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Journal of Hydrology 264 (2002) 69–86

Journal of Hydrology

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Modelling stream–aquifer seepage in an alluvial aquifer: an improved loosing-stream package for MODFLOW

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Received 28 June 2000; revised 25 January 2002; accepted 15 March 2002

Abstract

Seepage from a stream, which partially penetrates an unconfined alluvial aquifer, is studied for the case when the water table falls below the streambed level. Inadequacies are identified in current modelling approaches to this situation. A simple and improved method of incorporating such seepage into groundwater models is presented. This considers the effect on seepage flow of suction in the unsaturated part of the aquifer below a disconnected stream and allows for the variation of seepage with water table fluctuations. The suggested technique is incorporated into the saturated code MODFLOW and is tested by comparing its predictions with those of a widely used variably saturated model, SWMS_2D simulating water flow and solute transport in two-dimensional variably saturated media. Comparisons are made of both seepage flows and local mounding of the water table. The suggested technique compares very well with the results of variably saturated model simulations. Most currently used approaches are shown to underestimate the seepage and associated local water table mounding, sometimes substantially. The proposed method is simple, easy to implement and requires only a small amount of additional data about the aquifer hydraulic properties. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Stream; River; Aquifer; Seepage; Model; Simulating water flow and solute transport in two-dimensional variably saturated media; MODFLOW

1. Introduction

It is important to be able to quantify water exchanges between streams and aquifers. Some practical applications include (1) investigating the effects of aquifer drawdown or mine dewatering on nearby rivers and streams, (2) tracing of contaminants from stream to aquifer or vice versa, (3) estimation of irrigation canal losses, (4) estimation of groundwater recharge from rivers, (5) estimation of the base flow in streams.

Three different types of flow are involved: free surface flow in the stream, saturated groundwater flow in the aquifer and unsaturated flow in the vadose zone. If there is a clay or silt 'clogging' or 'impeding' layer in the bed of the stream with hydraulic properties different from the aquifer then this further complicates the modelling problem.

This paper studies the exchange of water between a stream, which partially penetrates an alluvial aquifer, with particular emphasis on the case in which the bed and banks are clogged. The analysis shows that the flow between stream and aquifer cannot be determined accurately unless the effects of the suction head beneath the clogging layer are taken into account.

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0022-1694/02/$ - see front matter
PII: S0022-1694(02)00067-7

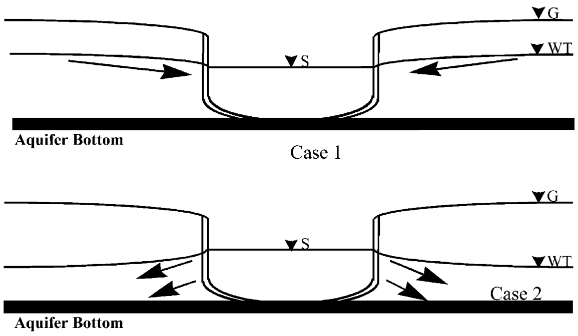

Fig. 1. Stream–aquifer relationships (fully penetrating stream).

Such an approach has been developed here and successfully incorporated into the widely used groundwater flow model, MODFLOW. The technique is new, simple to implement, and gives results much closer to those of complex variably saturated codes, such as simulating water flow and solute transport in two-dimensional variably saturated media (SWMS_2D), than previously used simple methods.

The paper is organised as follows: First, a brief theoretical background of stream–aquifer interaction for the cases of fully and partially penetrating clogged stream is given. Second, a review of previous investigations suggests deficiencies in how the phenomenon has been modelled up to now. Third, the improved technique for predicting a stream–aquifer seepage is explained. Fourth, the improved technique is tested by comparing its results to those from the variably saturated flow model, SWMS_2D, and the conventional model MODFLOW. The tests are conducted on a representative stream–aquifer flow system for selected cases thought to serve the subject of the paper. Fifth, comparison results are discussed and assessed. Finally conclusions reached by the paper are given.

2. Theoretical background

A stream can either fully or partially penetrate an unconfined aquifer. A stream fully penetrates if its bed is at or below the lower boundary of the aquifer. The stream partially penetrates when its bed is above the lower boundary. There is a major difference in the flow system behaviour between rivers having a clogging layer on their bed and banks and those devoid of it (Spalding and Khaleel, 1991). Clogging

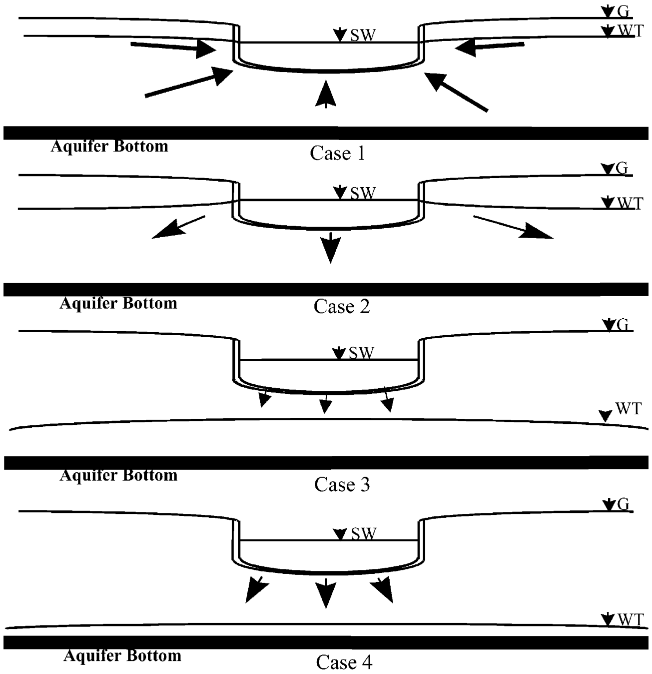

Fig. 2. Stream–aquifer relationships (partially penetrating stream).

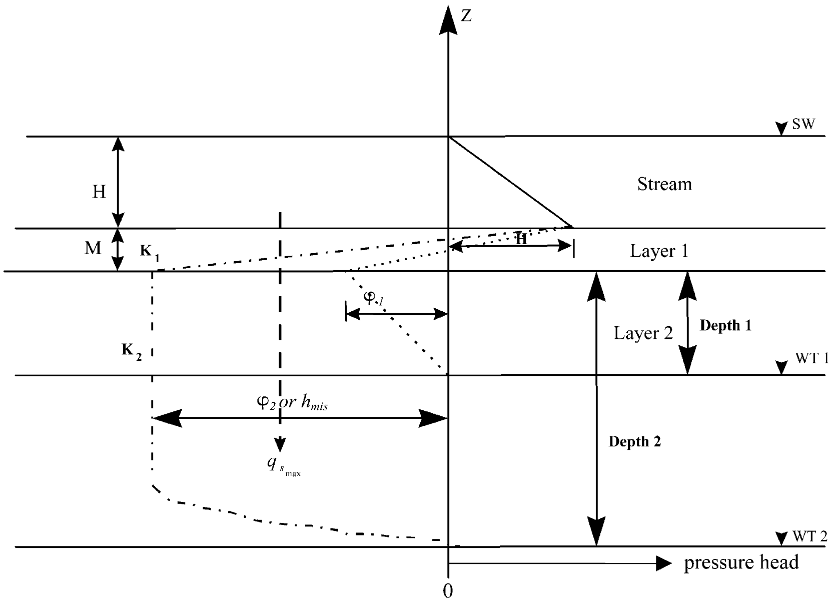

Fig. 3. Derivation of maximum suction head, h_{mis}, from one-dimensional steady state flow in a layered soil system.

layers on beds and banks of rivers consist of fine-grained clay or silt soils or biologically degraded organic matter. They usually have lower permeability than the underlying aquifer. This paper concentrates on modelling steady exchange flows for streams whose bed and banks are clogged (Brockway and Bloomsburg, 1968).

When a stream fully penetrates an unconfined aquifer there are two cases to be considered, Fig. 1. In the first case, called a connected gaining stream, the groundwater table is higher than the water level in the stream and water flows from the aquifer to the stream. In the second case, called a connected losing stream, the water table is below the stream water level and water flows from the stream into the aquifer. In both cases, the flow is predominantly through a saturated medium. When the stream partially penetrates the unconfined aquifer four cases can be distinguished, Fig. 2. The first two cases are the same as in Fig. 1 for the fully penetrating stream. Cases 3 and 4 occur when the water table in the unconfined aquifer falls below the streambed level and there is no longer a direct connection of saturated medium between aquifer and stream. The water table is said to disconnect from the stream base. Case 3, called a disconnected stream with shallow water table, is when the water table is not far below the streambed and can affect the flow from the stream. Case 4, called a disconnected stream with deep water table, is when the water table falls far below the streambed and any further drop does not affect the flow rate from the stream, Zaslavsky (1964, 1965). Fig. 3 (reproduced from Bear et al., 1968), shows the difference between shallow and deep water table conditions. It shows a two layered soil system in which water flows downwards from a ponded surface. The top layer has a saturated hydraulic conductivity (K_1) much smaller than that of the lower layer (K_2). In Fig. 3, the shallow water table condition is represented by the water table at Depth 1. Within this depth, water table fluctuations continue to affect flow through the top layer. The deep water table condition is represented by the water table at Depth 2. In the latter condition, the water table falls far below streambed (deep), in which case the flow through the top layer becomes independent of the water table position.

