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An Adapted DRAIN Package for SEEPAGE Problems

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ABSTRACT

The estimation of the location of actual and potential groundwater discharge areas is a key aspect in the protection and (re)development of groundwater dependent wetlands. Groundwater discharge areas can be simulated in MODFLOW by using the DRAIN Package. In possible groundwater discharge areas the drain level will be set to the topography, while the conductance will be set to an arbitrary high value. However, conceptual and practical problems, like e.g. free water table above the land surface, difficult parameterization of the conductance and high water balance errors, arise in the calculation of the groundwater discharge by the DRAIN Package. These problems are demonstrated by simulation of a simple groundwater discharge area test case.

To overcome these problems a new SEEPAGE Package is proposed. The basic idea of this package is an adaptable constant head cell. This type of cell is a variable head cell unless the groundwater rises above the seepage level in which case the cell becomes a constant head cell. The groundwater discharge out of a seepage cell is calculated on the basis of the water balance with the neighboring cells. Seepage level input to the package can be in different formats, e.g. as matrix useful for digital terrain models.

The calculation and input procedures are described and advantages over the DRAIN Package are explained. The package calculates accurately groundwater discharge areas as is discussed by simulation of the test case. The package can be used in situations where an upper boundary for a free water table is appropriate. It is further useful for identification of groundwater discharge, intermediate and recharge areas.

INTRODUCTION

Our current understanding of wetlands is insufficient to assess the effects of past and future wetland loss. While knowledge of wetland hydrology is crucial, groundwater flows are often neglected or uncertain (Hunt et al., 1996). Groundwater inflows to wetlands can be estimated by traditional Darcy's law calculations, stable isotope mass balances, temperature profile modeling and numerical water balance modeling (Hunt et al., 1996). Stoertz and Bradbury (1989) use the budget calculation of MODFLOW on an interpolated grid of a densely measured groundwater head field (all cells are set to constant head cells) to estimate the recharge and discharge areas.

Batelaan et al. (1993) describe a groundwater model for identification of seepage towards wetlands. The developed quasi 3-D groundwater model has as main characteristic that the groundwater table in the unconfined aquifer can not rise above a maximum allowed level. This upper boundary condition is implemented in the successive overrelaxation solver by checking if every newly calculated head rises above this level. In that case the head will be reset to that level. The maximum allowed level could be the land surface or a land surface minus average unsaturated zone in case of the presence of a dense ditch network. On basis of the calculated groundwater head a separation can be made in infiltration, intermediate and discharge areas. Infiltration areas are where the groundwater table is below the maximum allowed level. Intermediate or mixed areas are located where the groundwater table is equal to the maximum allowed level, but where there is still a vertical downward flux. So, in intermediate areas part of the recharge infiltrates and the remaining runs off. In groundwater discharge areas the groundwater table is equal to the maximum allowed level and there is an upward seepage which together with recharge results in the production of surface runoff.

The following conversation, question and reply, on the GMS Mailing List (Froukh, 1998 and Daehler-Wilking, 1998, respectively) shows clearly the inconvenience people feel with the MODFLOW concept towards the upper level of an unconfined aquifer.

> Question: In case of confined aquifer the top and bottom elevations are top of aquifer and bottom of aquifer. But if the aquifer is unconfined, what does the top elevation correspond to?
>
> Reply: In this case, the top elevation of the layer refers to the level of the soil surface, but IS NOT USED by MODFLOW! (Professionals: Please correct me if I'm wrong!) MODFLOW simply assumes that the soil in the top unconfined layer extends upward to infinity. The result of this is that if your model leads to heads that lie above the soil surface (that is, if your model predicts ponding), then the degree of ponding is over-stated by a factor of 1/porosity. You may wonder why MODFLOW makes such a fundamental mistake. I think the reason is that MODFLOW does exactly what it says it does: it models the saturated zone and nothing else.

