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Numerical investigation of lake bed seepage patterns: effects of porous medium and lake properties

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Abstract

Three-dimensional steady-state numerical models were used to investigate the relative significance of several factors controlling lake bed seepage patterns: lake depth, lake bed slope, orientation of an asymmetric lake with respect to a regional hydraulic gradient, lake bed sediments, and heterogeneity and anisotropy of the porous medium. We considered both inflow and flow-through lakes, and our focus was on the details of seepage flux at the lake bed (not on the surrounding porous medium).

While porous medium factors (anisotropy and heterogeneity) are important, we found several conditions where lake bed factors were nearly as important in controlling the distribution of seepage. Varying lake bed slope from 0.013 to 0.04 in different simulations had a significant effect on shoreline seepage (rates were 10–40% higher for lakes of low slope than lakes of steep slope). Also, significantly elevated seepage (in some cases, a local maximum) was observed offshore at the break in bed slope between the sloping side and flat central portions of the lake bed, whenever the surrounding porous medium had a high anisotropy (1000 or 100). For flow-through lakes in media of high anisotropy, the annual volume of groundwater inseepage was significantly higher (about 20%) in lakes with steep bed slope compared to those with low slope; this effect of slope was smaller at lower anisotropy. For an asymmetric flow-through lake (a lake with a steep bed slope on one side, moderate slope on the other) the percentage of lake bed experiencing inseepage was greatest when the steep side was downgradient, and the effect was larger at higher anisotropy. These effects illustrate the complex interaction between lake bed slope and the anisotropy of the surrounding porous medium in controlling lake:groundwater exchange.

Adding low-conductivity lake sediments, and decreasing their conductivity, shifted groundwater seepage further offshore in inflow lakes; increasing the anisotropy of the surrounding porous medium had the same effect. Adding sediments and increasing anisotropy also decreased nearshore seepage in flow-through lakes, but without increasing offshore seepage; in this case, the net effect was a smaller annual volume of lake:groundwater exchange. At the same time, the percentage of the lake bed experiencing inseepage increased in flow-through lakes, even as the annual volume of inseepage was decreasing. Thus, for flow-through lakes, a larger area of inseepage may not be a good indicator of a greater volume of inseepage. Lake depth did not have a significant effect on the quantity or distribution of seepage to inflow or flow-through lakes. Many of the physical factors investigated here influence the amount of lake:groundwater exchange and the proportions of nearshore and offshore seepage; therefore, they are potentially significant to lake water quality and ecology in addition to hydrology.

Keywords: Lake; Groundwater; Seepage; Hydrology; Surface water; Aquifer

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1. Introduction

There is a significant body of field data and numerical results indicating the importance of groundwater exchange between lakes and their surrounding porous media. Many studies have quantified rates or volumes of water exchange (Motz, 1998; LaBaugh et al., 1997; Harvey et al., 1997a; Corbett et al., 1997; Lesack and Melack, 1995; Wentz et al., 1995; Shaw and Prepas, 1990b; Krabbenhoft et al., 1990a), while others have documented lake:groundwater exchange of solutes as well as water (Schafran and Driscoll, 1993; Cherkauer et al., 1992; Krabbenhoft and Babiarz, 1992; Pollman et al., 1991; Kenoyer and Anderson, 1989). Other studies have focused on the physical dynamics of lake:aquifer exchange (Yechieli et al., 1995; Cheng and Anderson, 1994; Nield et al., 1994; Cherkauer and Hensel, 1986; Winter, 1983, 1978), detection of lake water in the groundwater downgradient of a lake (Katz et al., 1997; Yehdegho et al., 1997; Isiorho et al., 1996; Krabbenhoft and Webster, 1995; Katz et al., 1995; Darling et al., 1990; Krabbenhoft et al., 1990b), or new field or computer techniques (Isiorho and Meyer, 1999; Harvey et al., 1997b; Cheng and Anderson, 1993; Cherkauer and McBride, 1988).

A few studies have focused on spatial patterns of lake bed seepage. Several studies have noted an exponential decrease in seepage rate with increasing distance offshore, including McBride and Pfannkuch (1975), Pfannkuch and Winter (1984), Cherkauer and Zager (1989), and Shaw and Prepas (1990a,b). Other fieldwork documents deviations from the simple exponential decrease, involving local offshore seepage maxima (e.g. Cherkauer and Nader, 1989). Schafran and Driscoll (1993) make the connection between lake bed seepage pattern and lake chemical budgets by showing that seepage further offshore in a small lake in the Adirondack Mountains was higher in pH and alkalinity than seepage near shore. This is consistent with the deeper, longer subsurface flowpath followed by offshore seepage, as suggested by model studies (e.g. Winter, 1978).

Some studies have shown that lake bed seepage is influenced by the heterogeneity and anisotropy of the porous medium surrounding the lake and the heterogeneity of lake bed sediments. However, lake characteristics such as depth, bed slope, or sediments have received little attention. The goal of the work presented here is to evaluate the relative significance of lake and porous medium characteristics in controlling spatial patterns of lake bed seepage. Thus, our focus was on the details of water flux at the lake bed, as opposed to head and flow distributions in the surrounding porous medium. The method used was steady-state three-dimensional (3D) numerical modeling of both inflow and flow-through lakes. The models used did not allow for consideration of transient seepage effects associated with recharge events and shifting stagnation points near flow-through lakes (e.g. Winter, 1983). Again, our goal was not construction of the most complex and realistic lake:aquifer model possible; the objective was to assess the relative sensitivity of lake bed seepage patterns to different lake and porous medium properties, varying all these properties in a consistent set of simulations.

2. Models

Three-dimensional models of lake interaction with an unconfined porous medium were set up using the finite difference numerical groundwater flow code MODFLOW (e.g. McDonald and Harbaugh, 1988). In each model a circular lake occupied the center of a rectangular model domain. The model domain contained 15 layers, and either 60 rows and 60 columns (the "coarse grid") or 120 rows and 120 columns (the "fine grid"). In all the cases, the diameter of the lake in the uppermost model layer (where the lake was widest) was 1/3 the horizontal dimension of the model domain (i.e. 20 cells and 40 cells for coarse and fine grid models, respectively).

While numerical model grid spacings are unitless and not linked to any particular "real-world" sizes, we adopted and use here a consistent set of lengths that makes the connection between our simulations and realistic dimensions for small natural lakes: we refer to the model domain as being $6000 \times 6000\ m^2$, and the lakes as 2000 m in diameter across their surface. Thus, grid cells were 100 m on a side in the coarse grid, 50 m in the fine grid. In all cases, the model domain was 50 m thick from the top of the lake to the bottom of the domain, and any model layer penetrated by the lake was 2 m thick. Thus, models with shallow lakes (10 m deep) consisted of five 2 m layers overlying ten 4 m layers, and models with deep lakes

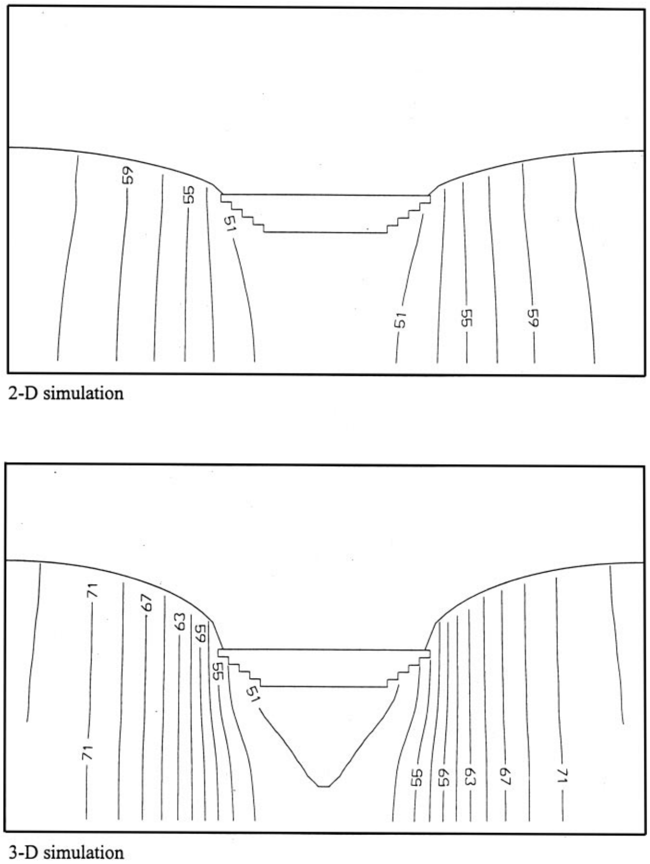

Fig. 1. Vertical cross-sections through the centers of 2D and 3D models with shallow inflow lakes of moderate slope. The lake outline is shown in the center of each cross-section. Contour lines are groundwater equipotentials, labeled with head values in meters (lake head = 50 m, elevation head = 0 at the base of the model domain). Anisotropy ratio R (ratio of horizontal to vertical hydraulic conductivity) is 100 in both models. The figure has substantial vertical exaggeration.