The seepage between the stream and the aquifer in the two disconnected cases is unsaturated in the aquifer below the streambed. The distinction between the two cases (shallow and deep) depends on the configuration of stream and aquifer, clogging layer and their hydraulic and geometric properties.

In the disconnected conditions of cases 3 and 4, the suction head, (φ_1) at the base of the clogging layer increases as the water table declines until it reaches a

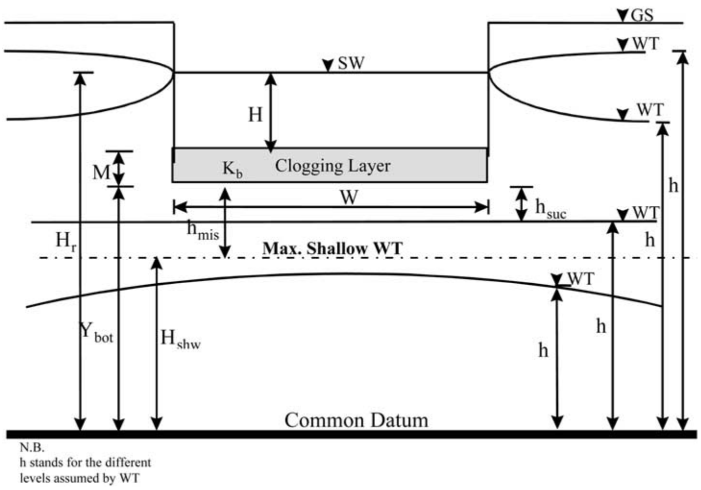

Fig. 4. Spatial relationships in MODFLOW and the developed technique.

maximum value (φ_2), and does not change any further even if the water table declines further. The flow from stream to aquifer increases with the increase in suction head and reaches a corresponding maximum. The clogging layer in most cases remains saturated since it has a high air entry value. Other factors that affect the flow to/from aquifer are the heterogeneity of the aquifer, e.g. aquifer stratification, aquifer anisotropy, the properties and thickness of the clogging layer, the changing stream water levels, and the lateral boundary condition of the flow domain. Some of these factors are considered later in this paper.

So, to accurately model the seepage in stream–aquifer flow system, a combined saturated–unsaturated flow model is required. (e.g. UNSAT2, SWMS_2D, VS2D, SWATRE, HYDRUS2, etc.); or at least a kind of model that can take account of any suction head, due to unsaturated conditions, prevailing below the streambed. (e.g. see Bouwer, 1969; Rovey, 1975).

3. Previous investigations

Much research has already been directed at quantifying stream–aquifer fluxes. The methods, which are well known, can be divided mainly into (i) model construction and (ii) field measurement methods. The models can be deterministic or stochastic. Field measurement methods include measuring stream seepage with a seepage meter at small scales and water balance (inflow/outflow) methods. This paper considers only deterministic modelling methods as implemented in widely used computer codes, such as MODFLOW (McDonald and Harbaugh, 1996).

3.1. Stream–aquifer seepage as modelled in MODFLOW

In the MODFLOW stream package (McDonald and Harbaugh, 1996), a stream is considered to be divided into sections, each linked to a cell in the underlying aquifer model. The stream water level is assumed to be the same throughout the section and constant during a stress period. Thus, the effect of water loss on the stream water levels is not taken into account. When the aquifer head is above the bed of the channel the seepage is assumed proportional to the difference in hydraulic heads between stream and aquifer as given by Eq. (1):

$$Q_s = \frac{K_b L W}{M}(H_r - h) = C_r(H_r - h) \quad (1)$$

where Q_s is the total seepage flow [L^3T^{-1}] from a river reach of length L [L], K_b the streambed saturated hydraulic conductivity [LT^{-1}], W the width of the stream [L], M the thickness of the streambed [L], H_r the elevation of the water surface of the stream and h the aquifer head [L],

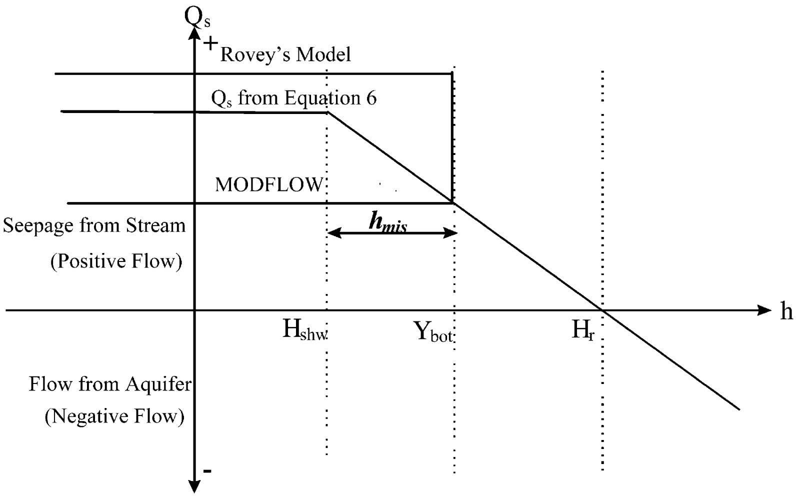

Fig. 5. Comparison of the seepage flow (Q_s) vs. head (h) relationship in MODFLOW, Rovey's model and our Eq. (6).

see Figs. 4 and 5. Note $C_r = K_b LW/M$ is called the streambed conductance $[L^2T^{-1}]$.

Once the aquifer head drops below the riverbed level however, the dependence of the flow on the aquifer head is assumed to disappear and the flow is assumed proportional to the stream stage alone, i.e.

$$Q_s = C_r(H_r - Y_{bot}) \tag{2}$$

where Y_{bot} is the elevation of the streambed [L].

It is implicitly assumed that there is sufficient water in the stream to supply the flow without affecting water levels. For a constant H_r, Eq. (2) will give a constant seepage flow regardless of the position of the water table in the aquifer. In the original release of MODFLOW, it is stated that, in Eq. (2), the aquifer bottom can be replaced by the depth at which seepage becomes constant. However, no means for determining this depth is given and it is recommended that it can be determined by calibration with data.

3.2. Other models of stream–aquifer interaction

3.2.1. Rovey's model

Rovey (1975) developed a saturated three-dimensional finite difference groundwater model to simulate a flow system domain which includes seepage between stream and aquifer. She used an expression based on Darcy's law to calculate stream losses in the case of a disconnected stream, $h < Y_{bot}$:

$$Q_s = C_r(H_r - Y_{bot} - h_a) \tag{3}$$

where h_a is the air entry (bubbling pressure) head of the clogging layer [L].

Note that, while it is an improvement on Eq. (2) and gives a greater seepage rate, Rovey's formula is still independent of water table elevation, h, and does not account for variations in the seepage rate due to water table variations below the clogging layer even for shallow water table conditions. Note also that this formula suggests an unrealistic jump in seepage rate as the water table drops below the base of the clogging layer as shown in Fig. 5.

The seepage Q_s in Eq. (3) is described by Rovey as a 'maximum seepage flow', which, for a given stream depth, cannot be exceeded, even if pressure heads at the base of the clogging layer become more negative than the air entry value h_a of the clogging layer. This is different from Zaslavsky (1964, 1965) who presents hydraulic arguments for the existence of a steady state vertical pressure profile in the deep water table case as shown in Fig. 3. He also suggests that the maximum infiltration rate for a given stream stage is dependent on the soil properties of both the clogging layer and the aquifer, and not just on the air entry pressure head of the clogging layer alone.

3.2.2. Bouwer's model

Bouwer (1969) utilised a formula similar to Eq. (3)

to compute stream losses in the case of disconnection. However, instead of using the air entry value of the clogging layer to designate the maximum seepage flux, he used a more representative average suction head in the underlying aquifer to replace the air entry value in the clogging layer. The formula he used to calculate the maximum seepage flow, also written in terms of previously defined parameters is

$$Q_s = C_r(H_r - Y_{bot} - h_{cr}) \quad (4)$$

where h_{cr} is the critical pressure head calculated as in Eq. (5).

