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Coupling of MODFLOW and WATFLOOD in hydrological modelling of a small watershed

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Abstract In water resources assessment, coupling of watershed and groundwater models integrates surface water and groundwater components. In this research, the coupling was performed by applying the recharge component of the WATFLOOD/SPL hydrological model to the MODFLOW groundwater model in the Laurel Creek watershed, Ontario, Canada. Net groundwater leakage computed by MODFLOW was combined with WATFLOOD/SPL surface flow and interflow. The flows obtained were compared with flows computed by the WATFLOOD/SPL model. Several runs were performed using radar-rainfall data and the hourly measured streamflow for the period 1993–1999. The results showed that use of adjusted radar precipitation improved the predicted streamflows. Running the MODFLOW model for 28 years of consecutive data showed that it takes about 20 years for the system to reach equilibrium, regardless of the starting heads. A simple lower-zone function (in WATFLOOD/SPL) was substituted for the MODFLOW to predict the streamflows.

Key words coupling; Laurel Creek, Canada; MODFLOW model; radar precipitation; WATFLOOD/SPL model

INTRODUCTION

Mathematical modelling of watersheds is a tool for assessing water resources. Current watershed models generally represent the surface water component adequately, but they simplify the dynamics of groundwater. On the other hand, groundwater models ignore the dynamics of surface water. VanderKwaak & Sudicky (1996) developed a fully coupled, surface-subsurface flow and solute transport model. A mathematical model for coupling the surface and subsurface flow was presented by Gandolfi & Savi (2000).

Groundwater forms an important source of municipal, industrial, agricultural and residential water supply in Ontario (MacRitchie *et al.*, 1994). The Regional Municipality of Waterloo and Grand River Conservation Authority are currently involved in detailed hydrological studies throughout the Laurel Creek watershed (part of the Grand River basin). The purpose of this paper is to couple WATFLOOD/SPL hydrological model with MODFLOW groundwater model in the Laurel Creek watershed. The study sought to determine whether replacing detailed aquifer properties by a simple function would affect simulation of streamflows.

MATERIALS AND METHODS

Hydrological model

The coupling process was performed by applying the WATFLOOD/SPL hydrological model to the Laurel Creek watershed (Fig. 1), taking the recharge component of this model and using it as an input to the MODFLOW groundwater model. The net groundwater leakage to the Laurel Creek is combined with surface flow and interflow computed by WATFLOOD/SPL and routed down the creek.

The surface hydrological processes are represented by the WATFLOOD/SPL modelling system, which consists of two parts: WATFLOOD is the data management system that includes a number of data pre-processing programs, and SPL is the hydrological simulation model (Kouwen & Mousavi, 2002). For subsurface hydrological processes, the MODFLOW groundwater model is used to simulate groundwater flow in three dimensions (Harbaugh & McDonald, 1996a,b).

Study area

The Laurel Creek watershed in southern Ontario, Canada (Fig. 1), with a drainage area of 70.45 km^2, was chosen. This watershed is located at longitude of 80°39′58″–80°28′46″W and latitude of 43°26′12″–43°30′24″N. Mean annual precipitation in the Grand River basin varies from 813 to 965 mm, and mean annual temperature of the region is about 7.4°C.

The square-grid (1 × 1 km) approach was used to allow for an easy interface with remotely sensed data, specially the radar rainfall measurements. Hourly rainfall

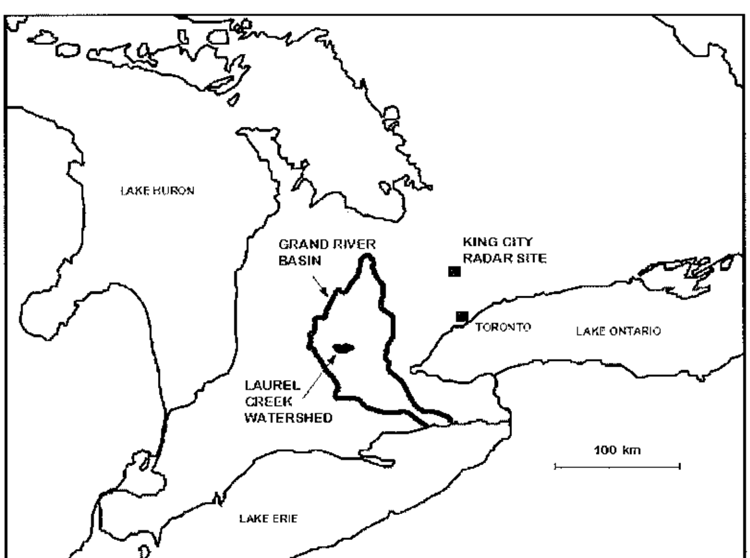

Fig. 1 Location map of Laurel Creek watershed.