DRAIN PACKAGE

The DRAIN Package is designed to simulate the effects of features such as agricultural drains, which remove water from the aquifer at a rate proportional to the difference between the head in the aquifer and some fixed head or elevation. The drainage continues as long as the head in the aquifer is above that elevation, but ceases if the head falls below that level. The functioning of the DRAIN Package is described by the equation pair (McDonald and Harbaugh, 1988):

$$QD_{i,j,k} = CD_{i,j,k}(h_{i,j,k} - d_{i,j,k}) \quad \text{for} \quad h_{i,j,k} > d_{i,j,k} \tag{1}$$

$$QD_{i,j,k} = 0 \quad \text{for} \quad h_{i,j,k} \leq d_{i,j,k} \tag{2}$$

Where $QD_{i,j,k}$ is the discharge from cell i,j,k into the drain, $h_{i,j,k}$ is the calculated head in cell i,j,k and $d_{i,j,k}$ is the drain elevation. The coefficient $CD_{i,j,k}$ is a lumped conductance describing all of the head loss between the drain and the region of cell i,j,k in which the head $h_{i,j,k}$ is assumed to prevail. The head losses are caused by convergent flow towards the drain, flow through the backfill material of the drain and flow through the wall of the drain.

Anderson and Woessner (1992) state that springs and seeps can normally be simulated with the DRAIN Package, by considering the elevation of the spring or seep, as it emerges at the land surface, as elevation of the drain. Also, diffuse flows, such as seepage to wetlands, could be simulated by specifying drain nodes in the area where seepage is likely to occur. The drain nodes will be activated only when the head in the aquifer equals or exceeds the land surface elevation. Conductance terms could be calculated from field-measured discharges and heads or estimated during model calibration. Examples of using MODFLOW's DRAIN Package to represent seepage to wetlands can be found in Patrick et al. (1989), Toran and Bradbury (1988) and Yager (1987).

To show the ability of MODFLOW's DRAIN Package to simulate seepage to wetlands, the following test case will be considered. Figure 1 shows the cross-sectional flow domain of length $L = 200m$, with a linear sloping land surface from $22m$ to $20m$ (slope is denoted by $-a$). The phreatic aquifer consists of one layer with a homogeneous isotropic conductivity ($K = 1m/d$) and impervious bottom and sides (water divides). The aquifer receives a constant recharge of $R = 1.5mm/d$ and any excess water on the land surface is assumed to runoff. Therefore, in the higher reach of the aquifer, the water table, h, will be lower than the land surface, and all recharge will infiltrate. But in the lower reach of the aquifer the water table will coincide with the land surface, and recharge together with seepage will run off. In view of the fact that the horizontal dimension is much larger than vertical dimension, the groundwater flow can be considered as predominantly