(20 m deep) consisted of ten 2 m layers overlying five 6 m layers. In all models, all grid cells defining the lake itself were assigned a constant head of 50 m. Horizontal hydraulic conductivity was set at 1 m/day, typical of medium to fine sand (e.g. Freeze and Cherry, 1979). The lake dimensions and porous medium thickness and conductivity are representative of small lakes and surficial deposits in many areas of North America and elsewhere. Vertical hydraulic conductivity ranged from 1 to 0.001 m/day, to allow porous medium anisotropy ratios (R) from 1 (isotropic) to 1000 (the same value used by Winter, 1978).

Two hydrogeologically different types of lake were simulated: inflow lakes which received groundwater inflow from all directions (the lake sat in a closed hydrologic basin and had the lowest head in the model domain) and flow-through lakes which sat in a regional groundwater flow gradient and experienced inseepage on one side (the upgradient side) and outseepage on the other. Inflow lake models were established with constant recharge on the top surface of the model domain (10 cm/yr, except for a few simulations with 20 cm/yr) and impermeable boundaries on the other five sides of the domain (bottom and four vertical sides). Thus, inflow lake models had one source of water (recharge) and one sink (seepage into the lake), as would a real inflow lake. Flow-through lake models were set up with no recharge, constant

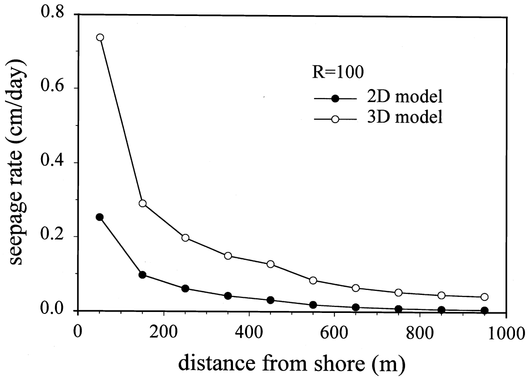

Fig. 2. Lake bed seepage rate vs. distance from shore for shallow inflow lakes of moderate slope in 2D and 3D models, $R = 100$. Seepage plots for inflow lakes need only span half the lake diameter (1000 m, shore to lake center) because of the radial symmetry in these lakes.

head on two opposing sides of the model domain (65 m on one, 35 m on the other, for an overall horizontal hydraulic gradient of $30/6000 = 0.005$ across the domain), and impermeable boundaries on the other two vertical sides and the bottom of the domain. There were two sources and two sinks for water in the porous medium in flow-through lake models: seepage out of the lake and seepage across the upgradient domain boundary were the sources, and the sinks were seepage into the lake and seepage across the downgradient domain boundary.

The aquifer:lake models were used to investigate the relative magnitude of effects on lake bed seepage distribution from varying:

- lake characteristics (depth, bed slope, low conductivity sediments, and orientation of an asymmetric lake bed with respect to a regional groundwater gradient);
- aquifer characteristics (anisotropy and heterogeneity).

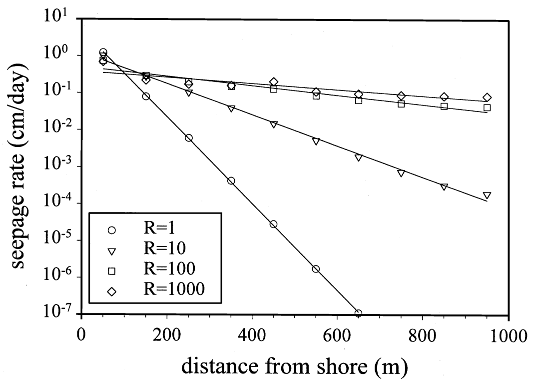

Fig. 3. Semi-log plot of lake bed seepage rate vs. distance from shore for shallow inflow lakes of moderate slope in porous media of different anisotropy.

3. General checks of model performance

Results from a two-dimensional (2D) vertical section model with a shallow inflow lake were compared to those from the analogous 3D model described above. The 3D model showed higher head values and lake bed seepage rates than the 2D model (Figs. 1 and 2), mainly because of the higher ratio of recharge area A_R to discharge area A_D (A_R/A_D was 10.6 for the 3D model and 2 for the 2D model). Given the same linear recharge rate (10 cm/yr), the higher A_R/A_D of the 3D model led directly to higher lake bed seepage rates, which in turn required higher groundwater heads and hydraulic gradients in the groundwater. The difference between the two models is especially apparent near the shoreline, where lake bed seepage rate is about three times higher for the 3D model (similar results were found at R values of 1, 10, 100, and 1000). The observed differences between the two models are in accord with expectations based on physical reasoning and previous work (e.g. Winter, 1978), and suggest both models are operating correctly. All other analyses were based on 3D models.

Results from both 2D and 3D models show a rapid decline in seepage rate with distance offshore. The decline in an isotropic medium is precisely fit by an exponential function, and the fit is good but shows slightly more scatter as the medium becomes more anisotropic (Fig. 3). This exponential seepage pattern has been observed in previous model studies (e.g. McBride and Pfannkuch, 1975; Pfannkuch and Winter, 1984), suggesting the models used in the present study performed correctly.

Comparison between coarse and fine grid models showed only minor, insignificant differences, suggesting that either was adequate for

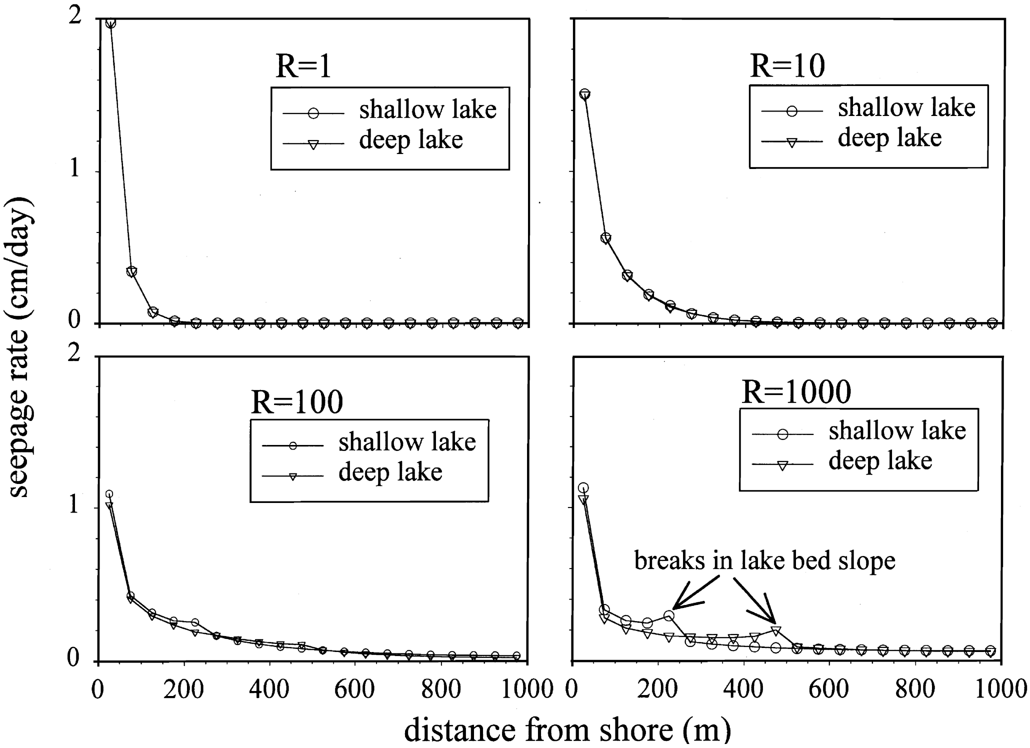

Fig. 4. Lake bed seepage rate vs. distance from shore for shallow and deep inflow lakes of steep slope in porous media of different anisotropy (R).

investigation of lake:aquifer interaction. Most of our analyses are based on fine grid models because they allow somewhat more flexibility and better resolution in setting up lakes of different shape.