Bouwer (1969) uses the expression 'critical pressure head' to describe the term h_{cr}. It is, in effect, a measure of the thickness of a fictitious capillary fringe that would be found in a hydrostatic moisture profile above the water table in the aquifer material that one is considering. He defined this critical pressure head as

$$h_{cr} = \int_0^{\varphi_w} \frac{K(\varphi)}{K_s} d\varphi \quad (5)$$

where $K(\varphi)$ is the aquifer unsaturated hydraulic conductivity function, [LT^{-1}]; K_s the aquifer saturated hydraulic conductivity, [LT^{-1}]; and φ_w is the pressure head at which moisture content and hydraulic conductivity essentially become irreducible (Bouwer, 1969) [L].

Laboratory studies by Bouwer (1964) indicate that Eq. (4) provides a viable method for computing maximum steady state seepage of surface water across a 'restricting layer', similar to the clogging layer considered in stream–aquifer studies, when the stream lies well above the capillary fringe of the water table below it. When the stream falls within the capillary fringe, Bouwer (1964) suggested that Eq. (4) can still be used for calculating seepage from the stream with the term h_{cr} replaced by the depth to the water table from the bottom of the stream. Therefore, Bouwer's (1969) method suggests that the maximum seepage from the stream is determined by the critical pressure h_{cr}, which in turn depends on the aquifer material hydraulic properties alone. He did not discuss the roles of the clogging layer properties and stream stage in this value of h_{cr}. According to Bouwer (1969) the value of the critical pressure in an aquifer should be the same in all cases regardless of the clogging layer material or stream stage. Consequently, for a given stream stage, the maximum stream seepage should be attained at the same water table depth in the aquifer. Therefore, while Bouwer's (1969) model is an improvement over Rovey's (1975) in considering the variations of seepage within the shallow water table, it does not take into consideration the roles of stream stage and clogging layer properties in determining the water table depth at which maximum seepage first occurs. Hence it will result in erroneous estimation of the maximum seepage flux.

3.2.3. Dillon and Liggett's model

Dillon and Liggett (1983) modelled the flow between an ephemeral stream and an unconfined aquifer with a disconnected water table. They simulated the negative pressure head, which they termed 'the changeover head' and put it into a Green–Ampt (Green and Ampt, 1911) algorithm for determining the delay time between incipient stream infiltration and subsequent recharge of the water table. However, as in the previous cases the model uses a constant suction head, and cannot respond to fluctuations of a shallow water table. Also, they did not show how to calculate this suction head.

Although the earlier models are improvements over conventional ones, two of them are incapable of estimating variable seepage in shallow water table conditions, and produce a constant maximum seepage the moment disconnection takes place, while the third one ignores factors other than aquifer properties in estimating the maximum suction head beneath a clogging layer.

4. Suggested improvement for loosing-streams in MODFLOW

Currently used simple models of stream aquifer interaction are not completely satisfactory. In theory, an unsaturated–saturated model could always be used in such cases, but since most groundwater flow modelling is done with saturated-only models, a more practical solution is to develop a model which addresses the deficiencies of existing approaches and yet can be implemented in the widely used saturated-only codes. Thus the technique suggested here is based on the theoretical mechanism of stream–aquifer seepage described earlier. It builds on the

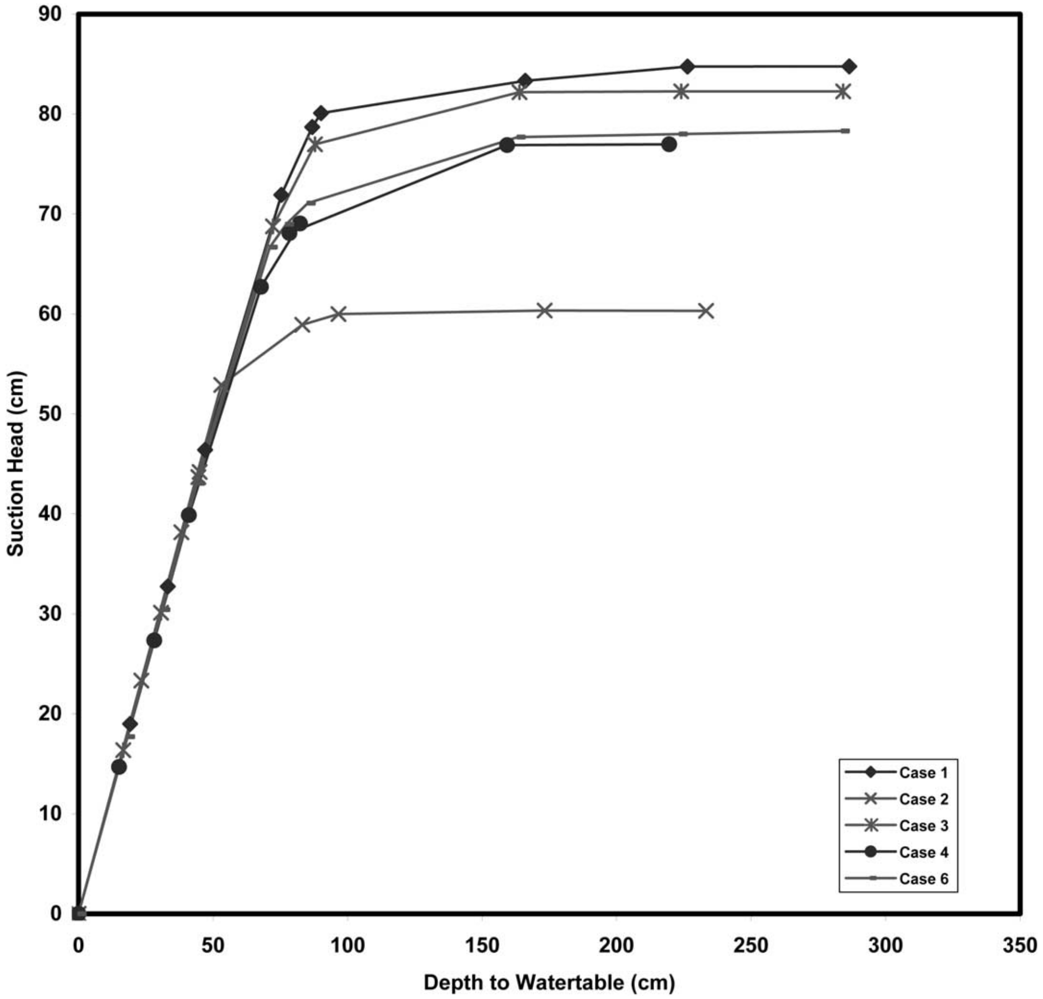

Fig. 6. Suction head vs. depth to water table.

earlier techniques of Bouwer (1969), Rovey (1975) and Dillon and Liggett (1983), by assuming that when there is a clogging layer seepage through this clogging layer is at all times represented by a fully saturated one-dimensional steady state flow equation. However, it differs from Rovey's (1975) scheme in that seepage flow during disconnection can vary with water table elevation over a wider range, and that the maximum seepage flow does not depend on the clogging layer alone. It also differs from Bouwer's (1969) scheme in that the maximum suction head does not depend on aquifer properties alone. The suggested technique estimates the suction head at the base of the clogging layer (h_{suc}) similar to Bouwer's (1969) as depth to water table from stream bottom when the water table is still within a shallow depth. However, the maximum seepage and its corresponding water table level are determined by evaluating the maximum suction at stream bottom for a particular set of stream stage, clogging layer and aquifer geometrical and material properties, altogether. In other words the important feature of this technique is the determination of the limiting shallow water table elevation (H_{shw}) for a given stream stage and clogging layer and aquifer configuration. Once H_{shw} is determined, the seepage flow can be calculated from:

$$Q_s = \begin{cases} C_r(H_r - h) & \text{for } h > Y_{bot} \\ C_r(H_r - Y_{bot} + h_{suc}) & \text{for } H_{shw} < h \le Y_{bot} \\ C_r(H_r - H_{shw}) & \text{for } h \le H_{shw} \end{cases} \tag{6}$$

where h_{suc} is the suction head [L] at the base of clogging layer, approximated by $Y_{bot} - h$, H_{shw} the limiting shallow water table elevation [L], approximated by $Y_{bot} - h_{mis}$, with h_{mis} as the maximum suction head [L] at the base of clogging layer for a given set of stream stage and clogging layer and aquifer materials and configurations. $C_r = K_b LW/M$, is the streambed conductance, where, L is the length [L] of the reach, W its width [L], and K_b is the saturated hydraulic conductivity of the bed material [LT^{-1}] and M [L] its thickness.

