakage, the discharge by the interceptor drain is simulated by MODFLOW as:

$Q_{DRAIN} = C_{DRAIN} * (h - H_{DRAIN})$ $\qquad$ $h > H_{DRAIN}$
$Q_{DRAIN} = 0$ $\qquad$ h £ H_{DRAIN}

where: Q_{DRAIN} = Drain discharge (can only be positive) $[L^3T^{-1}]$
C_{DRAIN} = Drain hydraulic conductance $[L^2T^{-1}]$
h = Piezometric level in the aquifer [L]
H_{DRAIN} = Drain level (elevation of drain) [L]

With the aid of Equation (3), the drain hydraulic conductance can be calculated as follows:

$$C_{DRAIN} = L_{DRAIN} * P_{DRAIN} / c_{DRAIN} \qquad (9)$$

where: L_{DRAIN} = Length of the drain segment [L]
P_{DRAIN} = Wetted perimeter of drain [L]

c_{DRAIN} = Drain entry resistance [T]

These equations imply that the differences between a canal and drain are:
A canal can both infiltrate and drain (depending on the groundwater level in relation to the water level in the canal), whereas a drain can only discharge water;
If the groundwater level drops to below the level of the canal bed, the canal will continue to infiltrate (at its maximum rate). If the groundwater level drops to below the drain level (level of the drain bed), the drain will stop to discharge water.

Generally, the drain hydraulic conductance has to be further quantified through *model calibration*, as not all involved parameters may be known in detail.

4 EXAMPLE OF CANAL AND DRAIN PARAMETER ASSESSMENT

4.1 General Outline

As stated in Section 3, the hydraulic conductance of the canal bed and the drain hydraulic conductance, generally, need to be quantified through model calibration. A first assessment of these parameters can be obtained from field data. Thereafter, the parameters can be further quantified through numerical modelling (“fitting”). Numerical models are based on *closed water balances*, hence the hydraulic conductance of the canal bed and the drain hydraulic conductance need to be calibrated (“fitted”) simultaneously.

An example of how to assess the canal infiltration resistance and the drain entry resistance from field data is shown in the following paragraphs. Paragraph 4.2 presents a summary of the field data that were used. The applied methods and materials are presented in Paragraph 4.3. The calculation results follow in Paragraph 4.4. The application of the numerical model is presented in a separate paper (Jansen et al, 2003).

4.2 Field Data

The data used for this example were retrieved from the monitoring system of the Fordwah Eastern Sadiqia (South) Project, Pakistan. A pilot (subsurface) interceptor drain was installed at a distance varying from approximately 45 to 60 metres from a main (unlined) irrigation canal (the Malik Branch Canal). The area is characterised by a thick phreatic aquifer, consisting of fine sands and loams (Euroconsult, 1994; IWASRI, 1998; Niazi et al.).

From 1994 to 1997 an extensive monitoring programme was executed. During 4 years the following data were monitored on a regular basis:
Water levels in the irrigation canal (upstream and downstream);
Groundwater levels in a dense network of observation wells and some piezometers (nested).

In addition, drain discharges (and water quality) were measured 13 times in the period from March 1996 to June 1997 (shortly after drain installation). Also a seepage measurement was executed by means of a ponding test during the closure period of January 1998. Finally the hydraulic conductivity was determined at 17 locations along the Malik Branch Canal. The distances between these conductivity measurements were 500 metres.

4.2.1 Interceptor drain

The interceptor drain has a total length of 1828 metres, divided in a northern section of 685 m (in the upstream direction of the irrigation canal), and a southern section of 1143 m. Both sections discharge into a sump, which is permanently pumped. The drain diameter varies from 8 inch (˜ 20 centimetres), upstream, to 10 inch (˜ 25 centimetres) at the outlet to the sump. The average installation depth is approximately 2.7 metres (below the topographic surface). De design discharge was 14 l/s (Euroconsult, 1994; IWASRI, 1998; Niazi et al).