Increasing recharge by a factor of two (from 10 to 20 cm/yr) in inflow lake models produced significant increases (15–20 m) in maximum groundwater head and lake bed seepage (seepage rates essentially doubled at all points on the lake beds). The higher head was required to move the greater water flux through the system, and the increased lake bed seepage indicates the models handled the additional recharge correctly. Taken together, this and the other points described above show that the models accurately reflect the basic physics of lake:aquifer interaction and can be used to assess the sensitivity of lake bed seepage patterns to changes in lake and porous medium properties.

4. Results: lake parameters

4.1. Lake depth

For inflow lakes, changing lake depth from shallow (10 m) to deep (20 m) had almost no effect on the maximum head in the groundwater system (i.e. head on the domain boundary in the uppermost layer, required by the boundary conditions to be the highest head in the model domain; see Fig. 1). The significance of maximum head for an inflow lake simulation is that the head was free to vary as parameters were changed in these simulations, and a higher head would indicate a greater resistance to flow through the system (with only the one exception mentioned in the previous section, each inflow lake simulation experienced the same recharge and hence the same total volumetric flux of groundwater; head adjusted to the level necessary to achieve this total flux).

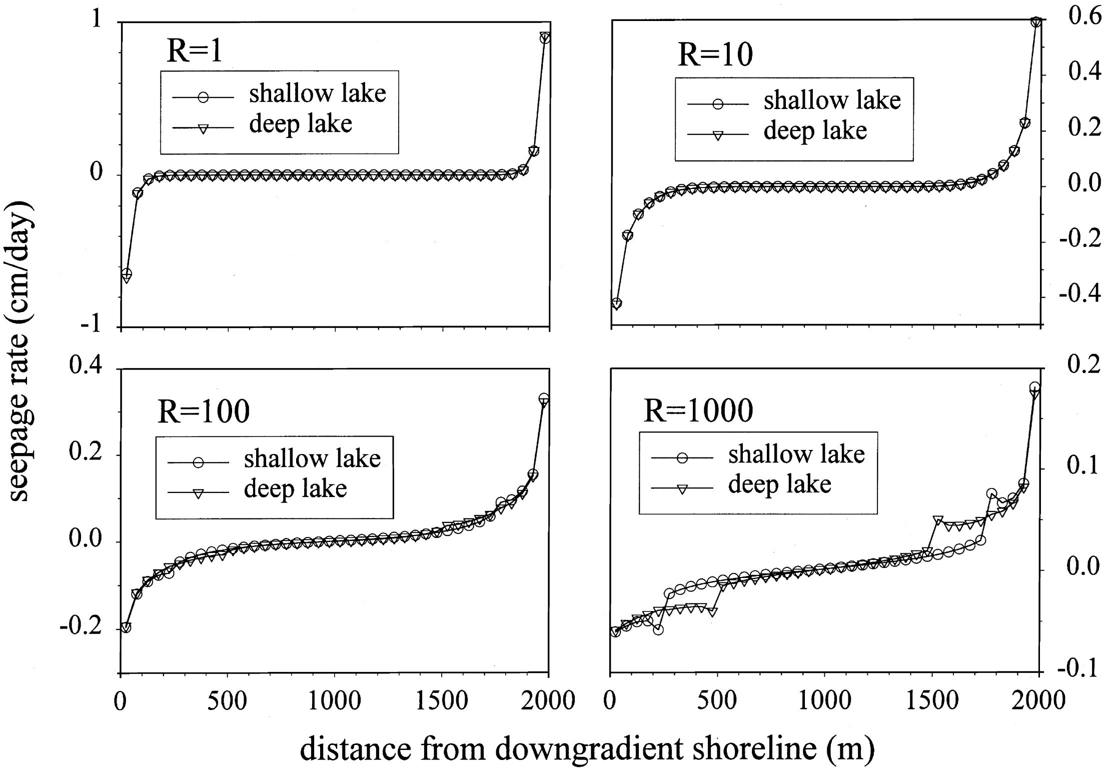

Fig. 5. Lake bed seepage rate vs. distance from the downgradient shore for shallow and deep flow-through lakes of steep slope in porous media of different anisotropy (R). This and other plots for flow-through lakes show the full lake diameter (2000 m) in a cross-section aligned with the regional groundwater flow gradient (groundwater flow from right to left).

Apparently changing lake depth did not affect the overall resistance to groundwater flow through the model domain.

Plots of seepage rate vs. distance from the shore were identical for deep and shallow inflow lakes in porous media of low or no anisotropy (Fig. 4); at higher anisotropy there were differences associated with locally elevated seepage found at breaks in lake bed slope, where the sloping sides met the flat (horizontal) center portions of the lake beds (Fig. 1). The break in bed slope occurred at the cell 200–250 m offshore for the shallow lake with steep slope and at 450–500 m offshore for the deep lake with steep slope. These cells showed significantly elevated seepage at $R = 1000$, and slightly elevated seepage at $R = 100$ (Fig. 4). Thus, while the shallow and deep inflow lakes had offshore seepage peaks at different places, the reason seems to be the difference in the location of the break in bed slope, not the difference in depth. At both $R = 100$ and $R = 1000$ the shallow lake had a shoreline seepage rate (points closest to shore in Fig. 4) about 7% greater than the deep lake; unlike the elevated seepage at the breaks in bed slope, this difference in shoreline seepage is probably associated directly with the difference in lake depth.

As for inflow lakes, shallow and deep flow-through lakes had differences in seepage distribution that increased with anisotropy and were associated more directly with breaks in lake bed slope than with lake depth (Fig. 5). Shallow and deep flow-through lakes had no significant difference in A_{IN}, the percentage of lake bed experiencing inseepage (Table 1). Also, these lakes experienced nearly identical integrated annual volumes of groundwater inseepage. However, when normalized by lake volume the deep flow-through lake experienced less groundwater exchange because its volume was about 15% greater (Table 1).

Table 1
Percentage of lake bed experiencing groundwater inseepage (A_{IN}) and annual inseepage as a percentage of lake volume (V_{IN}) for shallow and deep flow-through lakes of moderate bed slope, in porous media with different anisotropy ratios (R). Each entry has the form: A_{IN}, V_{IN}. A_{IN} was not available (NA) from models with $R = 1$ because seepage rates computed by MODFLOW for the center of the lake had absolute values less than 10^{-9} m/day and could not be reliably distinguished from zero. In this case it was impossible to accurately locate the inseepage–outseepage boundary in the center of the lake

Lake depth (m)	Lake volume (10^7 m^3)	Area and volume of groundwater inseepage			
		$R = 1$	$R = 10$	$R = 100$	$R = 1000$
10	1.832	NA, 2.37	52.4, 2.25	53.2, 1.82	55.0, 1.06
20	2.094	NA, 2.07	52.4, 1.98	53.2, 1.60	54.6, 0.95

This is one sense in which lake depth may influence lake water quality, through its effect on dilution and lake water residence time as opposed to a direct influence on the dynamics of lake bed seepage.

4.2. Lake bed slope

Fine-grid models with shallow lakes (10 m deep) were set up with three different lake bed slopes: low (0.013), moderate (0.02), and steep (0.04). These values are within the range of slopes found for small lakes in the central US and Canada in previous field studies. Half-lake cross-sections (shoreline to lake center; Fig. 6) show that our lakes of steep slope had one grid cell on each "step" of the stair-step lake bed slope; moderate slope required two cells per step, and shallow slope three cells per step.

For inflow lakes, each simulation with a lake of steep slope had a maximum head at the domain boundary 2–3.5 m higher than the corresponding simulation with low slope. Varying lake bed slope from 0.013 to 0.02 to 0.04 in different simulations caused shoreline seepage to change by 18–34% in inflow lakes; shoreline seepage was highest for the lake of low bed slope and lowest for the lake of steep slope, except at $R = 1$ (Fig. 7).

Assessment of differences in seepage distribution was complicated somewhat at high anisotropy by an "oscillating" pattern of seepage rate with distance offshore (Fig. 7). This oscillation was an artifact of the need to create the moderate slope with two cells per step, and the low slope with three cells per step. Each cell of the lake bed shared a horizontal face (2500 m^2) with the porous medium, but the lake cell nearest to shore on each step also shared a vertical face (100 m^2) with the porous medium (Fig. 6). The horizontal face was 25× larger than the vertical, but the conductivity normal to the vertical face was 100 or 1000× larger than that normal to the horizontal face (at our two highest anisotropy ratios). Thus, at high anisotropy, the lake cells sharing a vertical face with the porous medium experienced a slightly elevated seepage rate.