The proposed relationship is shown in Figs. 4–6. Fig. 4 defines the parameters in Eq. (6). Fig. 5 shows the variation of the seepage flow with hydraulic head in the aquifer for the proposed technique. When the water table drops below the streambed, the seepage flow continues to respond linearly to the water table position until it falls below the shallow WT elevation limit (H_{shw}), after which it remains constant. Thus, the essential difference between this and MODFLOW method is that the range of water table elevations at which the seepage remains proportional to water table elevation is extended downwards. Also, the lower limit for shallow water table conditions can vary depending on the material of the aquifer and clogging layer, and the elevations of the water table and stream. The part of the curve between the points corresponding to $h = Y_{bot}$ and $h = H_{shw}$ is the additional seepage flow resulting from the suction at the base of the clogging layer which is mainly missed by the current MODFLOW method. However, the manuals for early versions of MODFLOW did suggest that the stream bottom could be replaced by the depth at which seepage becomes constant. Fig. 6 relates suction head at the base of the clogging layer (h_{suc}), obtained with the variably saturated code SWMS_2D, to depth to water table (below clogging layer) for some specific test combinations of clogging layer and aquifer properties. These are the same combinations used in Section 5 to test the proposed improved method and are described in more detail in that section. Fig. 6 emphasises clearly that depth to water table is proportional to suction head and hence it is an extremely important parameter in estimating seepage from a losing stream and should not be ignored. Fig. 6 also shows that the maximum suction head attained in any case, and consequently the depth to shallow water table, is a function of the set of stream stage and clogging layer and aquifer geometry and properties. An important conclusion from Fig. 6 is that, under steady state one-dimensional flow across a clogging layer, similar to Bouwer's (1969), the suction head at the base of clogging layer can be replaced by the depth to water table below the clogging layer base when the water table is shallow, i.e. $h_{suc} \approx Y_{bot} - h$.

To use the proposed method, h_{mis} or H_{shw} must first be determined. Estimates of h_{mis} are based on the theory of one-dimensional steady state flow in a layered soil derived by Zaslavsky (1964, 1965). Fig. 3 is reproduced from the latter reference to explain the relationship between downward flux (flow through unit area), $q_{s_{max}}$, [LT^{-1}] across a clogging layer and the unsaturated hydraulic conductivity in the aquifer.

In one-dimensional steady state downward flow in a two layered system of soil in which the upper layer has a saturated hydraulic conductivity (K_1) much less than the lower one (K_2), the deep water table condition in the lower layer is attained when the unsaturated downward flux through the lower layer becomes equivalent to the unsaturated hydraulic conductivity of its soil. In other words, the deep water table condition is established when the vertical hydraulic gradient in the lower layer becomes unity. At this point the maximum seepage flux, $q_{s_{max}}$, [LT^{-1}] occurs, so that

$$q_{s_{max}} = K_2(h_{mis}) \tag{7}$$

where $K_2(\ )$ is the unsaturated hydraulic conductivity of the aquifer and is a function of suction head. Here we represent K_2 with van Genuchten's (1980) equation which expresses the unsaturated hydraulic conductivity, K, and moisture content, θ_w, as functions of pressure head φ:

$$\theta_w(\varphi) = \theta_r + \frac{\theta_s - \theta_r}{[1 + |\alpha\varphi|^n]^m} \tag{8a}$$

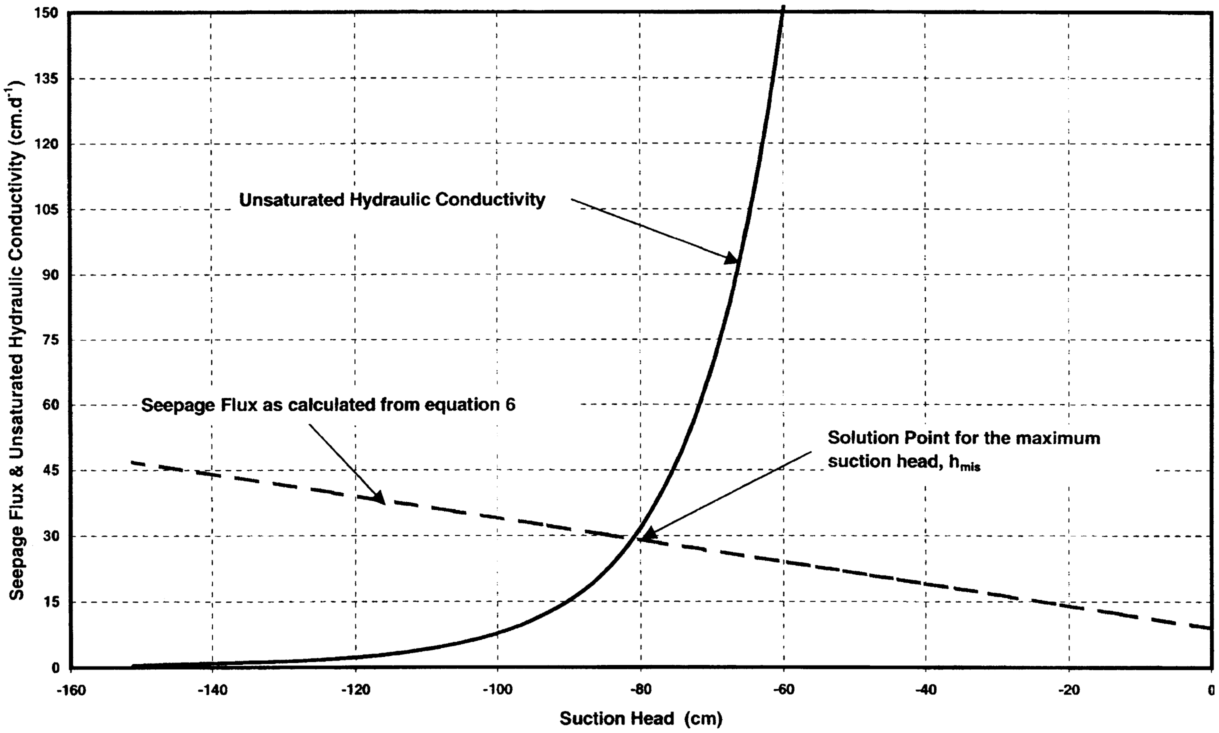

Fig. 7. Left and right hand side terms of Eq. (10) (reference case).

$$K(\varphi) = K_s S_e^{1/2}\left[1 - \left(1 - S_e^{1/m}\right)\right]^2 \tag{8b}$$

with

$$S_e = \frac{\theta_w - \theta_r}{\theta_s - \theta_r} \tag{8c}$$

where θ_s is the saturated moisture content, dimensionless; θ_r the residual moisture content, dimensionless; α a parameter in the soil retention function, [L]; n an exponent in the soil retention function ($n > 1$), dimensionless; $m = 1 - 1/n$, dimensionless; and K_s is the soil saturated hydraulic conductivity, [LT^{-1}].

Since the flow is steady, this unsaturated flux through the aquifer, q_s [LT^{-1}], given by Eq. (7), must equal the saturated flux through the clogging layer, which will also be at its maximum. This is given by Eq. (6) with $h_{suc} = h_{mis}$ as

$$q_{s_{max}} = \frac{K_b}{M}(H_r - Y_{bot} + h_{mis}) \tag{9}$$

$q_{s_{max}}$ can be found by combining Eqs. (7) and (9), solving for h_{mis}

$$K_2(h_{mis}) = \frac{K_b}{M}(H_r - Y_{bot} + h_{mis}) \tag{10}$$

Eq. (10) is non-linear in h_{mis} because of the complex relationship between it and K_2, but can be solved by any good root finding method. The resulting value of the suction head, h_{mis}, is the maximum for that particular stream, clogging layer and aquifer configuration. The limiting depth for shallow water table conditions, H_{shw}, can then found by subtracting h_{mis} from the stream bottom elevation Y_{bot}, as $H_{shw} = (Y_{bot} - h_{mis})$. Fig. 7 shows how the left and right hand side terms of Eq. (10) vary with suction head. The solution for h_{mis} is where the curves intersect.