The northern section is equipped with 2 manholes (Manhole 1 and 2) which allow for monitoring the drain (discharge and water quality) over various sections. Only Manhole 1 had been monitored. The southern section is also equipped with 2 manholes (Manhole 3 and 4), which had both been monitored. The discharges from the drain sections were measured in the period from March 1996 to June 1997. The average measured discharges are presented in Table 1.

Table 1 Average drain discharge (13 measurements). Source: IWASRI, 1998.

Drain section	Length	Discharge	Specific discharge

	(m)	(l/s)	(m^2/day)
Northern Section			
Upstream of Manhole 1	» 258	0.70	0.23
Entire section north of sump	» 685	1.62	0.20
Southern Section			
Upstream of Manhole 4	457	1.4	0.26
Between Manhole 4 and Manhole 3	376	0.4	0.09
Between Manhole 3 and the sump	310	1.14	0.32
Entire section south of sump	1143	2.94	0.22

The average specific discharge of the interceptor drains is in the order of 0.21 (m^2/day). The discharge of the interceptor drains is much lower than the design capacity.

4.2.2 Irrigation Canal

The Malik Branch Canal is one of the main irrigation canals in the Fordwah Eastern Sadiqia (South) Project. The canal has a width of approximately 35 metres and a (design) water depth of approximately 2.5 metres.

Figure 4 shows that the water level in the canal is rather constant over the year (except for the closure period).

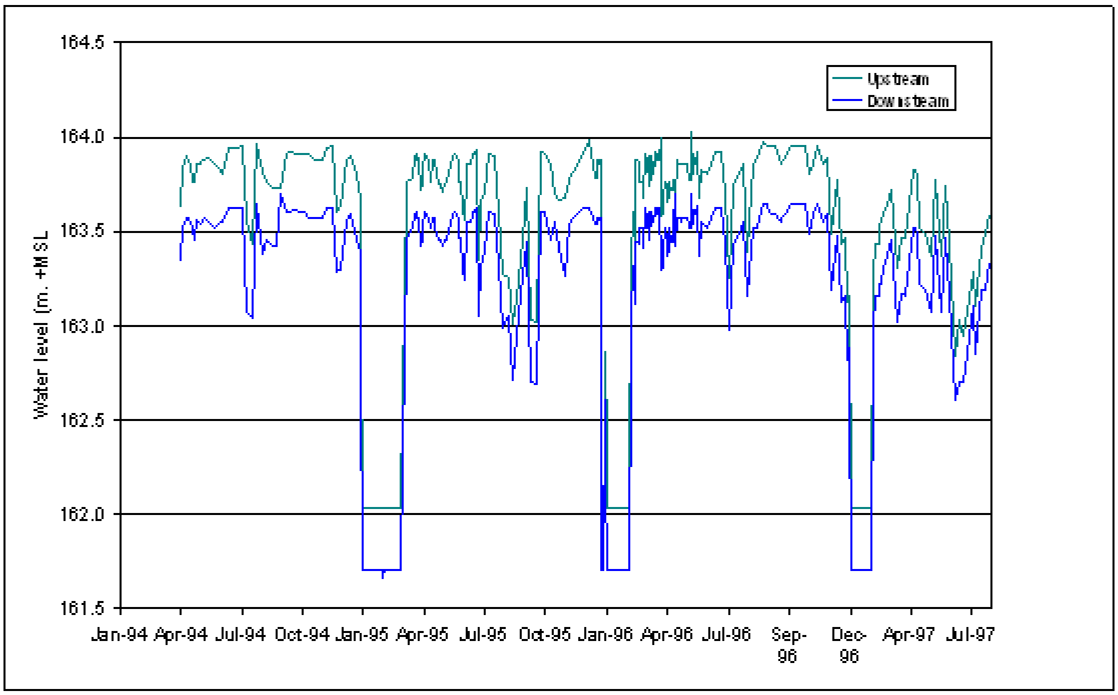


Figure 4 Water levels Malik Branch irrigation canal 1994-1997. Source: IWASRI, 1998.

The average long-term water level in the canal outside the closure period ranges from (downstream) 163.4 to (upstream) 163.7 m. +MSL (=Mean Sea Level).