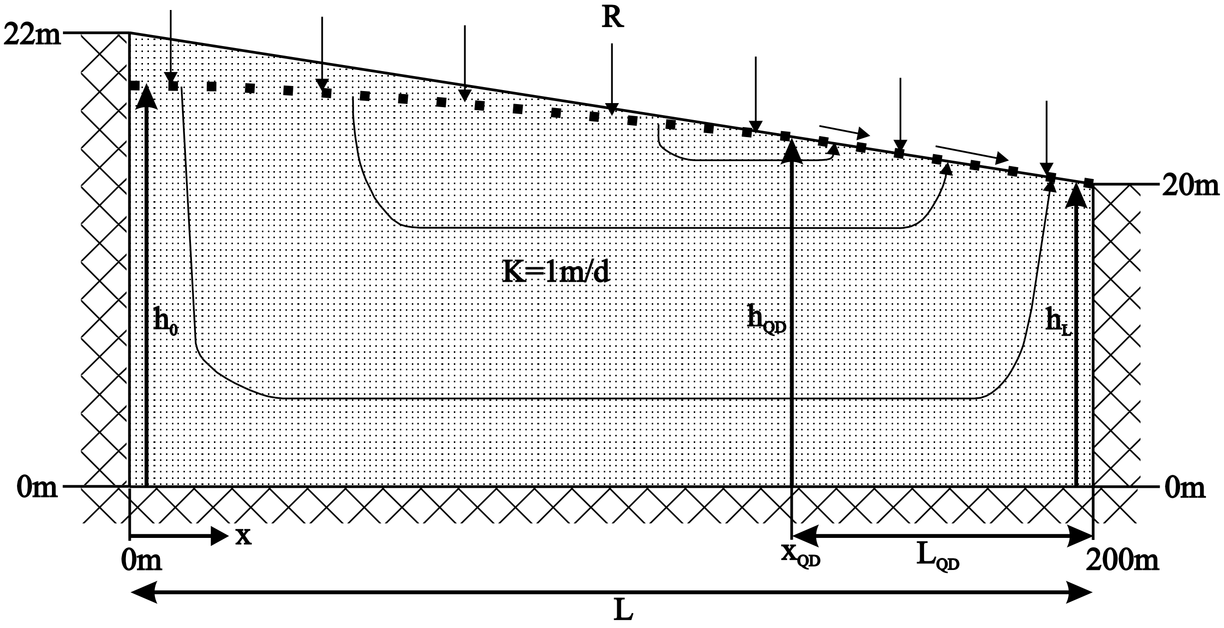

Figure 1: Cross-sectional flow to a groundwater discharge area

horizontal. Hence, under the Dupuit assumption the flow through any vertical section at position x is given by:

$$q = -Kh\frac{dh}{dx} \tag{3}$$

where q is the discharge per unit width, which is also equal to the recharge amount over length x in the infiltration area. Along the length of the groundwater discharge area, L_{QD}, the slope of the water table is $dh/dx = -a$. Hence, at the boundary between infiltration and discharge areas, the following equations apply:

$$h_{QD} = h_L + aL_{QD} \tag{4}$$

$$R(L - L_{QD}) = Ka(h_L + aL_{QD}) \tag{5}$$

or,

$$L_{QD} = \frac{RL - Kah_L}{R + Ka^2} \tag{6}$$

where h_L is the water table elevation at $x = L$, and h_{QD} at the boundary between discharge and recharge zones. Substituting the values in equation (6) results in a length for the groundwater discharge area of $L_{QD} = 62.5m$. By integrating Dupuit's equation (3) and finding the integration constant from $x_{QD} = 137.5m$ with water table level $h_{QD} = 20.625$, the maximum height of the parabolic water table at $x = 0$ can be calculated as $h_0 = 21.3m$.

To simulate this problem with MODFLOW a one layer model is set up, with cells of 1 by $1m$ arranged in one row and 201 columns. The lower and side boundaries are no-flow and the top receives a recharge of $1.5mm/day$. The initial head is taken as $22.0m$. Several cases were considered as shown in Table (1). In the first seven cases the DRAIN Package was used to simulate the seepage with the drain level set equal to the topography and assuming different conductances. Case 1 and 4 are performed with standard MODFLOW88 (McDonald and Harbaugh, 1988) as is implemented in GMS version 2.1. Case $2,5$ and 6 are run with MODFLOW96 version 3.2 (Harbaugh and McDonald, 1996a). Case 3 and 7 are tested with a double precision version of MODFLOW96. In all cases the solution was obtained with the PCG2 solver (Hill, 1990) with maximum 50 inner iterations and head change and residual criterion for convergence set to 10^{-5}. Under the section Discussion the results of the different cases are compared.

SEEPAGE PACKAGE

Batelaan et al. (1993) developed a technique for simulation of discharge and infiltration areas. However, due to the grouping of hydrological boundary conditions in different MODFLOW packages, a direct implementation in MODFLOW was not feasible. Therefore, a new SEEPAGE Package, based on the DRAIN Package, was developed. In this SEEPAGE Package the free water table will be limited to a maximum allowed level, e.g. the land surface, and when the water table becomes equal to this level it will calculate the groundwater discharge (seepage) to the surface.