5. Testing the improved MODFLOW loosing-stream package

To evaluate the performance of the suggested technique described earlier, it is incorporated into RIV5FM and RIV5BD modules of the MODFLOW

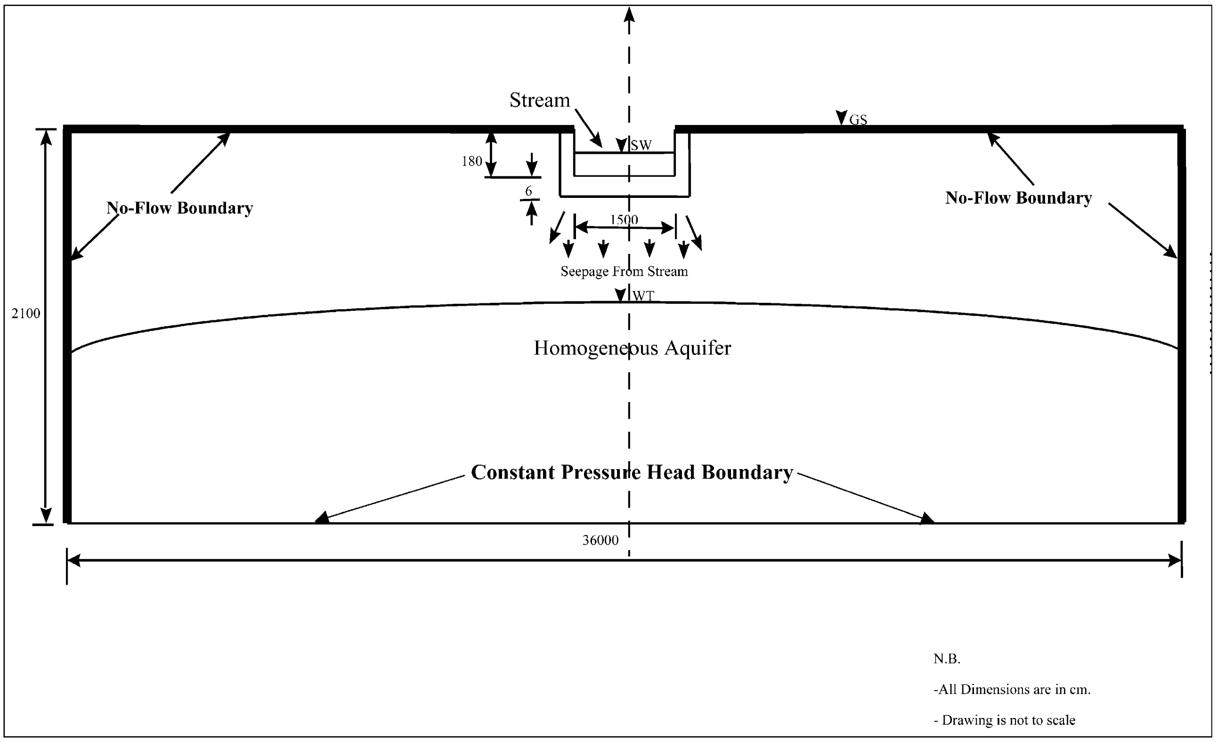

Fig. 8. Simple stream/aquifer flow system.

River Package. Some modifications were also made to the main program and other modules to read in the unsaturated hydraulic properties for the aquifer plus the saturated hydraulic conductivity of the clogging layer. The new version of MODFLOW that contains these modifications is called MOBFLOW and it is tested by comparing its results with those from a variably saturated flow model and the original MODFLOW.

The test consists of (i) selecting the variably saturated and saturated models, (ii) forming an appropriate simulation test domain, (iii) conducting and analysing the steady state simulations and (iv) comparing the results from the three simulators.

The code SWMS_2D by Simunek et al. (1994) is used here for the variably saturated numerical test. It uses a Galerkin linear finite element formulation to solve a two-dimensional form of Richards' equation, for water flow with a sink term, coupled with a convection–dispersion equation for solute transport. The hydraulic properties of the unsaturated soil are represented by the model of Vogel and Cislerova (1988), which under certain conditions becomes the van Genuchten (1980) model. The flow and transport can occur in a vertical plane, horizontal plane, or in a three-dimensional region exhibiting radial symmetry about a vertical axis. Verifications of the code by comparison with field data or the output of other variably saturated codes, e.g. UNSAT2, SWATRE are well documented in its manual and are not discussed here. Some minor modifications have been made to the code to suit the present problem. The widely used MODFLOW code (McDonald and Harbaugh, 1996) is used here in the saturated numerical test as an example for the conventional saturated codes.

To investigate the factors affecting stream–aquifer seepage, a simplified two-dimensional (vertical plane) groundwater flow system is used. It consists of a section through a rectangular stream channel (with a clogging layer on its bank and bed) which partially penetrates an alluvial unconfined aquifer as shown in Fig. 8. Infiltration and evapotranspiration from the ground surface are ignored (i.e. no-flow boundary on the ground surface), and the two lateral boundaries are

Table 1
Soil types and characteristics according to van Genuchten's model (h_c: air entry value (cm), θ_s: saturated moisture content, θ_r; residual moisture content, K_s: saturated hydraulic conductivity (cm d^{-1}), α: parameter in the soil water retention function (cm), n: exponent in the soil water retention function ($n > 1$))

Material no.	Soil type	h_c	θ_s	θ_r	K_s	α	n
Aquifer materials							
Mat. 1	Coarse sand	0	0.30	0.03	24 000	27.9	4.62
Mat. 2	Medium sand	0	0.34	0.05	3000	17.9	3.07
Mat. 3	Loamy sand	0	0.38	0.15	150	12.9	2.61
Clogging layer materials							
Mat. 4	Sandy silt	120	0.40	0.18	30.0	4.29	4.10
Mat. 5	Silt loam	128	0.42	0.22	3.0	4.04	3.84
Mat. 6	Clay loam	135	0.44	0.30	1.5	3.69	3.37
Mat. 7	Silty clay	143	0.46	0.36	0.3	3.06	2.78

taken either as no-flow or fixed head boundaries. When the lateral boundaries are no-flow boundaries, the only exchange of water within the model domain is through the streambed and banks, and through the bottom boundary of the domain where water can drain to or rise from the lower part of the aquifer. The dimensions of the flow domain are typical of Irish riverine systems. Seven types of soils are simulated in this study. Three different soil types are used as the aquifer material and the remaining as clogging materials or any intermediate stratum as required. Soil parameters used in Table 1, which are arbitrarily chosen, are taken from a study conducted by Peterson (1989) and are expressed here in terms of the van Genuchten model.

Since the flow system in Fig. 8 is symmetrical, only half of this domain is simulated. The domain is sufficiently wide so that its width and lateral boundary conditions do not influence significantly the solution.

Since the study is mainly a comparative one, a 'reference' case was defined which is then used as a common base for comparisons. It consists of a vertical section through a river flowing over an aquifer of medium sand (mat. 2) of width 360 m, depth 21 m and with no-flow lateral boundary conditions. The river has 30 cm of water over a clogging layer 6 cm thick made up of clay loam (mat. 6). Steady state simulations were conducted for this reference case and six other cases (viz. Table 2) which are chosen to investigate how the geometry and material properties of the system can influence the seepage and water table behaviour. In particular, the effects of the hydraulic head difference between stream and aquifer and of the thickness and hydraulic properties of the clogging layer and aquifer are reported here.

6. Results and discussion

The simulation domain (half of the symmetrical domain in Fig. 8) is discretised into a model domain consisting of 2607 nodes and 2505 rectangular elements. The mesh becomes gradually coarser with increasing distance from the stream and from the expected location of the wetting front. Steady state runs were conducted on the reference case and for each of the other six cases defined in Table 2. Twenty-five runs were done for each case, each one with a different pressure head at the bottom of the simulation domain (representing different regional aquifer conditions). Starting with a pressure head of 20.1 m the pressure head is reduced in steps of between 15 and 60 cm for each run, down to a pressure head of 9 m so that a large range of stream–aquifer conditions is covered. A summary of the simulation results with SWMS_2D, for all the cases listed in Table 2, is shown in Table 3.

6.1. MOBFLOW unique characteristics

As a first step in assessing the performance of the suggested technique, the values of h_{mis}, h_c of the clogging layer and h_{cr} of Bouwer's (1969), for the cases of Table 2 together with the corresponding

Table 2
Definitions of the cases simulated (all dimensions and materials referred to the flow domain in Fig. 8; D. width: width of the domain, D. depth: depth of the domain, C.L. thick.: clogging layer thickness, C. layer mat.: clogging layer material type as defined in Table 1, Mat. 2: material number 2 as defined in Table 1, S. stage: stream stage, B.B. cond.: bottom boundary condition, L.B. cond.: lateral (right) boundary condition of the domain, Const. P.H.: constant pressure head (Dirichlet type))

Case	D. width (m)	D. depth (m)	C.L. thick (cm)	C. layer mat.	Aquifer mat.	S. stage (cm)	B.B. cond.	L.B. cond.
Case 1 (reference case)	360	21	6	Mat. 6	Mat. 2	30	Const. P.H.	No-flow
Case 2	360	21	6	Mat. 6	Mat. 1	30	Const. P.H.	No-flow
Case 3	360	21	6	Mat. 6	Mat. 2	60	Const. P.H.	No-flow
Case 4	360	21	6	Mat. 5	Mat. 2	30	Const. P.H.	No-flow
Case 5	360	21	3	Mat. 6	Mat. 2	30	Const. P.H.	No-flow
Case 6	360	21	6	Mat. 6	Mat. 3	30	Const. P.H.	No-flow
Case 7	360	21	6	Mat. 7	Mat. 2	30	Const. P.H.	No-flow

maximum seepage flux for each case were computed from the formulae of Rovey (1975), Bouwer (1969), and Eq. (6). The computed values are compared with the estimates given by SWMS_2D in Table 4 which confirms that h_{mis} neither depend on the clogging layer properties alone nor on the aquifer properties alone. It is a function of the whole stream–aquifer configuration. It is different from Bouwer's (1969) h_{cr}, since it has different values for the same aquifer as in cases 1, 5, 8, and 14. The maximum flux computed by the four models is also different. While Rovey's (1975) method overestimates the maximum flux, Bouwer's (1969) method seriously underestimates the maximum flux. The technique suggested in this paper gives a maximum flux much closer to SWMS-2D.