In January 1998 a ponding test was executed, which showed a (net) infiltration rate in the order of 25–35 mm/day (IWASRI, 1998).

4.2.3 Groundwater

Groundwater levels were monitored to assess the effectiveness of the interceptor drains and to determine the relation between the surface water and the groundwater. The results of the groundwater monitoring programme showed:

- No significant change of the groundwater levels occurred after the installation of the interceptor drain;
- The response of the groundwater to changes in the water level in the canal (e.g. the lowering during the closure period) is very direct.

Given the constant canal water level (the closure period excepted) and the direct relation between the canal water level and the groundwater level, the groundwater system can be considered as a steady-state.

4.2.4 Hydraulic conductivity

The hydraulic conductivity of the shallow soil layers was determined by testing 17 boreholes having a depth of 3 metres (10 feet). The lithology was further investigated by drilling 13 boreholes with a depth of 12 metres (40 feet). The average hydraulic conductivity (used for the drain design) amounted to 0.75 m/day (Euroconsult, 1994). No spatial trend was observed.

5 METHODS AND MATERIALS

No other materials have been used than an EXCEL spreadsheet, in which the Equations (4) and (5) were programmed. Equation (4) was split in two components in order to calculate both the flow above the drain level and the flow below the drains. The Dupuit Formula was also programmed in the spreadsheet, to allow for the evaluation of the concept of *equivalent depth*.

The calculation results can be represented tabularly and graphically.

- The spreadsheet requires the following data:
- Distance between the irrigation canal and interceptor drain;
- Drain internal diameter (ID);
- Depth of aquifer below the drain;
- Hydraulic conductivity of the aquifer;
- Drain depth.

The equivalent depth (according to Equation (5)) and the specific drain discharge (according to Equation (4)) are calculated by the spreadsheet.

6 RESULTS AND ANALYSIS

6.1 Partial Penetration Losses

The following data were used for the assessment of the canal and drain parameters (based on the situation of the Malik Branch Canal):

Parameter:	Value:
Distance between the irrigation canal and interceptor drain	Variable
Drain internal diameter (ID)	0.2032 m. (8 inch)
Depth of aquifer below the drain	9.5 m. (value used for the drain design)
Hydraulic conductivity of the aquifer	0.75 m/day
Drain depth	2.7 m. (average value)

At first, the effect of partial penetration of the interceptor drain was evaluated.

Figure 5 presents the calculated specific groundwater flow to the interceptor drain, as a function of the distance between the irrigation canal and the interceptor drain. It is noted that the (topographic) distance between the canal and drain varies from 45 m. (in most of the area) to 60 metres. The calculated specific discharge for these distances is, respectively, 0.21 and 0.18 m^2/day. This specific discharge would, theoretically, occur *if no other hydraulic losses than the partial penetration losses and aquifer losses would exist*.