Seepage maps of the shallow inflow lake beds show small differences among the different lake bed slopes, mainly in the nearshore region. Increasing bed slope led to a smaller fraction of the lake bed in

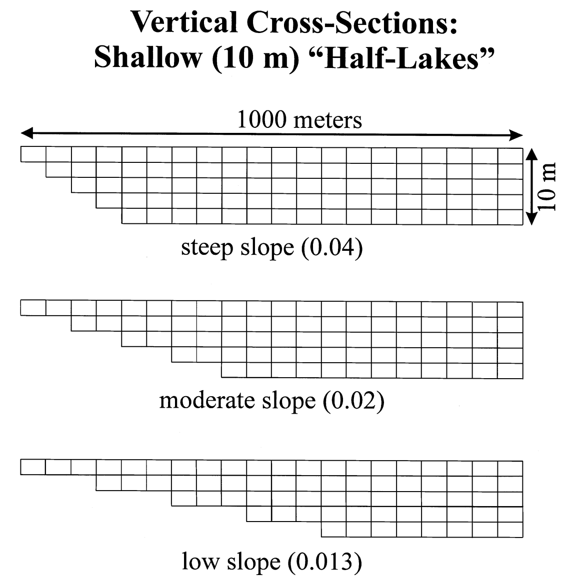

Fig. 6. "Half-lake" vertical cross-sections (shore to lake center) through shallow lakes of different slope, showing the grid cells and the "stair-step" structure of the sloping side portion of the lake beds. Deep lakes were analogous but reached to twice the depth (20 m, penetrating the top 10 layers of the model domain).

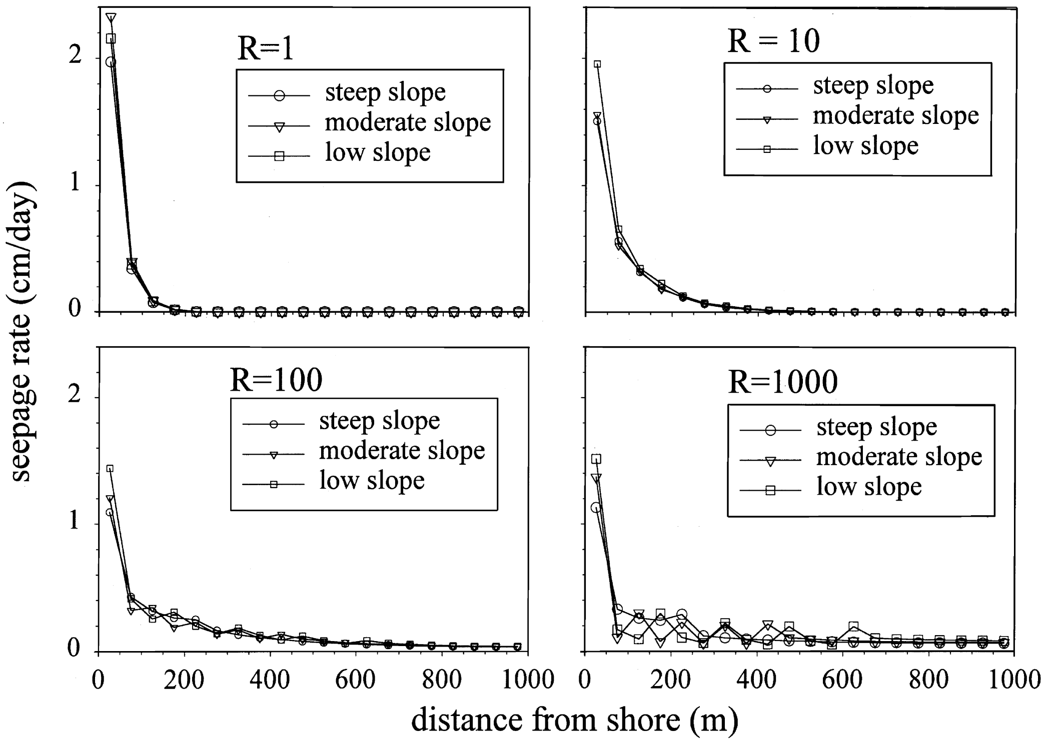

Fig. 7. Lake bed seepage rate vs. distance from shore for shallow inflow lakes of low, moderate, and steep slope in porous media of different anisotropy (*R*).

the highest seepage class (Fig. 8), a trend not evident at $R = 1$ but increasingly evident as R was raised from 10 to 100 to 1000. The same general conclusions held true for a few simulations run with deep inflow lakes. This is consistent with the differences in shoreline seepage mentioned above (Fig. 7), and with the results of Pfannkuch and Winter (1984) showing greater convergence of groundwater streamlines near the shore (leading to greater shoreline seepage) in lakes of lower bed slope.

In addition to the differences in shoreline seepage, another effect of lake bed slope was the locally elevated seepage at the break in slope. As noted earlier, this effect was large at $R = 1000$, smaller but still noticeable at $R = 100$, and absent at $R = 1$ and $R = 10$; in Fig. 7 the effect is most noticeable for the lake with steep slope (the oscillating pattern mentioned above confounds the effect somewhat at low and moderate slope).

In shallow flow-through lakes, the overall distribution of seepage showed little dependence on lake bed slope, though shoreline seepage was 10–40% higher in lakes of low bed slope (Figs. 9 and 10). The fraction of lake bed experiencing inseepage showed little or no dependence on bed slope (Table 2). However, integrating over the lake bed, the annual amounts of groundwater inseepage and outseepage increased slightly with slope. The difference in annual inseepage between the lakes with steep slope and low slope was 1.2% at $R = 1$, 2.4% at $R = 10$, 10% at $R = 100$, and 19% at $R = 1000$. When the annual volumes of groundwater inseepage were normalized by the volumes of the lakes, the trend was the opposite: though the lake with steep bed slope experienced the greatest absolute amount of inseepage, it had the smallest amount of inseepage as a percentage of lake volume, because of its larger volume (Table 2).

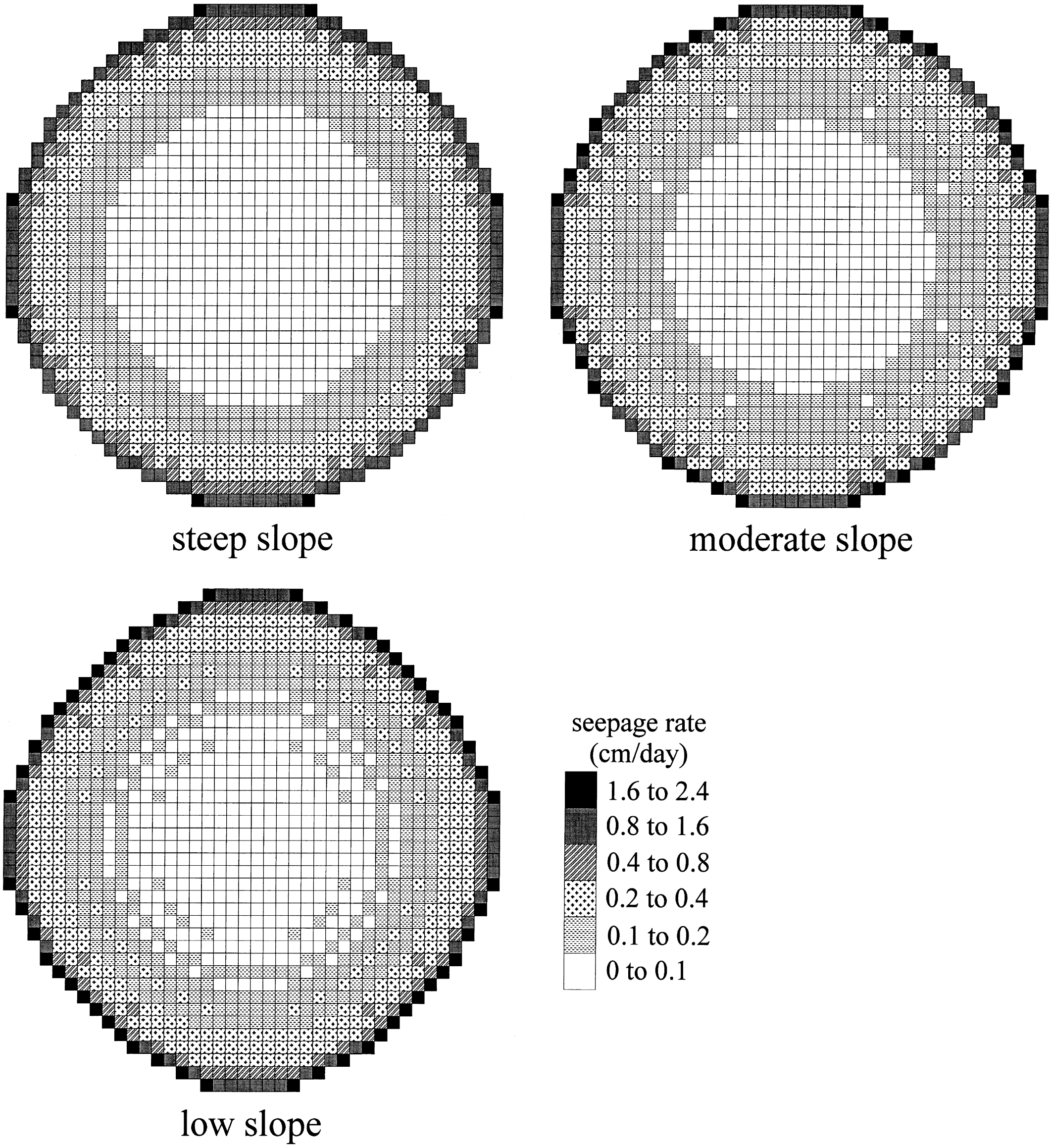

Fig. 8. Lake bed seepage rate (cm/day) in shallow inflow lakes of different slope, $R = 100$. Each lake bed grid cell was assigned to one of the six seepage classes shown, based on the seepage rate between the cell and the lake. The number of cells in the highest seepage class increased as bed slope decreased. In order to accommodate it's shape, the low-slope lake bed had slightly fewer cells than the other two (1188 instead of 1240).