6.2. Results from SWMS_2D

Fig. 9 shows the variation of steady state seepage flows as the water table varies for the reference simulation. As expected, seepage varies linearly with decrease in water table until it reaches a maximum and remains constant at this value irrespective of any further drop in water table level. Three distinct points on the curve should be noted. The first is the 'hydrostatic condition' point, which is the point at which the stream and aquifer heads are equal, and it separates cases 1 and 2 of Fig. 2. The second is the 'incipient disconnection' point, which is the point at which the water table in the aquifer disconnects from the stream, i.e. there is no longer a saturated connection with the stream bottom. This point separates cases 2 and 3 in Fig. 2. The third, is the

Table 3
Summary of simulation results from SWMS_2D (U.H.: underlying head or head at aquifer lower boundary, S. flow: seepage flow, WT. level: water table level)

Case no.	Incipient disconnection			Max. incipient seepage			Max. suction head (cm)	Max. moisture content
	U.H. (cm)	S. flow ($cm^3\ d^{-1}\ cm^{-1}$)	WT. level (cm)	U.H. (cm)	S. flow ($cm^3\ d^{-1}\ cm^{-1}$)	WT. level (cm)		
1	1890	10 961	1894.8	1800	20 801	1808.9	84.5	0.138
2	1890	11 725	1890.7	1830	16 899	1830.9	59.9	0.058
3	1890	17 577	1897.4	1740	26 433	1750.3	82.0	0.143
4	1890	20 387	1899.0	1800	39 718	1835.4	76.6	0.159
5	1890	20 250	1898.9	1740	38 475	1839.9	77.6	0.158
6	1830	8890	1906.7	1620	15 259	1752.6	64.4	0.310
7	1890	2315	1891.0	1815	4424	1816.9	107.4	0.051

Table 4
Maximum suction head (h_{mis}) and seepage flux (q_s) for different stream stages, clogging layers and aquifer parameters (C.L. mat.: clogging layer material, C.L. thick.: clogging layer thickness, C.L. h_c: clogging layer air entry value, h_{cr}: aquifer critical pressure according to Eq. (5) of Bouwer (1969), h_{mis}: maximum suction head at the base of the clogging layer, $q_{s_{max}}$: maximum seepage flux)

Case no.	Stream stage (cm)	C.L. thick. (cm)	C.L. h_c (cm)	h_{cr} (cm)	h_{mis} (cm)	$q_{s_{max}}$ (cm d^{-1})			
						Rovey's	Bouwer's	Eq. (6)	SWMS_2D
Case 1	30	6	135	−33.5	81.6	42.8	17.4	29.4	26.6
Case 2	30	6	135	−27.3	57.1	42.8	15.8	23.3	21.7
Case 3	60	6	135	−33.5	78.7	42.8	17.4	28.7	33.9
Case 4	30	6	127	−33.5	73.4	81.5	34.7	54.7	50.9
Case 5	30	3	135	−33.5	73.4	85.5	34.7	54.7	49.3
Case 6	30	6	135	−40.7	61.0	42.8	19.2	24.3	19.6
Case 7	30	6	143	−33.5	107.4	8.9	3.5	7.2	5.7

'maximum incipient seepage' point, which is the highest point at which deep water table behaviour starts, and it separates cases 3 and 4 in Fig. 2. The last two depend only on the flow system configuration and properties (i.e. aquifer head, seepage flow and suction head at stream base as these points are different for each case considered). Fig. 9 is similar to Rushton's (1997) results for the unclogged case, for which disconnection does not take place. It shows that stream seepage responds almost linearly to changes in water table level for connected stream conditions and even for a disconnected stream with shallow water table conditions. This direct and linear increase in seepage flow with decline of water table only changes when the water table approaches the deep water table conditions, where the straight line curves sharply downward and thereafter the seepage remains the same irrespective of any further decline in water table.

Fig. 10 shows the variation of seepage flows with water table level for three different aquifer materials (coarse, medium, and loamy sands) from SWMS_2D and the MOBFLOW simulators. Focusing on the SWMS_2D graphs in Fig. 10, two important observations can be made. First, for a given water table level, lower than the stream bottom level, but above the point at which maximum seepage is reached, the seepage flow in case 6 (loamy sand aquifer) is less than in both case 2 (coarse sand aquifer) and the reference case (medium sand aquifer). However, the maximum seepage for the coarse sand aquifer is less than that of the medium sand aquifer because the latter allows a greater suction head to develop at the base of the clogging layer. It is the unsaturated aquifer properties and particularly the relationship between unsaturated hydraulic conductivity and suction ($K-\varphi$) which govern here and not the saturated properties. Second, the value of the maximum seepage flow is strongly dependent on the hydraulic material properties of the aquifer, and so also are the position of the points of incipient disconnection and maximum incipient seepage. This agrees with Zaslavsky's (1964, 1965) one-dimensional analysis, summarised in Fig. 3, showing that the maximum seepage flow depends mainly on the maximum suction head developed at the underside of the clogging layer. The maximum suction head attained for a given set of stream stage, aquifer and clogging layer materials, and stream and aquifer geometry, is determined mainly by a unique unsaturated hydraulic conductivity–pressure head ($K-\varphi$) relationship for the aquifer material.

Comparison of simulation results in Table 3 for three different clogging layer material types (case 7, silty clay; case 4, silty loam and the reference case 1, clay loam) shows, as expected, that seepage increases with increase in the saturated hydraulic conductivity of the clogging layer as does the maximum seepage flow reached in each case. Also, the suction head at the base of the clogging layer does not reach the air entry values of the respective clogging layer material, so the clogging layer remains saturated. The point of maximum incipient seepage is reached at higher water table levels for the lower permeability

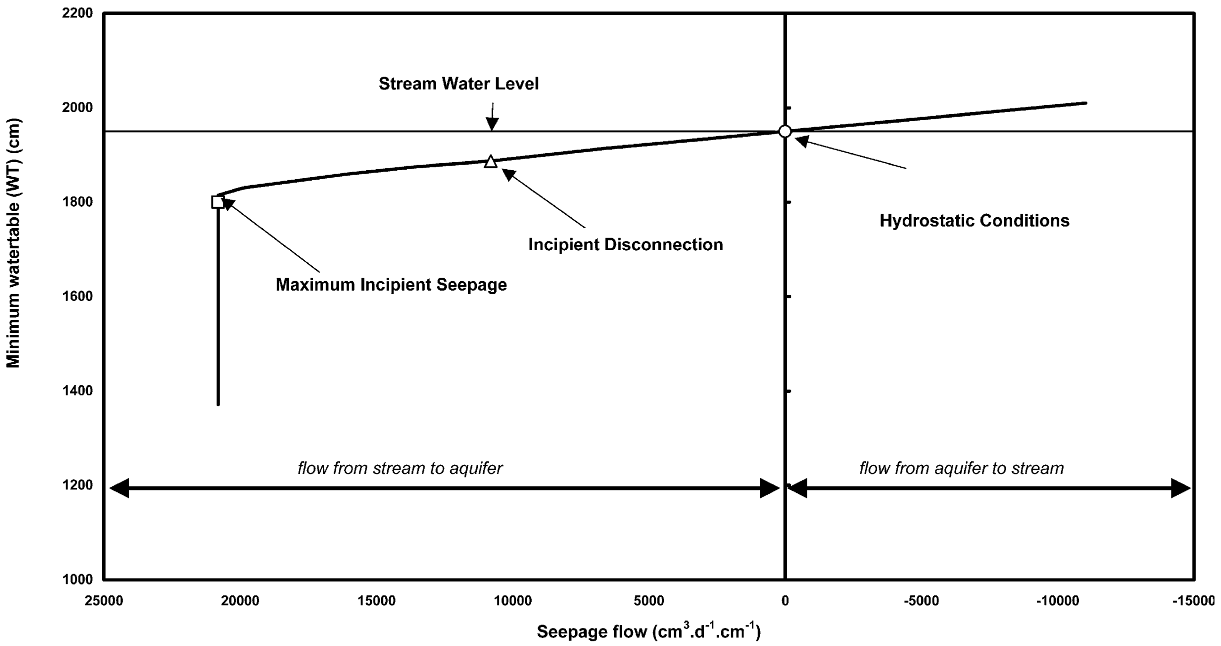

Fig. 9. Seepage flow vs. minimum water table from SWMS_2D reference simulation.