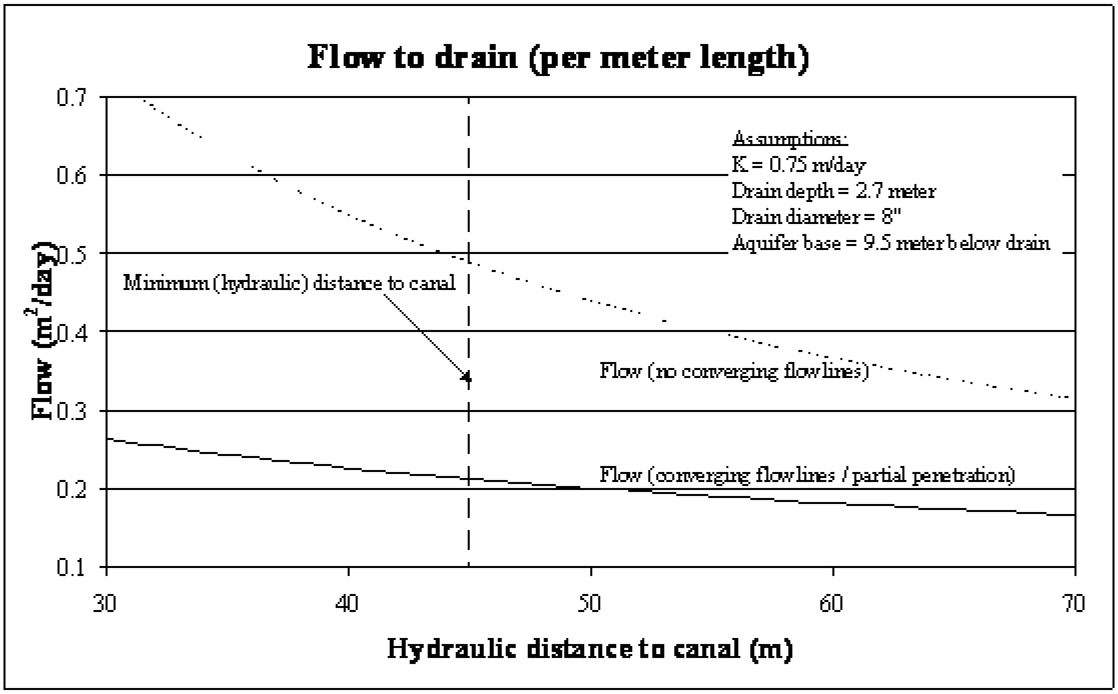


Figure 5 Reduced flow to drain due to partial penetration.

Figure 5 also presents the calculated specific groundwater flow to the interceptor drain in the case that no partial penetration losses exist (Dupuit flow; no converging flow lines). It can thus be concluded that the partial penetration of the interceptor drain results in a flow reduction with a factor 2 – 2.5 in comparison with a fully penetrating drain.

It seems that the partial penetration losses of the drain were not considered in the design procedure, as the reported design discharge (14 l/s) is considerably higher than the theoretical maximum discharge shown in Figure 5 (0.21 m^2/day corresponds with approximately 4.4 l/s)[4]. The calculated maximum drain discharge in Figure 5 is very well in line with the observed drain discharge (on average 0.20–0.22 m^2/day; see Table 1).

6.2 Canal Infiltration Losses

As the observed drain discharge is approximately equal to the theoretical maximum drain discharge, this indicates that there are hardly any other hydraulic losses than the aquifer losses and partial penetration losses (some additional drain entry losses may, however, still be involved, which will be explained below).

This implies that the canal infiltration resistance, $c_{CANAL,}$ is very small. Other facts confirming the small canal infiltration resistance are:

The observed direct response of the groundwater levels to the lowering of the water level in the canal (see Section 4.2). A significant hydraulic resistance would cause a time lag in the response;
The ponding test, which showed that the canal can infiltrate at a much higher rate, if the groundwater levels are lowered. During the ponding test an infiltration rate in the order of 25–35 mm/day was measured (see Section 4.2), which corresponds with approximately 1 m^2/day (the wetted perimeter of the canal is approximately 30-35 m.). In other words: the canal is not the limiting factor.

The canal infiltration resistance is expected to be a few days at maximum (which is common for sandy soils). The infiltration resistance cannot be further quantified with the available data. For a more detailed assessment, a numerical model could be applied (see Jansen et al., 2003). However, the canal infiltration resistance is, most probably, not a very sensitive parameter for the presented case, as this parameter is not the limiting factor for groundwater flow.

6.3 Drain Entry Losses

Although the observed drain discharge is approximately equal to the theoretical maximum drain discharge, some additional drain entry losses may occur, in addition to the partial penetration losses, as the theoretical maximum discharge in Figure 5 assumed only leakage from the irrigation canal. In reality also some groundwater from the adjacent irrigated lands will be discharged. The observed gradient between the groundwater level and the drain level (at the drain location) also indicates drain entry resistance.