4.3. Orientation of an asymmetric lake

We investigated three different orientations of an asymmetric flow-through lake (a lake with steep bed slope on one side and moderate slope on the other) with respect to a regional groundwater gradient: steep side downgradient (SSD), steep side upgradient (SSU), and intermediate between SSD and SSU, with the straight line bisecting the lake between the steep and moderate sides parallel to the regional gradient (PRG). The models were set up by keeping the same asymmetric lake fixed in position and chan-

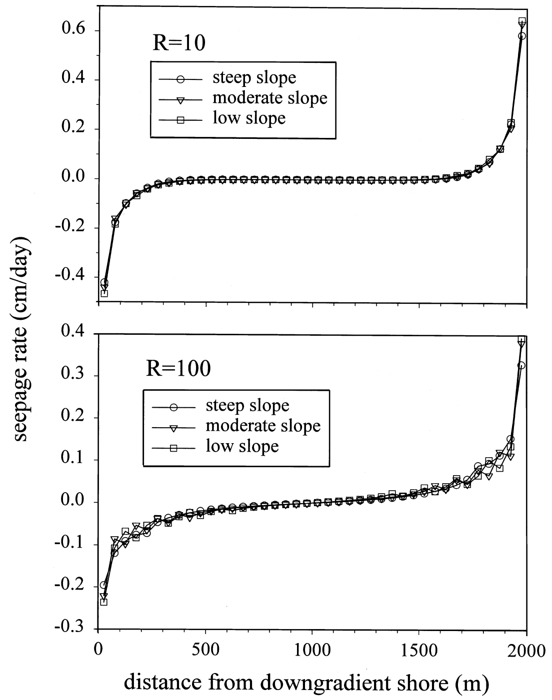

Fig. 9. Lake bed seepage rate vs. distance from the downgradient shore for shallow flow-through lakes of low, moderate, and steep slope, $R = 10$, $R = 100$.

ging the model boundary conditions such that the groundwater flow direction for SSU was exactly opposite (180°) that for SSD, and the direction for PRG was 90° from those of SSU and SSD.

The inseepage area of the lake bed was greatest for SSD models, smallest for SSU, and intermediate for PRG; the magnitude of the difference increased with anisotropy (Table 3). For example, comparing SSD and SSU models, the percentage of lake bed experiencing inseepage (A_{IN}) differed by 1.9, 2.4 and 3.6% at $R = 10$, 100, and 1000, respectively (the percentage could not be accurately defined at $R = 1$ because of the large area of extremely low seepage in the lake center). The 3.6% difference at $R = 1000$ corresponds to about 112,000 m^2 (11.2 ha) of the lake bed. Thus, while A_{IN} was not affected by bed slope in radially symmetric flow-through lakes (Section 4.2), A_{IN} was affected by introducing areas of different slope in an individual lake, and changing the direction of the regional groundwater gradient around the lake. Other than this difference, the models with asymmetric lakes were fairly similar in their overall patterns of lake bed seepage.

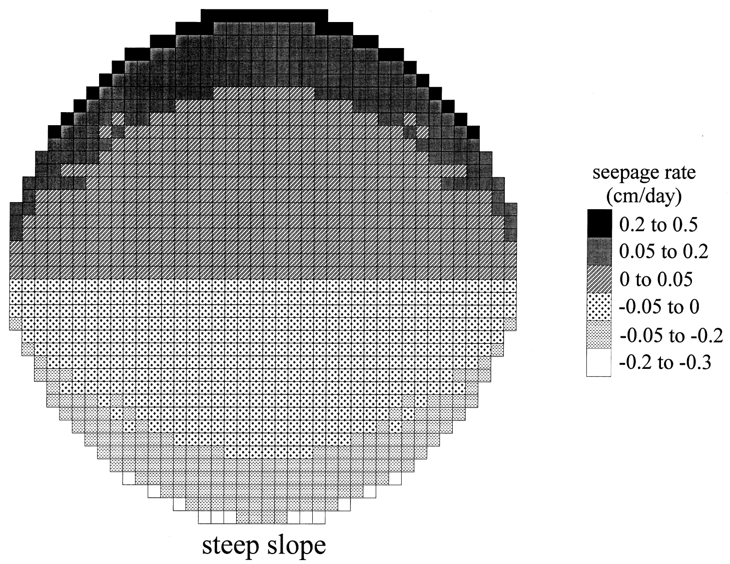

Fig. 10. Lake bed seepage rate (cm/day) for a shallow flow-through lake of steep slope, $R = 100$. Three of the six seepage classes represent lake inseepage (positive values), the other three outseepage. The regional groundwater flow direction is from top to bottom of the figure.

Table 2
Percentage of lake bed experiencing groundwater inseepage (A_{IN}) and annual inseepage as a percentage of lake volume (V_{IN}) for shallow flow-through lakes with different bed slopes, in porous media of different anisotropy. Each entry has the form: A_{IN}, V_{IN}

Lake bed slope	Lake volume (10^7 m^3)	Area and volume of groundwater inseepage			
		$R = 1$	$R = 10$	$R = 100$	$R = 1000$
Steep (0.04)	2.422	NA, 1.79	52.4, 1.74	53.2, 1.45	54.2, 0.90
Moderate (0.02)	1.832	NA, 2.37	52.4, 2.25	53.2, 1.82	55.0, 1.06
Low (0.013)	1.342	NA, 3.20	52.4, 3.06	53.4, 2.38	54.8, 1.35

4.4. Lake bed sediments

Several simulations were done to investigate the effect of low-permeability lake sediments on the spatial distribution of lake bed seepage. The porous medium cells in direct contact with the lake bed were designated as sediment cells; they were made isotropic and assigned a hydraulic conductivity (K_s) of 10^{-2}, 10^{-3}, or 10^{-4} m/day in different models. The surrounding porous medium had an anisotropy ratio of 100 in all models with lake sediments.

Adding lake bed sediments and lowering their conductivity evened-out the distribution of seepage on all the lakes. This was accomplished in inflow lakes by shifting seepage further offshore, lowering shoreline seepage and increasing offshore seepage (Fig. 11). This effect was obvious in seepage maps showing the progressive leveling of seepage across the lake bed (Fig. 12).

In flow-through lake models the overall groundwater gradient from domain boundary to lake was fixed, but the amount of groundwater exchange was not. In contrast to the inflow lake models, reductions in nearshore seepage in flow-through lakes were not accompanied by increases in offshore seepage (Fig. 13). Thus, the net effect of adding lake sediments and decreasing their conductivity was a reduction in annual groundwater inseepage (V_{IN}) to flow-through lakes (Table 4). However, A_{IN} increased even as V_{IN} decreased (Table 4); thus, A_{IN} does not serve as a simple surrogate or index for V_{IN} in assessing the amount of lake:groundwater exchange.

Results show that low-permeability lake bed sediments can have a major effect on the spatial distribution of lake bed seepage in both inflow or flow-through lakes, even when the sediments are of constant thickness over the entire lake bed.