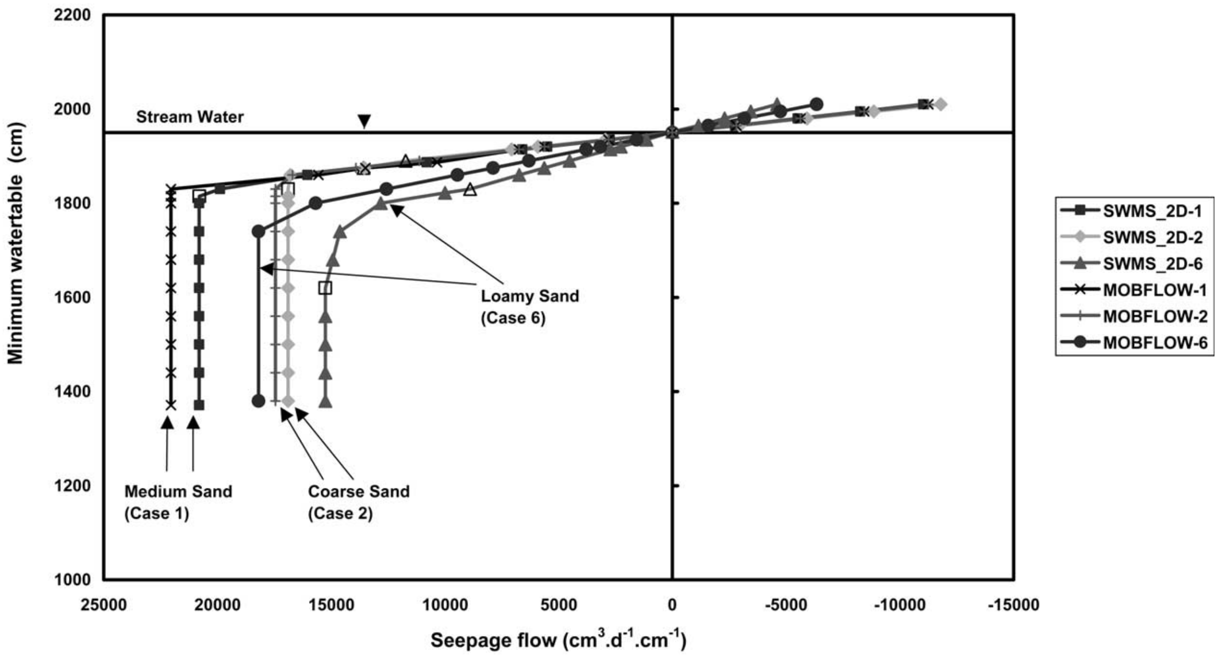

Fig. 10. Seepage flow from SWMS_2D and MOBFLOW for different aquifer materials.

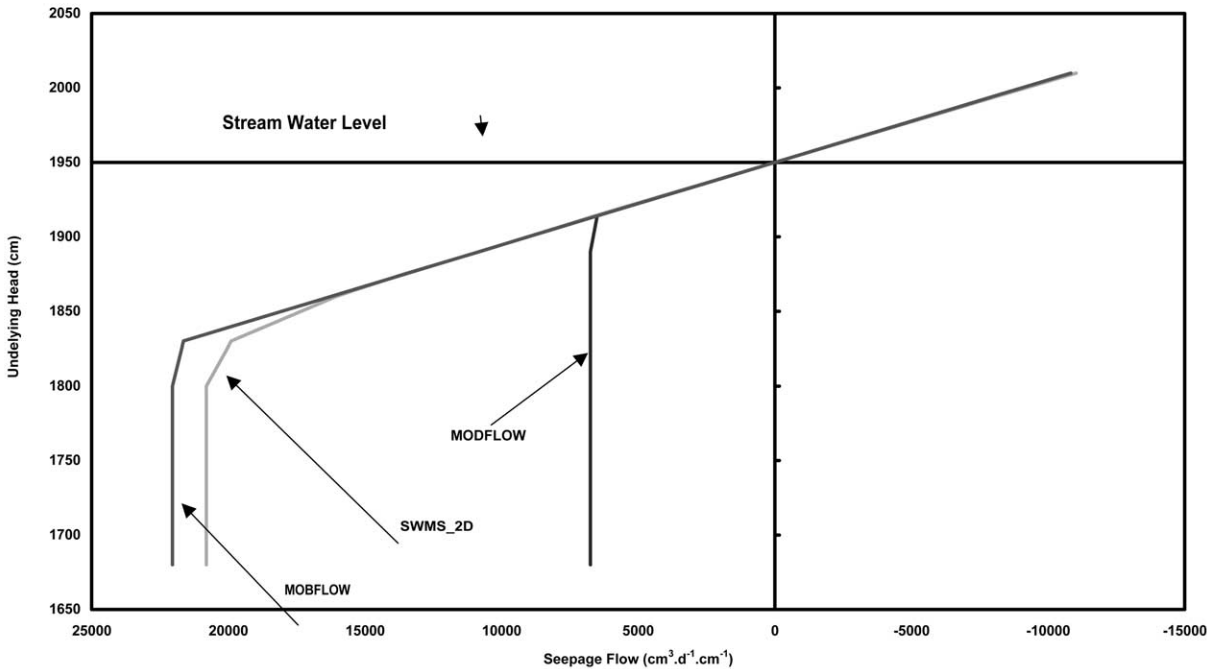

Fig. 11. Seepage flow from MODFLOW, SMWMS_2D and MOBFLOW models (reference case).

clogging layers than for the higher ones. This is also expected since seepage is restricted more by a lower permeability material than a higher permeability one, which means less 'mounding' of the water table. Thus, the water table under the stream responds more closely to changes in aquifer head for the lower permeability clogging layer case than for the higher permeability one.

Similarly, comparison of results in Table 3 for cases with different clogging layer thickness, namely, case 5 (clogging layer is 3 cm thick) and the reference case (clogging layer is 6 cm thick) shows that seepage flow is inversely proportional to the thickness of clogging layer and maximum incipient seepage conditions are reached at relatively higher water table levels for thicker clogging layers than for thinner ones. Nevertheless, for both cases, the suction heads at the base of the clogging layer are still lower than the air entry value of the clogging layer. This indicates that clogging layers tend to remain saturated, even when they are thin. The relatively higher suction heads at the base of the thinner clogging layer explains the deeper depths reached by water table before deep water table conditions occur.

6.3. Comparison between SWMS_2D and MODFLOW

Steady state seepage flows are plotted vs. underlying heads from SWMS_2D, MODFLOW, and MOBFLOW simulators in Fig. 11 for the reference simulation. The curves from SWMS_2D and MODFLOW are similar until the point where MODFLOW determines that disconnection has taken place (i.e. when water table level falls below streambed level). At this point, MODFLOW assumes that atmospheric pressure exists at the base of the clogging layer, and the seepage rate, computed as in Eq. (2), remains unchanged. In a very clear contrast, the variably saturated simulator SWMS_2D indicates that stream seepage continues to increase with decline in the water table. Consequently, the maximum stream seepage reached by the two models is significantly different. The maximum steady state seepage flow computed by MODFLOW is 6750 $cm^3\ d^{-1}\ cm^{-1}$, whereas the variably saturated simulator SWMS_2D