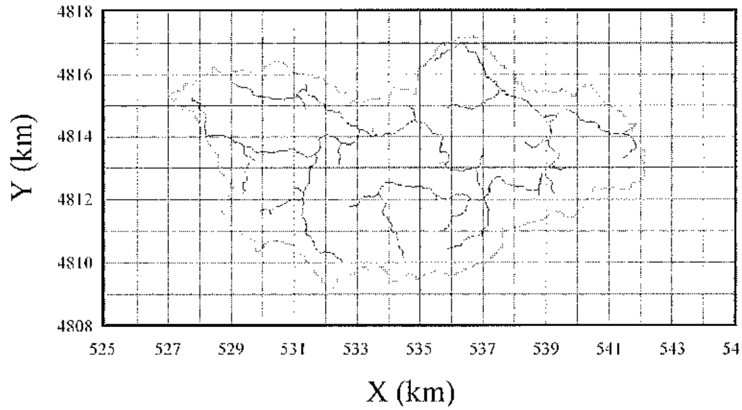

Fig. 2 Grid pattern for Laurel Creek watershed.

and temperature data of 1993–1999 were used. The Universal Transverse Mercator (UTM) coordinates were adopted for the surface and ground water models. The X-coordinates are from 525 to 545 km and Y-coordinates are from 4808 to 4818 km (Fig. 2).

Modelling scenarios

Three approaches were compared. First, WATFLOOD/SPL was applied and surface flow, interflow and groundwater outflow were computed. Next, the groundwater recharge was computed in WATFLOOD/SPL and used in MODFLOW. Two cases were considered in MODFLOW: (a) the groundwater system was considered as one unconfined aquifer, and (b) the groundwater system consisted of one unconfined and three confined aquifers.

Since actual water table depth (as the starting head) of each cell was not known in MODFLOW, three different positions of water table were assumed: (a) full saturation, or starting head equal to the average surface elevation of the cell; (b) starting head equal to average elevation minus 10% of the aquifer thickness; and (c) starting head equal to average elevation minus 20% of the aquifer thickness. Thirteen wells are discharging groundwater at a rate of minimum 0.0108 to maximum 0.0415 $m^3 s^{-1}$. It was assumed that the wells are running 12 h a day for the whole year. The MOD-FLOW model was run for 7 years (1993–1999) using the above starting heads. Then, another 7 and 14 years of consecutive synthetic data were incorporated into the model to attain the equilibrium.

RESULTS AND DISCUSSION

Behaviour of the coupled models

Several runs were performed using the hourly-measured streamflow at the Weber gauge station (located at X and Y coordinates of 539 and 4813 UTM, respectively) for