In the case that the hydraulic losses due to partial penetration of the drains are incorporated in the drain entry resistance (see also Section 2), the drain entry resistance should be at least (see also Equation 3 and 4):

$$c_{DRAIN} \quad {}^{3}\ (h - H_{DRAIN}) * P_{DRAIN} / q$$

or:

$$c_{DRAIN} \quad {}^{3}\ 2 * (h - H_{DRAIN}) * P_{DRAIN} * L / \{K * (H_{CANAL} - H_{DRAIN})^2 + 2 * K * d * (H_{CANAL} - H_{DRAIN})\} \qquad (10)$$

With Equation (10) the minimum drain entry resistance can be determined. The parameters can be estimated from the layout of the canal and drain system and the monitoring data:

Parameter:	Value:
$h - H_{DRAIN}$	» 2 m (on average)
L	» 45 m
K	» 0.75 m/day
$H_{CANAL} - H_{DRAIN}$	» 2.7 m
d	» 3.4 m. (calculated)

By substituting these values in Equation (10), we obtain c_{DRAIN} ³ (» 9.4 * P_{DRAIN}) days. The wetted perimeter, P_{DRAIN}, is sometimes difficult to determine, as any envelope, gravel pack or high permeable backfill must also be taken into account.

This calculation is only a first estimate of the drain entry resistance. As other hydraulic losses than partial penetration losses occur in and near the interceptor drain, the actual value of c_{DRAIN} should be more than (9.4 * P_{DRAIN}) days. The drain entry resistance cannot be further quantified with the available data. For a more detailed assessment, a numerical model could be used (see Jansen et al., 2003).

It is noted that the wetted perimeter, P_{DRAIN}, is not directly required for modelling with MODFLOW: Substituting c_{DRAIN} ³ (9.4 * P_{DRAIN}) in Equation (9) gives:

$$C_{DRAIN} \ £ \ L_{DRAIN} / 9.4.$$

The value of L_{DRAIN} merely depends on the geometry of the applied model (grid size; see also Jansen et al., 2003), which confirms that C_{DRAIN} has no explicit physical meaning (Section 3). For example, if the length of the grid node that contains a drain segment is 20 metres, C_{DRAIN} will be less than 2.1 m^2/day. If the grid note has a length of 50 metres, C_{DRAIN} will be less than 5.3 m^2/day (hence C_{DRAIN} is not merely determined by the hydraulic properties of the drain).

6.4 Synthesis

The above assessment shows that the canal infiltration and drain entry resistances can sometimes be estimated from monitoring data. In addition to (separate) calculations of the individual parameters, the entire system can also be looked upon.

From the Equations (1), (2) and (3), it follows that

$$q = P_{CANAL} * D_1 / c_{CANAL} = D_{AQ} * D_2 / c_{AQ} = P_{DRAIN} * D_3 / c_{DRAIN}$$

If the canal infiltration resistance is not more than a few days, P_{CANAL} / c_{CANAL} is an order of magnitude larger than P_{DRAIN} / c_{DRAIN} (at least a factor 100). This means that D_1 is negligible in comparison with D_3. With q = 0.21 m^2/day and P_{DRAIN} / c_{DRAIN} £ 1/9.4 m/day, D_3 is at least (in the order of) 2 m. Similarly D_2 can be estimated at (in the order of) 1 m. The sum of D_2 and D_3 is indeed close to the observed value of ($H_{CANAL} - H_{DRAIN}$) of 2.7 m.

As the hydraulic head losses in the aquifer and the losses due to partial penetration of the drain are both an order of magnitude more than the hydraulic losses in the canal bed, any increase of the drain discharge capacity (higher P_{DRAIN} / c_{DRAIN}) will result in more canal leakage. The process of induced leakage will only stop when, finally, an unsaturated zone appears under the canal bed.

The process of induced leakage is further detailed, for various conditions, with a numerical model (see Jansen et al., 2003).

6.5 Final Remarks

It can be seen in Figure 5, that the existence of canal infiltration resistance and /or drain entry resistance has the same hydraulic effect as an increased (topographical) distance between the canal and drain. To account for these losses, the concept “hydraulic distance” was introduced in Figure 5. Obviously, the hydraulic distance is at least the topographic distance.