Table 3
Percentage of lake bed experiencing groundwater inseepage (A_{IN}) for shallow asymmetric flow-through lakes in different orientations (see text), in porous media of different anisotropy

Lake orientation	Area of groundwater inseepage			
	$R = 1$	$R = 10$	$R = 100$	$R = 1000$
SSD	NA	53.5	54.8	57.1
PRG	NA	53.1	53.4	54.7
SSU	NA	51.6	52.4	53.5

5. Results: porous medium parameters

5.1. Anisotropy

The anisotropy of the porous medium is known to be an important control on lake:groundwater interaction (e.g. Pfannkuch and Winter, 1984; Winter and Pfannkuch, 1984); the results of our simulations

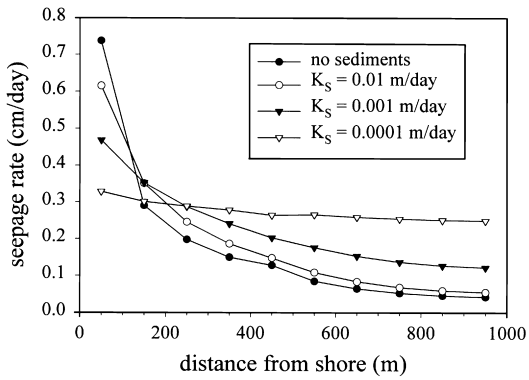

Fig. 11. Lake bed seepage rate vs. distance from shore for shallow inflow lakes of moderate slope, $R = 100$, without lake bed sediments and with sediments of different conductivity.

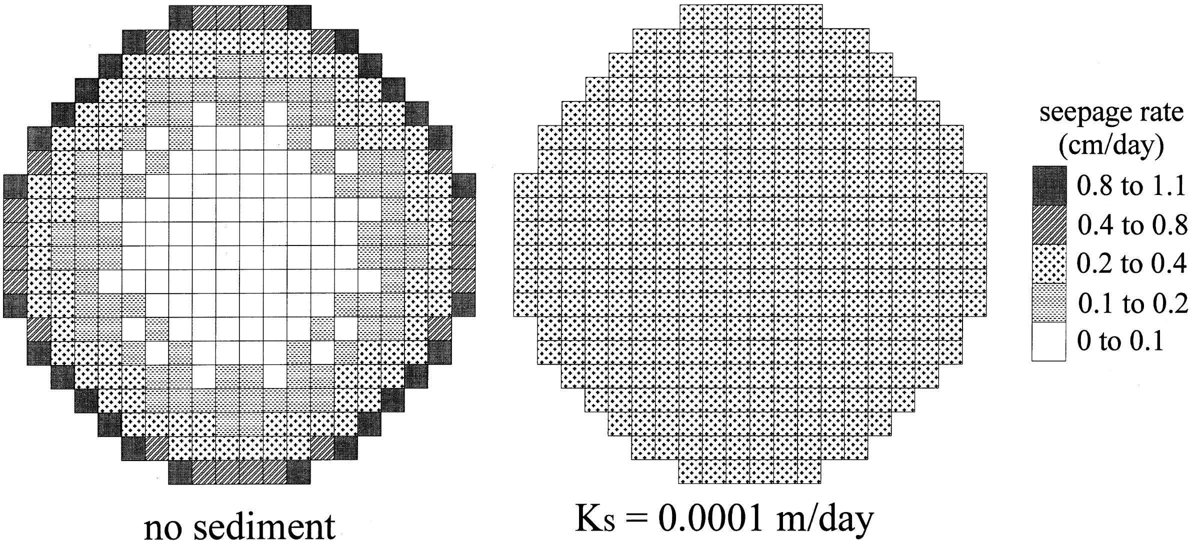

Fig. 12. Lake bed seepage rate (cm/day) for shallow inflow lakes of moderate slope, $R = 100$, with and without sediments (coarse grid simulations).

bear this out. Increasing the anisotropy ratio (R) from 1 to 1000 in inflow lake simulations increased the maximum groundwater head by 10–13 m and sharply increased vertical gradients. This is consistent with the greater resistance to flow at higher R (we increased R by holding horizontal K constant and decreasing vertical K).

In inflow lakes, increasing R also lowered shoreline seepage rates and shifted lake bed seepage farther offshore (Fig. 3). Seepage maps (not shown) generally show a smaller fraction of the lake bed in the highest seepage class with increasing anisotropy. In flow-through lakes the area of inseepage increased slightly as R increased, and the total annual inseepage was significantly lower at higher R (Tables 1 and 2). As with inflow lakes, nearshore seepage rates in flow-through lakes were significantly lower at higher R.

The effects of increasing R were very similar to the effects caused by introducing and lowering the

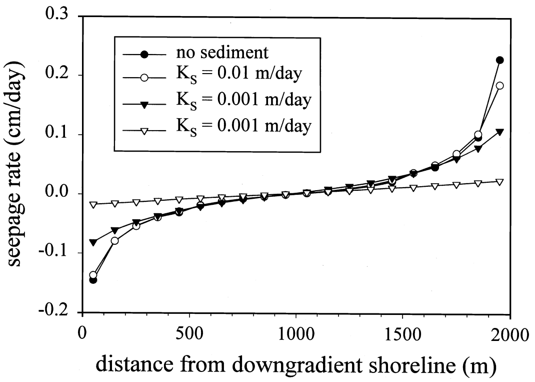

Fig. 13. Lake bed seepage rate vs. distance from downgradient shore for shallow flow-through lakes of moderate slope, $R = 100$, without lake bed sediments and with sediments of different conductivity.

Table 4
Effects of low-permeability lake sediment on the percentage of lake bed experiencing inseepage (A_{IN}) and the annual inseepage as a percentage of lake volume (V_{IN}) in flow-through lakes. Results are for shallow lakes of moderate bed slope, in a porous medium of $R = 100$

Lake sediment conductivity (m/day)	Area and volume of groundwater inseepage	
	A_{IN}	V_{IN}
No sediment	53.2	1.82
0.01	55.2	1.70
0.001	56.5	1.28
0.0001	57.4	0.40

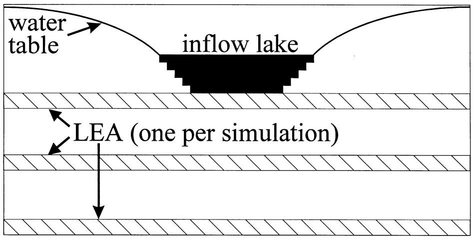

Fig. 14. Schematic vertical cross-section through the center of a model domain, showing the three locations in which laterally extensive aquifers (LEAs) were placed in different simulations (one LEA per simulation). For the shallow inflow lake model shown, the LEA occupied model layer 6 (touching the lake bottom), 15 (bottom of the domain), or 11 (intermediate). The cross-section is not to scale and is vertically exaggerated.

conductivity of low-permeability lake sediments (Section 4.4). Also, as discussed in Sections 4.1 and 4.3 and elaborated on further in Section 6, the effects of lake bed slope on lake bed seepage were closely linked to the anisotropy of the porous medium.

5.2. Heterogeneity

The effects of heterogeneity on lake bed seepage were investigated by introducing "laterally extensive aquifers" (LEAs) and "laterally restricted aquifers" (LRAs) into the model domains. These "aquifers" were zones with the same anisotropy ($R = 100$) but $100\times$ the conductivity of the surrounding porous medium, and were similar in concept to the heterogeneities used by Winter (1978). LEAs occupied a single full model layer, and were introduced at three different depths in different simulations (one LEA per simulation; Fig. 14): the bottom layer of the model domain (layer 15), the layer just under the lake and touching the lake bed (layer 6 for shallow lakes, 11 for deep lakes), and an intermediate position (layer 11 for shallow lakes, 13 for deep lakes). LRAs occupied a third of a model layer ($2000 \times 6000\ m^2$, in layer 11 for shallow lakes, 13 for deep lakes), and were introduced in three different positions in different simulations (one LRA per simulation; Fig. 15). For inflow lakes, LRAs were introduced at the edge of the model domain (three sides of the LRA on the domain boundary, no part of the LRA directly under the lake), partially under the lake (center of the LRA directly under the lake shore), or directly under the lake (center of the LRA directly under the center of the

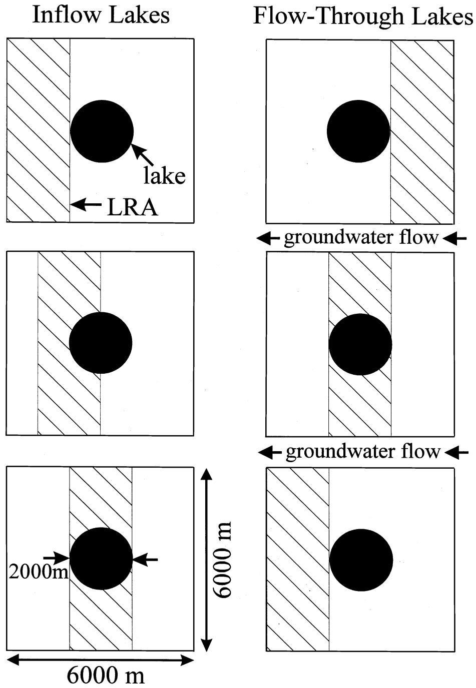

Fig. 15. Plan (map) view of model domains showing the locations in which laterally restricted aquifers (LRAs) were placed in different simulations (one LRA per simulation). The left column shows LRA locations for inflow lake simulations, the right column locations for flow-through lake simulations. Each LRA occupied a third of a model layer (2000 × 6000 m).

lake). For flow-through lakes, LRAs were positioned directly under the lake, or on the upgradient or downgradient side of the model domain (Fig. 15).