Table 1: Test cases for DRAIN and SEEPAGE Packages

CASE #	MODFLOW	PREC.	COND.	L_{QD}	h_0	W.B. ERR.	ITER.
1	DRAIN-88	single	$1000m^2/d$	-	no conv.	-	1000
2	DRAIN-96	single	$1000m^2/d$	$63+1m$	$21.31m$	-9.18%	199
3	DRAIN-96	double	$1000m^2/d$	$63+1m$	$21.31m$	0.00%	187
4	DRAIN-88	single	$100m^2/d$	$63+1m$	$21.31m$	1.19%	113
5	DRAIN-96	single	$10m^2/d$	$64m$	$21.31m$	0.10%	59
6	DRAIN-96	single	$1m^2/d$	$67m$	$21.31m$	0.02%	29
7	DRAIN-96	double	$1m^2/d$	$67m$	$21.31m$	0.00%	29
8	SEEP-96	double	N.A.	$63-1m$	$21.31m$	0.00%	279
9	SEEP-96	single	N.A.	$63-1m$	$21.31m$	0.00%	279
10	SEEP-96	single	N.A.	$72m$	$21.32m$	0.00%	233

The procedure which is followed (Streng and van Ellen, 1997) is that for every defined SEEPAGE cell the calculated head is checked whether it is equal or above the SEEPAGE level. If this is the case then the flux in or out of the cell is calculated according Equation (7).

$$QD_{i,j,k} = \sum_{n=1}^{nn} CD_n(h_{i,j,k} - h_n) \tag{7}$$

where $QD_{i,j,k}$ is the flux in or out of the cell i,j,k, nn is the number of neighbor cells of cell i,j,k, CD_n is the conductance between cell i,j,k and its neighbor n and $h_{i,j,k}$ and h_n are the hydraulic heads in cell i,j,k and n, respectively. If the flux is negative, i.e. groundwater leaves the cell, then the cell is turned into a constant head cell. If the flux is positive but smaller than an available recharge then the cell is intermediate, part of the recharge infiltrates while the rest runs off. An intermediate cell is also turned into a constant head cell. If the flux is equal or bigger than the recharge then the cell is turned into a variable head cell. Every iteration this checking is repeated, constant head SEEPAGE cells are not skipped, hence they can become variable again. After convergence the budget for every SEEPAGE cell is calculated. Groundwater discharge areas are easily recognized as SEEPAGE cells with negative fluxes (outflow). Intermediate cells appear in the budget with positive SEEPAGE fluxes. Infiltration areas have zero fluxes.

Since this SEEPAGE Package was based on the DRAIN Package (version 5), it is completely compatible with its parent. This means that DRAIN datafiles, MODFLOW88 or MODFLOW96 type, can be used by the SEEPAGE Package. In that case the defined conductance will be ignored. Additionally, SEEPAGE can receive matrix type of input by defining a mask and a seepage level matrix. If the mask value is bigger than 0 the SEEPAGE level will be activated.

In order to check the functioning of this SEEPAGE Package, the test problem of Figure (1) was simulated with SEEPAGE for three cases (8, 9 and 10, Table 1). Case 8 uses MODFLOW96 version 3.2 (Harbaugh and McDonald, 1996a) in double precision. Case 9 is tested with single precision (standard version). In case 10 a model with 22 layers, as in Streng and van Ellen (1997), was used to simulate the test problem. The layers are horizontal and have a vertical dimension of $1m$. In all cases the head change and residual criterion for convergence was set to 10^{-5}.

DISCUSSION

Based on the description of the DRAIN Package (McDonald and Harbaugh, 1988) it is clear that it was not meant for application of seepage problems towards wetlands. Since often the location of the groundwater discharge areas are not known a priori and measurements of the groundwater discharge to wetlands are very difficult, it is not feasible to parameterize the conductance term in the DRAIN Package. Therefore, in the SEEPAGE Package the more logical assumption is made to have no specific resistance connected to diffuse seepage of groundwater to wetlands.

A common misunderstanding of the DRAIN Package is that it drains when the water table equals or exceeds the land surface. In reality it starts to drain when the water table is slightly above the drain level. Conceptually, it is more appealing to limit the groundwater level to a maximum (e.g. land surface). Therefore, in the SEEPAGE Package a maximum allowed groundwater level is introduced, similar to the rising water table option in AQUIFEM-1 (Townley and Wilson, 1980). The method of calculation of the position of the free water table is not rigorously solved in MODFLOW or in SEEPAGE (Anderson and Woessner, 1992). No deformation of the grid with the moving water table is allowed and no nodes are fixed along the water table as e.g. is implemented in AQUIFEM-N (Townley, 1990). However, Potter and Gburek (1986) showed that incorporating a seepage face into a solution based on Dupuit assumptions, like in SEEPAGE, is theoretically justified.