It is, finally, noted that the use of larger diameter drains will result in a relatively small decrease of partial penetration losses. Large-diameter drains are, therefore, not very effective to reduce these losses (they may, of course, have other benefits).

7 CONCLUSIONS

An assessment of all components of the hydraulic losses between the canal and the interceptor drain has to be made before feasible solutions for waterlogging problems can be identified. The hydraulic losses are a result of canal infiltration resistance, hydraulic resistance in the aquifer and drain entry resistances.

With this regard, it is critical to assess the hydraulic losses due to partial penetration of the interceptor drain. Especially in thick aquifers, these losses can be considerable. The partial penetration losses can be assessed with the concept of “equivalent depth”, which was also used by Hooghoudt. The example from Pakistan shows that partial penetration losses may reduce the groundwater flow by a factor of 2 to 2.5.

The introduction of interceptor drains will cause induced leakage from the canals, which, therefore, reduces the effectiveness of the drain.

Only in the case of an unsaturated zone under the canal bed, the installation of an interceptor drain will not cause an increase of canal leakage. In such a case, also the impact of canal lining is independent of the aquifer characteristics.

A detailed quantitative assessment, generally, requires numerical modelling, as the canal infiltration and drain entry resistances are often difficult to determine directly by monitoring. The hydrological concepts of canal leakage and interceptor drains can, relatively, easily be converted to model parameters. Further details on the application of a numerical model to assess the impact of interceptor drainage and lining are presented in a separate paper (Jansen et al., 2003).

8 ACKNOWLEDGEMENTS

The author wants to thank Dr. M.N. Bhutta and Eng. I. Javed of the International Waterlogging and Salinity Research Institute at Lahore, Pakistan, and Dr. W. Wolters of Alterra-ILRI, Wageningen, The Netherlands, for providing valuable data that could be used to illustrate and support the presented concepts, and for their constructive remarks and contributions to this paper.

9 REFERENCES

Bhutta, M.N. and W. Wolters, 2000. Reducing drainage requirement through interceptor drains and lining? Proceedings 8th International Drainage Workshop, Volume II: Integration of Drainage, Flood Control and Water Management: pp. 137-152. ICID, New Delhi, India.

Euroconsult, 1994. Fordwah Eastern Sadiqia (South). The design of trial interceptor drains along Hakra and Malik Branch Canals. Pakistan Water and Power Development Authority.

IWASRI, 1998. Monitoring of Interceptor Drainage Trial Site Along Malik Branch Canal. International Waterlogging and Salinity Research Institute. Internal Report 98/32. Water and Power Development Authority, Pakistan.

Jansen, H.C, Bhutta, M.N, Javed, I, and Wolters, W, 2003. Groundwater Modelling to Assess the Effect of Interceptor Drainage and Lining. Example of model application in the Fordwah Eastern Sadiqia Project, Pakistan. 9th International Drainage Workshop, September 10-13, 2003, Utrecht, The Netherlands.

Niazi, M.F.K, Siddiqui, W.Z, Bhutta, M.N. Effectiveness of interceptor drains at Fordwah Eastern Sadiqia South (FESS) Project.

Ritzema, H.P. (ed.), 1994. Drainage Principles and Applications, Second Edition. ILRI Publication 16. Wageningen, The Netherlands.

Saleem Bashir, M, Wolters, W, Ittfaq, M, Bhutta, M.N, 1995. Interceptor Drainage Research in CRBC and FESS. In: Proceedings of Seminar on Interceptor drainage. November 7, 1995. Publication No. 180. Pakistan Water and Power Development Authority.

---

[1] Paper No 131. Presented at the 9th International Drainage Workshop, September 10 – 13, 2003, Utrecht, The Netherlands.

[2] H.C. Jansen, Alterra-ILRI: International Institute for Land Reclamation and Improvement/ILRI, PO Box 47, 6700 AA Wageningen, The Netherlands, Tel. + 31 317 495549, Fax. + 31 317 495590, e-mail: ilri@ilri.nl

[3] 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.

[4] Assuming that only canal leakage needs to be intercepted.