For inflow lakes, adding an LEA and moving it upward in the model domain lowered heads in the model domain and shifted seepage offshore (Fig. 16). Seepage profiles seemed to rotate counterclockwise about a point roughly 175 m offshore. Small local seepage maxima at breaks in lake bed slope became much larger when the LEA was in its uppermost position, in contact with the lake bed. In this case, seepage rate was greater at the offshore seepage peak than at the shoreline (Fig. 16), something not seen in any other inflow lake simulation.

Introduction of an LRA in inflow lake simulations also lowered heads in the model domain, though not as much as the LEA. It also introduced asymmetry in lake bed seepage (Figs. 17 and 18). Compared to the same simulation with no LRA (Fig. 8), introducing an

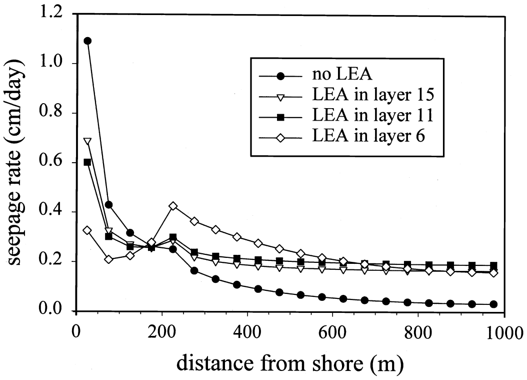

Fig. 16. Lake bed seepage rate vs. distance from shore for shallow inflow lakes of steep slope, $R = 100$, with no LEA and with LEAs in different positions in the model domain.

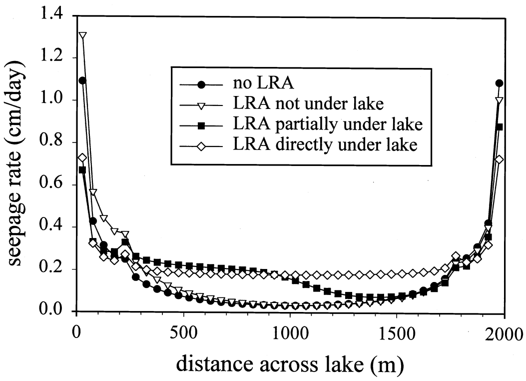

Fig. 17. Lake bed seepage vs. distance from shore for shallow inflow lakes of steep slope, $R = 100$, with no LRA and with LRAs in different positions in the model domain. The entire distance across the lake (2000 m) is shown, unlike with other inflow lake results, because of the asymmetry in seepage caused by the LRA. In moving from not under to partially under to directly under the lake, the LRA moved from left to right with respect to the figure.

LRA partially under the lake elevated lake bed seepage just above the LRA and shifted the zone of low lake bed seepage away from the LRA (Fig. 18).

Introducing and raising the elevation of an LEA had no effect on the area of inseepage in flow-through lakes (Table 5), but, as with inflow lakes, the seepage profiles along the regional gradient seemed to rotate counterclockwise, this time about the point of zero seepage on the seepage boundary (Fig. 19). Again, points of slightly elevated seepage at the breaks in lake bed slope became pronounced seepage maxima when the LEA touched these points; the net effect was to increase rates of inseepage and outseepage over broad areas of the lake bed. Thus, introducing and

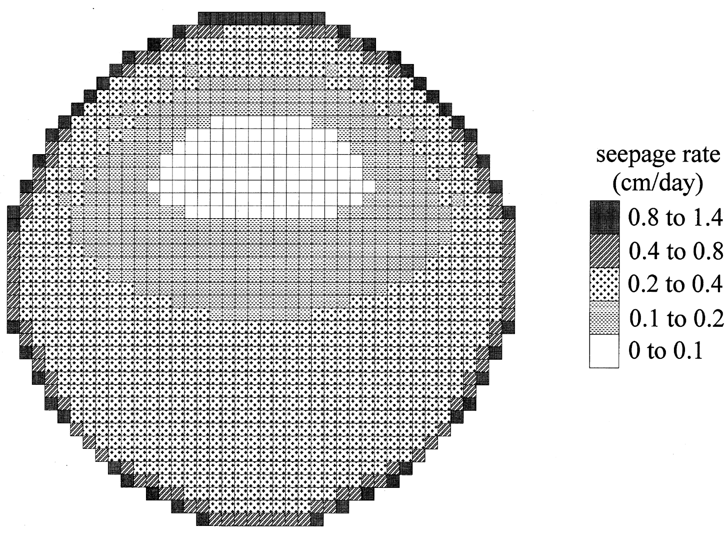

Fig. 18. Lake bed seepage rate (cm/day) for a shallow inflow lake of steep slope with an LRA partially under the lake, $R = 100$. (center of the LRA directly below the shoreline at the bottom of the map; see text). In comparison to the analogous map with no LRA (Fig. 8), the low seepage zone in Fig. 18 is displaced to one side, away from the LRA.

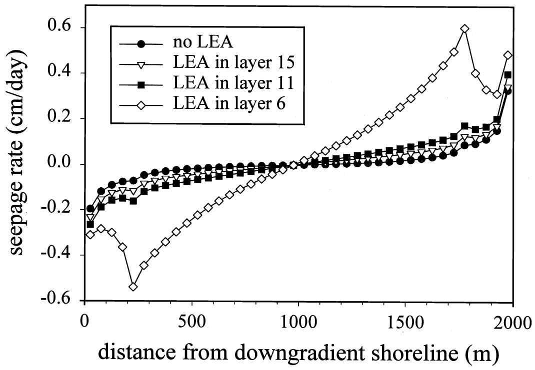

Fig. 19. Lake bed seepage rate vs. distance from downgradient shore for shallow flow-through lakes of steep slope, $R = 100$, with no LEA and with LEAs in different positions in the model domain.

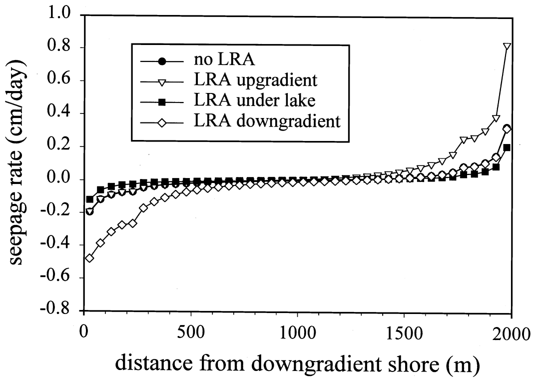

Fig. 20. Lake bed seepage rate vs. distance from the downgradient shore for shallow flow-through lakes of steep slope, $R = 100$, with no LRA and with LRAs in different positions in the model domain.

raising the LEA also increased the amount of groundwater exchange with flow-through lakes (Table 5).

Introducing an LRA upgradient of a flow-through lake significantly increased both the area and amount of inseepage, while placing the LRA downgradient of the lake had the opposite effect (Figs. 20 and 21, Table 6). Introducing an LRA directly below the lake center led to a large increase in the area of groundwater inseepage, but a decrease in the amount of inseepage.

6. Significance and conclusions

Our results are in accordance with the previous work showing that the spatial distribution of lake bed seepage can be strongly influenced by heterogeneity and anisotropy in the porous medium surrounding the lake. In addition, our results show some cases in which lake parameters (depth, bed slope, the alignment of an asymmetric lake with respect to a groundwater gradient, the presence and permeability of lake sediments) may play almost as important a role as porous medium characteristics. In some of these cases, lake bed slope and porous medium anisotropy interact to affect lake bed seepage.