Comparing the different test DRAIN cases (Table 1) shows that all single precision MODFLOW cases (no. $1,2,4$, 5 and 6) have too high water balance errors. This is caused by the very small head differences between the calculated groundwater level and the DRAIN level. This single precision accuracy problem is also notified by the compiler message ’IEEE floating-point exception flags raised: inexact; underflow;’. The water balance error is the result of the accumulation of this inaccurate head difference times the conductance value. Smaller conductance values (case $4,5$ and 6) cause bigger head differences resulting in smaller water balance errors. However, the head rises up to $4cm$ above the drain level (case 6) and the groundwater discharge length (L_{QD}) becomes too big. Harbaugh and McDonald (1996a and 1996b) recognized the limitations of a single precision budget calculation in MODFLOW88. The budget calculation of the DRAIN Package in MODFLOW96 is improved to double precision (see improvement from test case 1 to 2). However, this cannot resolve all inaccuracies in the water balance calculations (case $2,5$ and 6). Therefore, it is necessary to fully convert the model to double precision (Harbaugh and McDonald, 1996a). Case 3 and 7 show that indeed the water balance errors are resolved in MODFLOW96 if the complete model is converted to double precision.

In case $2,3$ and 4 the last node at which the DRAIN Package shows groundwater discharge is at $L_{QD} = 63m$. However, with 4 digits significance the node at $L_{QD} = 64m$ also shows a head equal to the drain level. Case $5,6$ and 7 result in a bigger error of the groundwater discharge length compared to the analytical solution ($L_{QD} = 62.5m$), due to the lower conductances. From the seven DRAIN cases it is concluded that the DRAIN Package has serious problems (convergence, water balance errors and too big groundwater discharge lengths) in the simulation of seepage to wetlands. If the DRAIN Package is used, a completely to double precision converted MODFLOW model should be used.

Test case 8 and 9 show that both the double and the single precision version of MODFLOW96 with the SEEPAGE Package have no water balance budget problems. The last node at which groundwater discharge occurs is at $L_{QD} = 62m$. But, the water budget of the node at $L_{QD} = 63m$ shows a positive flux, i.e. part of the recharge infiltrates, the remaining runs off. Hence, the cell at $L_{QD} = 63m$ is an intermediate cell. It can be concluded that with the SEEPAGE Package an accurate groundwater discharge length and water balance can be obtained in single precision. The penalty for it is the higher required number of iterations. All DRAIN and SEEPAGE test cases accurately calculate head h_0.

A multi-layer version of the test case problem (Figure 1) was analyzed by Streng and van Ellen (1997). They used two models, a finite element model, with an adaptable mesh, and MODFLOW88, with a similar adaptation as in the SEEPAGE Package. By comparing the results from these two models they showed that the groundwater discharge length is between $70 - 72m$. Test case 10 shows that the discharge length, simulated with the SEEPAGE Package, is $72m$ (Table 1). The budget calculations of SEEPAGE reveal that between $x = 128m$ (node where $L_{QD} = 72m$) and $x = 144m$ (node where $L_{QD} = 56m$) there is an intermediate area. Hence the water table is equal to the land surface, but part of the recharge infiltrates.

The input to the SEEPAGE Package is also improved over the DRAIN Package because not only list type but also matrix type of input is possible. This allows to use digital terrain models with the package as upper limit of the unconfined aquifer. The results of the SEEPAGE budget will show the location of groundwater discharge, intermediate and recharge areas.

The SEEPAGE Package is useful as upper limit for an unconfined aquifer, as identification tool for estimation of recharge, intermediate and discharge areas, and for hypothesis testing of groundwater discharge to actual or potential wetlands. The SEEPAGE Package, with documentation, is available from: `http://homepages.vub.ac.be/˜batelaan/`

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