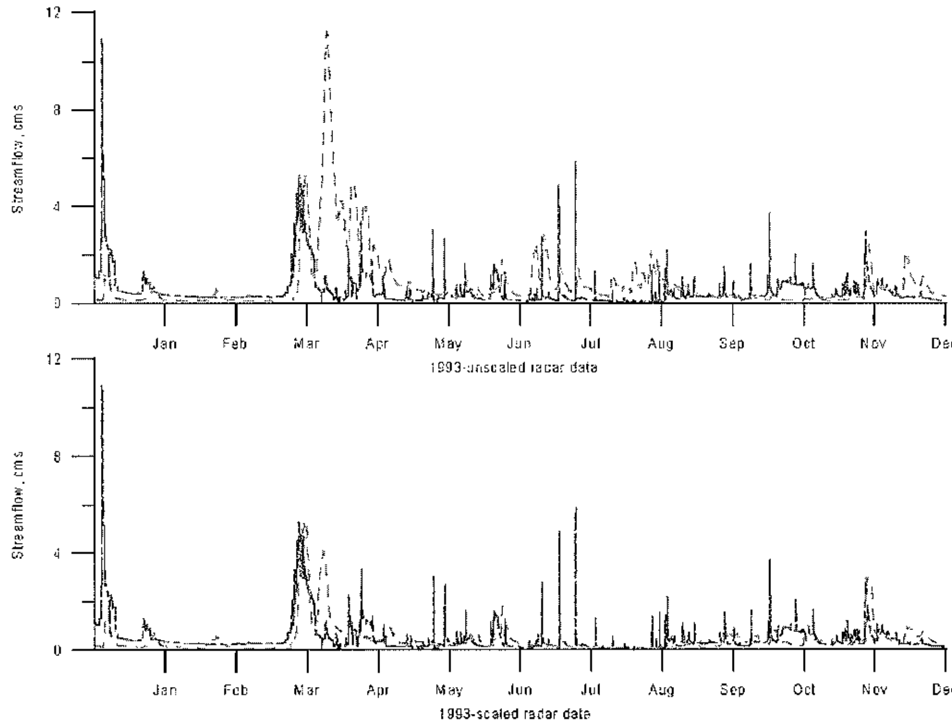

Fig. 3 Computed (broken line) *vs* measured (solid line) streamflow in 1993. Radar rainfall data were used to compute the hydrographs. The lowER hydrograph was obtained by using the calibrated radar rainfall data.

the period 1993–1999. Figure 3 shows the computed *vs* measured streamflow for 1993. Although there are large differences between gauge and radar accumulation for many of the individual events (because of underestimation or overestimation) (Fassnacht *et al.*, 1998), nevertheless, radar–rainfall data for this year are quite reliable. As seen, the computed curve does not fit the measured curve very well, especially in April. Snowmelt in March and April has produced a lot of runoff. In April, the highest predicted streamflow by WATFLOOD/SPL model was about 10.9 $m^3 s^{-1}$, while the highest measured flow was around 5.5 $m^3 s^{-1}$. Changing the scale factors for conversion of radar rainfall (Fassnacht *et al.*, 1999) improved the fit and decreased the discrepancies. After running the MODFLOW for 7 years (1993–1999), the final heads were obtained in each grid.

Comparison of the results (not shown here) showed that there is not much difference between head changes of the one-layer and four-layer models in many grids. This result shows that detailed information of different layers may not be necessary to improve the final-head prediction by MODFLOW. Since the exact position of the water table was not available, three arbitrary positions were assumed and MODFLOW was run for 28 years of consecutive data. Figure 4 shows that, at the beginning of the simulation, there is a large difference between the scenarios. But, as time passes, these differences diminish. On the basis of this figure, it takes about 20 years for the system to reach equilibrium, regardless of the starting heads.

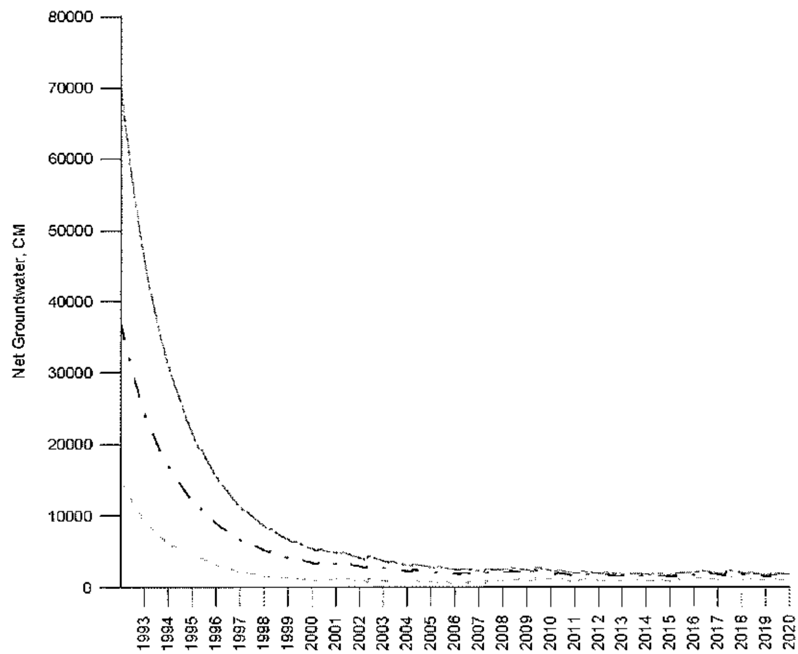

Fig. 4 Net groundwater leakage to the Laurel Creek. Starting head scenarios (top, middle, and bottom lines) are the starting head equal to the average surface elevation, the average elevation minus 10%, and the average elevation minus 20% of the aquifer thickness, respectively.