Varying lake bed slope from 0.013 to 0.02 to 0.04 in different simulations caused shoreline seepage to change by 18–34% in inflow lakes, 10–40% in flow-through lakes; generally shoreline seepage was highest for lakes of low bed slope and lowest for lakes of steep slope, consistent with related results of Pfannkuch and Winter (1984). Within individual simulations, an elevated seepage was observed at the break in bed slope (between sloping side and horizontal center portions of the lake bed), whenever the surrounding porous medium had a high anisotropy (local seepage maxima occurred at $R = 1000$, and smaller but still elevated seepage at $R = 100$). This

Table 5
Effect of a laterally extensive aquifer (LEA) on the percentage of lake bed experiencing groundwater inseepage (A_{IN}) and annual groundwater inseepage as a percentage of lake volume (V_{IN}) to shallow flow-through lakes of steep bed slope, in a porous medium of $R = 100$

Position of LEA	A_{IN}	V_{IN}
No LEA	53.2	1.45
Layer 15 (base of domain)	53.2	1.70
Layer 11	53.2	2.16
Layer 6 (touching lake)	53.2	4.74

Table 6
Effect of a laterally restricted aquifer (LRA) on the percent of lake bed experiencing groundwater inseepage (A_{IN}) and the annual groundwater inseepage as a percentage of lake volume (V_{IN}) for shallow flow-through lakes with steep bed slope in a porous medium of $R = 100$

Position of LRA	A_{IN}	V_{IN}
No LRA	53.2	1.45
Upgradient	63.4	3.67
Under lake	64.8	0.81
Downgradient	40.3	1.23

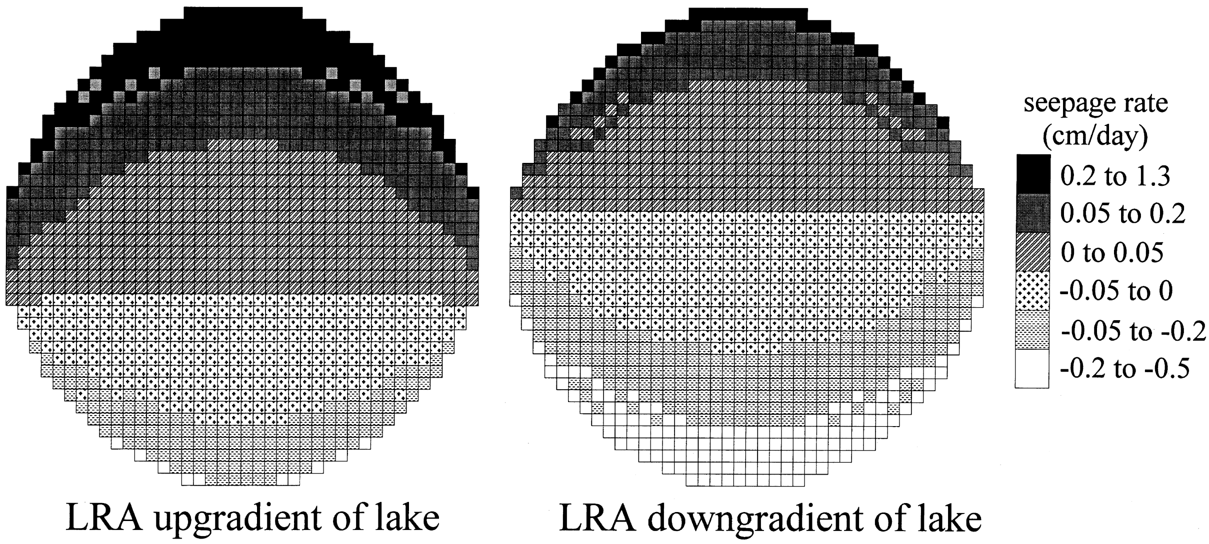

Fig. 21. Lake bed seepage rate (cm/day) for shallow flow-though lakes of steep slope, $R = 100$, with LRAs upgradient and downgradient of the lake. The analogous map for a simulation with no LEA is in Fig. 10. The regional groundwater flow direction is from top to bottom.

is one manifestation of the interaction between bed slope and anisotropy: neither a break in slope nor a high anisotropy alone is sufficient to cause elevated offshore seepage, but together they produce the effect. Based on this result we expect the opposite phenomenon may occur (though we have not simulated it): offshore local seepage minima at breaks in bed slope where there is a higher slope further offshore (as opposed to the breaks with lower slope offshore simulated here).

Offshore peaks in seepage have been observed in some real lakes, and generally interpreted as due to locally thin or absent lake bed sediments (e.g. Cherkauer and Nader, 1989) or subsurface heterogeneity beneath the lake. Our results show another physical hydrogeological condition by which these offshore seepage maxima can occur: high anisotropy in combination with a sharp break in lake bed slope (lower slope offshore). The elevated seepage is most likely produced by convergence of flow lines around the break in bed slope, in much the same way that flow lines converge in a horizontal section (i.e. in map view) around embayments in lake shores (e.g. Cherkauer and McKereghan, 1991).

For flow-through lakes in media of high anisotropy, the annual volume of groundwater inseepage was significantly higher (19%) for lakes with steep bed slope compared to those with low slope (though steep lakes had the lowest inseepage when the inseepage was normalized by lake volume); this effect of slope was smaller at lower anisotropy. The orientation of an asymmetric lake in a regional groundwater gradient (a lake with a steep bed slope on one side, moderate slope on the other) affected groundwater exchange with the lake; the inseepage area was greatest when the steep side was downgradient, and the effect was larger at higher anisotropy. These effects, along with the elevated seepage at breaks in bed slope, illustrate the complex interaction between lake bed slope and the anisotropy of the surrounding porous medium in controlling lake:groundwater exchange.

Adding low-conductivity lake sediments and decreasing their conductivity had an effect very similar to increasing anisotropy in the surrounding porous medium: seepage rates were evened out over the lake bed. This occurred in inflow lakes through seepage being shifted further offshore, and in flow-through lakes by reducing nearshore seepage (without increasing offshore seepage). The net effect was a smaller annual volume of lake-groundwater exchange in flow-through lakes. While the volume of annual inseepage (V_{IN}) was lower, the percentage of the lake bed experiencing inseepage (A_{IN}) was actually higher. Thus, A_{IN} and V_{IN} do not necessarily vary together;

comparing between different lakes, a lake of higher A_{IN} might have lower V_{IN} (e.g. Table 4), and lakes of equal A_{IN} may have different V_{IN} (e.g. Tables 2 and 5). A laterally extensive high-conductivity zone beneath a flow-through lake may have no effect on A_{IN} but a large effect on V_{IN}, while a laterally restricted zone representing a more localized geologic bed may strongly affect both A_{IN} and V_{IN} (Tables 5 and 6).

The "de-coupling" shown here between A_{IN} and V_{IN} is an important consideration in studies of groundwater interaction with lakes, especially with regard to tools such as towed conductivity probes for detecting groundwater inflow on lake beds. The usefulness of such probes in detecting groundwater inflow (and thereby potentially estimating A_{IN}) has been discussed (e.g. Harvey et al., 1997b), though caution must be used in drawing conclusions about V_{IN} from data on A_{IN}.

Many of the phenomena discussed above (offshore local seepage maxima, decreases in nearshore seepage and/or increases in offshore seepage) could have significant implications for lake water quality, and therefore ecology. Schafran and Driscoll (1993) found that offshore seepage to a lake in New York had higher pH and alkalinity, higher nitrate and base cation concentrations, and lower sulfate and organic anion concentrations than did seepage close to shore. We expect that these differences between nearshore and offshore seepage are not uncommon. Thus, physical factors that influence the distribution of seepage (in particular, the mix of nearshore and offshore seepage) may influence lake water quality.

For example, for lakes in porous media of high anisotropy, those with breaks in bed slope could have higher alkalinity inputs than those without such breaks (because of the locally elevated offshore seepage experienced by the former lakes). Also, lakes of low bed slope may have lower alkalinity inputs than lakes of steep bed slope (because of their relatively higher seepage at the shoreline, where alkalinity may be lower). Lakes of low bed slope also have lower total annual volumes of groundwater inseepage, another reason why their alkalinity inputs may be lower. However, when normalized by lake volume, a lake of low slope may have a higher annual amount of groundwater inseepage than an analogous lake of steep bed slope (because of the smaller lake volume at low slope, if lake area and depth are equal; Table 2, Section 4.2). The water quality effects of groundwater inseepage are probably best interpreted with the seepage normalized by lake volume.

Lake depth did not have a significant effect on the quantity or distribution of seepage to inflow or flow-through lakes. However, because deep and shallow lakes experienced roughly the same amount of seepage, and the volume of the deep lake was larger than that of the shallow lake, the annual inseepage to the deep lake represented a smaller fraction of lake volume. Though there does not seem to be a direct effect of depth on lake bed seepage, the dilution of the same inseepage in the smaller volume of the shallow lake suggests the potential for a larger effect of groundwater exchange on the water quality of the shallow lake.

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