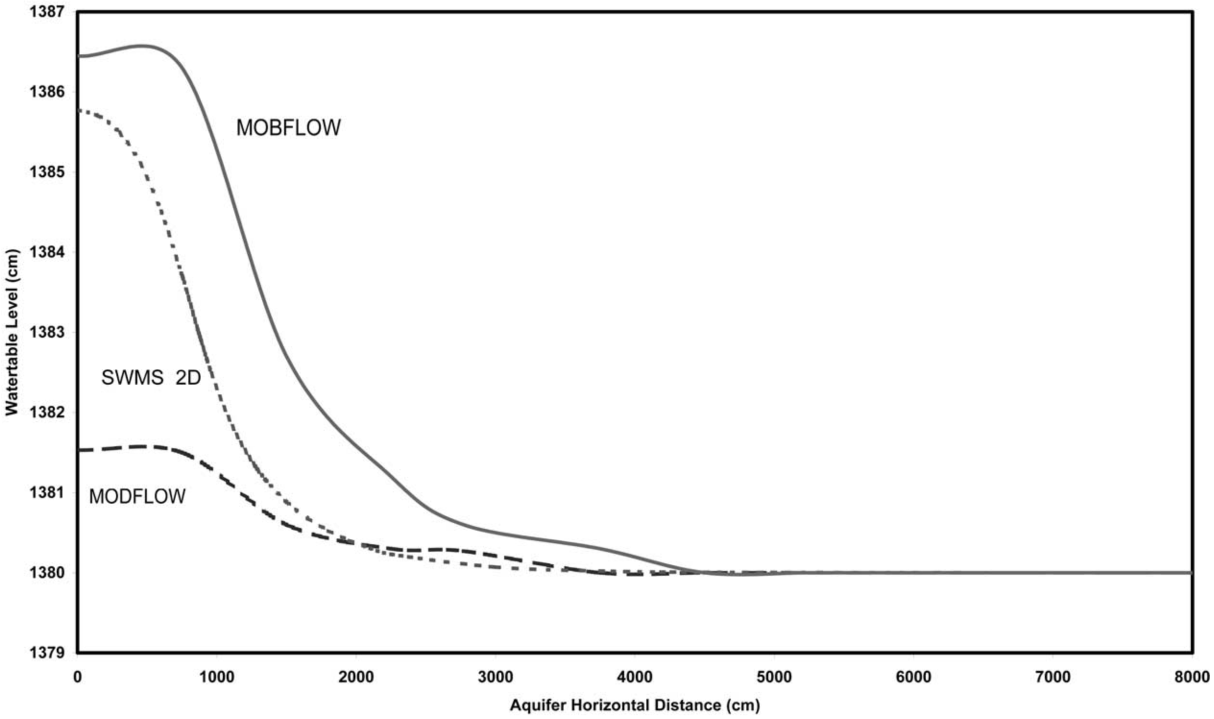

Fig. 12. Water table behaviour from MODFLOW, SMWMS_2D and MOBFLOW models (reference case).

computes it as 20 801 $cm^3 d^{-1} cm^{-1}$. Note that the MODFLOW estimate is less than one-third of that estimated by the variably saturated code, so the difference is substantial.

The influence of the seepage on the position of the water table level in a stream–aquifer system estimated by the different modelling approaches is shown in Fig. 12. It shows the water table behaviour for disconnected deep water table conditions (case 4 of Fig. 2) calculated by the three programs. The water table elevations are calculated for the reference simulation aquifer at underlying head of 1380 cm. Due to the underestimation of stream seepage by MODFLOW, water table levels calculated by it for the area underneath the streambed are lower than those calculated by SWMS_2D. The greatest

Table 5

Summary of simulation results from SWMS_2D, MODFLOW and MOBFLOW (Q_{IDS}: incipient disconnection seepage ($cm^3 d^{-1} cm^{-1}$), Q_{MIS}: maximum incipient seepage ($cm^3 d^{-1} cm^{-1}$), h_{mis}: maximum suction head at the base of the clogging layer (cm), H_{shw}: maximum height of shallow water table (cm))

Case no.	SWMS_2D				MOBFLOW				MODFLOW
	Q_{IDS}	Q_{MIS}	h_{mis}	H_{shw}	Q_{IDS}	Q_{MIS}	h_{mis}	H_{shw}	Q_{MIS}
1	10 961	20 801	84.5	1808.9	10 825	22 046	81.6	1832.4	6750
2	11 725	16 899	59.9	1830.9	11 195	17 453	57.1	1856.9	6750
3	17 568	26 433	82.0	1750.3	16 238	27 126	78.7	1835.3	12 375
4	20 387	39 718	76.6	1838.4	20 863	41 041	73.4	1840.6	13 500
5	20 250	38 475	77.6	1839.9	20 863	39 916	73.4	1840.6	12 375
6	8890	15 259	64.4	1749.0	7882	18 192	61.0	1853.0	6750
7	2316	4424	107.4	1816.9	2232	5127	100.7	1813.3	1350

disparities occur directly under the streambed and decrease and vanish towards the ends of the flow domain. This is clearly attributed to the greater incoming seepage from the stream in this area.

It is worth mentioning that MODFLOW would yield equal and constant maximum seepage flows for different aquifer materials for a given stream stage, clogging layer material and thickness and domain geometry since they would be calculated from Eq. (2), and this is obviously unrealistic.

6.4. Comparison of SWM_2D, MODFLOW and MOBFLOW

The newly proposed code MOBFLOW and the original MODFLOW are compared to the variably saturated code SWMS_2D. The comparative simulation results of the three codes are shown in Table 5 and in the accompanying figures. Steady state seepage flow is plotted vs. aquifer water table estimated by SWMS_2D, MODFLOW, and MOBFLOW in Fig. 11 for the reference simulation case. The seepage flow from MOBFLOW matches very well with that of SWMS_2D in all stages and is an improvement over MODFLOW. The main difference is that, MOBFLOW takes account of suction heads at the base of the clogging layer when the water table drops below the streambed level and continues to respond to water table changes until deep water table conditions are reached. The maximum seepage flow computed by MOBFLOW is 22 050 $cm^3\ d^{-1}\ cm^{-1}$ with a maximum suction head of 81.6 cm, whereas the actual value computed by SWMS_2D is 20 801 $cm^3\ d^{-1}\ cm^{-1}$ with a maximum suction head of 84.3 cm. The corresponding MODFLOW value, 6750 $cm^3\ d^{-1}\ cm^{-1}$, seriously underestimates the maximum seepage. The relatively small, 6%, overestimation by MOBFLOW of the maximum incipient seepage, which could be due to the approximations used in representing the soil properties and evaluating the suction head, is definitely better than the 67.5% underestimation by MODFLOW. Therefore, the improvement achieved by the proposed method is valuable, and may be especially important when the groundwater model is calibrated when the stream and aquifer are connected and used when the systems are disconnected.

Fig. 12 shows the water table behaviour obtained by the three models for the reference simulation case at aquifer head of 1380 cm. The MOBFLOW water table curve is close to that of SWMS_2D, especially directly below the stream. The MODFLOW curve is quite different and shows much less mounding. There is a slight overestimation by MOBFLOW compared with SWMS_2D, which could be explained by the approximations used in determining h_{mis}. Again, the improvement here is a direct result of accounting for suction head effects. All the three methods yield almost the same water table level at distance away from the stream.

The test for the effect of aquifer material is conducted here to assess the performance of the proposed code, MOBFLOW, on predicting seepage flow for the three different aquifer materials already discussed. The three aquifers give different seepage flow-head curves for both connected and disconnected conditions, including different points of maximum incipient seepage attained in each case, see Fig. 10. This is in stark contrast to MODFLOW's expected estimates based on Eq. (2). Thus, the proposed MOBFLOW is capable of accounting for different aquifer materials especially during disconnection.

7. Conclusions

This paper assesses the main factors influencing stream–aquifer seepage for a loosing-stream with a clogged layer using a variably saturated flow code with the purpose of producing a simple technique to improve the current status of modelling stream–aquifer seepage in conventional saturated models.

Simple numerical approaches for modelling stream–aquifer interactions through clogging layers have been reviewed and the differences between them have been evaluated. The most commonly used technique tends to underestimate stream losses because it ignores suction heads below the clogging layer.

Aquifer material properties strongly affect seepage flow rates in all stages of stream–aquifer relationships. These effects become very obvious when the stream disconnects from the aquifer. Therefore, seepage from a disconnected stream cannot be determined correctly unless the unsaturated hydraulic properties of the aquifer and clogging layer, and the stream water level are known.

Previously used saturated flow approaches seriously underestimate stream losses, hydraulic heads and water table levels for disconnected conditions. It is the inability of the conventional saturated codes to accurately estimate the stream losses that is the major cause of disparities between SWMS_2D and MODFLOW in estimating seepage flows and water levels.

The improved MODFLOW code, MOBFLOW, gives stream seepage and water table levels that match very well with those from the variably saturated flow code SWMS_2D. Therefore, it could be used in simulating stream–aquifer systems, especially when the stream disconnects from its adjacent aquifer.

Acknowledgments

The authors would like to thank Dr Jirka Simunek of the US Salinity Laboratory for providing the SWMS_2D code. The constructive criticisms and comments made by Prof. Ken Rushton, Birmingham University, and the anonymous reviewers are highly appreciated by the authors. Finally, the first author would like to acknowledge the financial support he received from the Centre for Water Resources Research, UCD, during his PhD course.

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