Comparison of stand-alone WATFLOOD and coupled WATFLOOD–MODFLOW

In WATFLOOD/SPL, an exponential groundwater depletion function is used to gradually deplete the lower-zone storage:

$$QLZ = LZF.LZS^{PWR} \quad (1)$$

Where *QLZ* is lower-zone discharge, *LZF* is a lower-zone function, *LZS* is lower-zone storage, and *PWR* is an exponent. The LZF value of equation (1) was set to a very low value (e.g. 10^{-15}) to produce only surface flow and interflow. The recharge computed by WATFLOOD/SPL was used to drive MODFLOW. The leakage computed by MODFLOW was then combined with the WATFLOOD/SPL surface runoff and interflow to produce inflow to the stream system. The combined flows were routed in the creek. Figures 5 and 6 compare the flows computed with the stand-alone WATFLOOD/SPL and the combined model for 1993–1996. Initially, the two models show different results. However, as time passes, the differences between the two hydrographs diminish and eventually, both methods result in the same flow. The simulation results for 1997–1999 are not shown because they are similar to 1996.

The conclusion from comparing the hydrographs in Figs 5 and 6 is that the simple lower-zone function can substitute the MODFLOW model in this particular watershed, and detailed aquifer properties are not needed to forecast the streamflow.

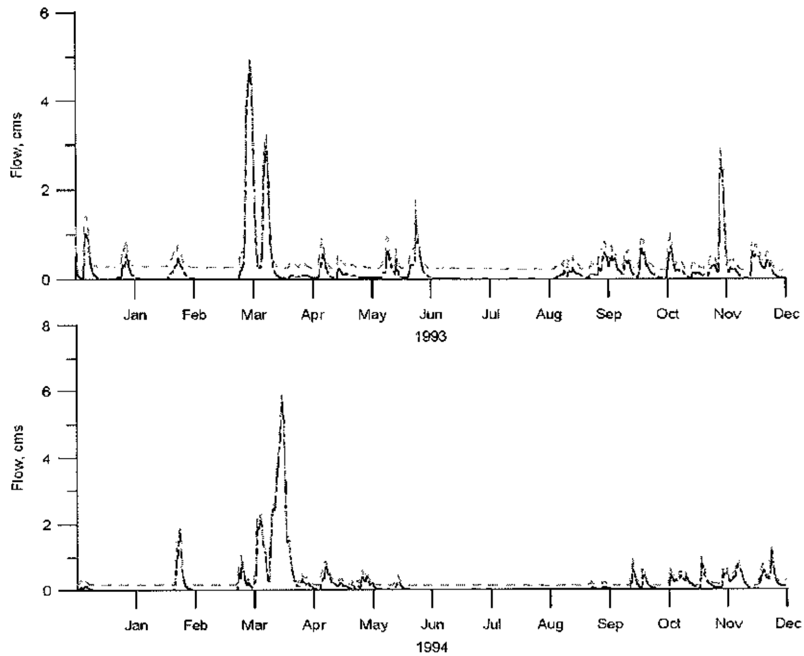

Fig. 5 Comparison of the simulated hydrographs with the stand alone WATFLOOD (solid line) and the combined WATFLOOD–MODFLOW (broken line) for 1993 and 1994.

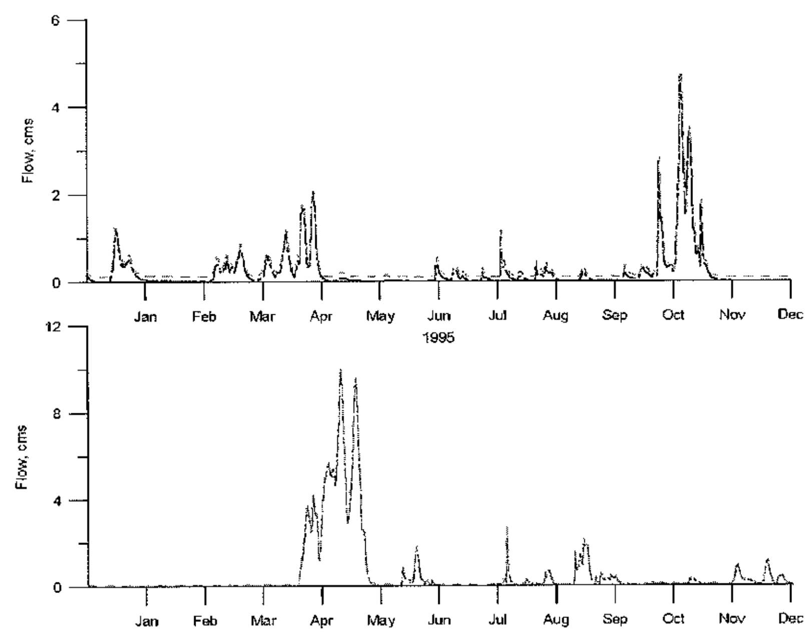

Fig. 6 Comparison of the simulated hydrographs with the stand-alone WATFLOOD (solid line) and the combined WATFLOOD –MODFLOW (broken line) for 1995 and 1996.

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