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Short note

An areal recharge and discharge simulating method for MODFLOW

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A B S T R A C T

As a widely used groundwater flow model, MODFLOW offers a set of packages to simulate hydrologic stresses, inflows and outflows, to a groundwater system. Specifically, MODFLOW lacks a general method to process areally distributed recharge and discharge to groundwater. One solution would be to create a new package for MODFLOW. Alternatively, it is also possible to make the best use of existing code to the same effect. In this note, a simple, yet effective method to simulate areal recharge and discharge is proposed based on the recharge (RCH) package of MODFLOW, allowing multiple instances of the RCH package to be used in one model. The method has been implemented in MODFLOW2000/2005 and has been successfully applied to a regional groundwater flow model to simulate areally distributed precipitation recharge, agricultural discharge and irrigation infiltration recharge in a simple approach.

1. Introduction

As the most widely-used groundwater flow model in the world, MODFLOW can simulate external flow stresses such as wells, areal recharge, evapotranspiration, drains and rivers with a set of stress packages (Harbaugh et al., 2000; Harbaugh, 2005). According to the different characteristics, these packages can be classified into three categories, point, line and area features. The well (WEL) package can simulate specified recharge or discharge point feature such as wells. The general head boundary (GHB) package, the river (RIV) package and the drain (DRN) package usually represent line features of inflows and outflows to a groundwater system. Area features such as precipitation, plant transpiration and direct evaporation can be simulated with the recharge (RCH) package and the evapotranspiration (ET) package, respectively.

The area-feature packages do not provide a general method to process areally distributed recharge/discharge to groundwater, compared to the point-feature package and the line-feature package. The RCH package is designed to simulate areally distributed recharge, or discharge if negative recharge rates are specified. However, RCH does not allow for recharge or discharge to occur simultaneously at multiple depths in the same vertical column, because natural recharge enters the groundwater system only at its top (McDonald and Harbaugh, 1988). A general areal recharge and discharge (ARD) method can enhance the capability of MODFLOW to process inflows and outflows distributed areally, and facilitate the development of large groundwater models.

Areally distributed recharge from precipitation would be one of the most obvious sources of areal recharge or discharge in a groundwater flow model. However, there are other types of areal recharge and discharge when modeling regional groundwater system, especially large basins with developed agricultural pumping and irrigation systems. In a vast area of a regional groundwater system, even in a model discretized with a relatively high resolution, a single cell could still include an area of about 1–10 km^2. Such an area generally contains at least one pumping well in most agricultural regions. Thus, each cell of the agricultural region, likely occupying great parts of the whole basin, will have at least one pumping well in the model. Therefore, the agricultural groundwater pumping in this situation could be considered as areally distributed discharge according to different rates. Likewise, irrigation infiltration return to the groundwater system could be considered as areally distributed recharge to the groundwater system.

Compared to the traditional method using the WEL package to simulate agricultural pumping discharge and using net recharge to represent precipitation recharge and irrigation return recharge, the ARD method is more convenient for the development and results analysis of models. Users do not need to take care of a large number of wells, setting different screened intervals and pumping rates series for each well in multiple layers. In addition, with the ARD method, it is easy to classify discharge into agricultural, industrial and domestic usage when calculating the water budget. Another method, the farm process package (Schmid et al., 2006; Schmid and Hanson, 2009), can dynamically simulate the integrated supply-and-demand components of irrigated

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agricultural and thus consider the relations between extractions and extra recharge. Given enough information of farm activities, the FMP can represent more complete hydrologic components. Since most agricultural areas do not have metered pumpage, even do not have the numbers and locations of pumping wells, groundwater pumpage are estimated indirectly from electrical power records or land-use maps. In this situation, the ARD method can be a simple and powerful approach.

2. Conceptualization and implementation

There are two options available for developing a general areal recharge and discharge tool for MODFLOW: programming a brand new package or using the existing MODFLOW capabilities of the RCH package. A new package is more elegant, but requires more development work and a new input instruction for users. The other solution is to make the best use of existing MODFLOW capabilities and develop an areal recharge and discharge tool based on the RCH package of MODFLOW. This is the best way to preserve the integrity of MODFLOW and minimize human effort for coding.

Wang et al. (2008) accomplished this by modifying the RCH package, adding one new option code "4" for NRCHOP representing recharging to all layers of the model. The disadvantage of this method is that the input format would be changed and users would need to spend additional effort to add different areal recharge and discharge together in each cell layer by layer. In this work, a common programming technique, the idea of code reuse was employed. That is, using an existing code, the RCH package in this case, to create a general areal recharge and discharge processing tool. Code reuse of the RCH package is a better approach to reduce redundant work, and therefore was the option chosen in this work.

The modular structure of MODFLOW makes reuse of the RCH package efficient. All that needs to be done is to call the RCH subroutines needed without changing the code of the RCH package. Thus, the ARD method can be developed by adding multiple RCH to the main program of MODFLOW. These new RCH packages added were named ARD1, ARD2, etc., and each is corresponding to a unit number so they could be read and entered into the entire calculation process.

The ARD method has been implemented into MODFLOW2000 and MODFLOW2005, named MF2K-ARD and MF2005-ARD, respectively. They are executed in the same manner as standard MODFLOW and the input instructions are also kept the same except for some slight changes as described in the following. File types of the name file are expanded, adding ARD1, ARD2, etc., for each areal recharge or discharge used in the model. The input format of ARD follows RCH convention, benefiting from code reuse. In each ARD input file, the recharge option code can be used to apply different recharge or discharge. The Multiplier File and the Zone File, if used, also need to be modified by adding corresponding items for ARD1, ARD2, etc.

The ARD method was verified using a simple synthetic problem. The problem was simulated using two ARDs first, and then an equivalent model was created using the WEL package. The simulated heads of each cell using the ARD method are exactly the same as these simulated with the WEL package. Other results of the two methods were compared in Table 1. Benefiting from the RCH package, the efficiency of the ARD method is higher than the WEL package.

Table 1
Simulation results of the synthetic problem using two methods.

Method	Budget of ARD1 m^3	Budget of ARD2 m^3	Budget of wells m^3	Executioin times[a]
ARDs	6635.1743	7896.6138	/	0.104
WEL	/	/	14531.7891	0.302

[a] The execution time is an average value of three execution runs.

3. Application

In order to show the practical applicability of the ARD method, a case study is presented of regional groundwater flow in the Pinggu basin, Beijing, China. The study area is surrounded by mountains, including about 459 km^2. Large groundwater reservoirs are present, consisting of mainly Quaternary-aged water-bearing formations. The basin, comprised of one unconfined and three confined aquifers according to the hydrogeological data, has a good groundwater supply capacity due to large precipitation recharge and lateral runoff recharge from surrounded mountains. There are 1209 pumping wells in the agricultural irrigation regions, accounting for over 80 percent of the total study area. The discharge of agriculture has a total yearly average extracted groundwater volume of 25 10^8 m^3/yr, while the irrigation return coefficient, defined as the ratio of the return recharge to the total discharge, is 0.14–0.18 according to different soil types and hydrological conditions. The average precipitation is 624.7 mm/yr and the effective infiltration coefficient ranges from 0.18 to 0.25. All spatial data were discretized with a resolution of 200 by 200 m.

The recharge and discharge connected with irrigation are simulated in the form of areally distributed recharge or discharge

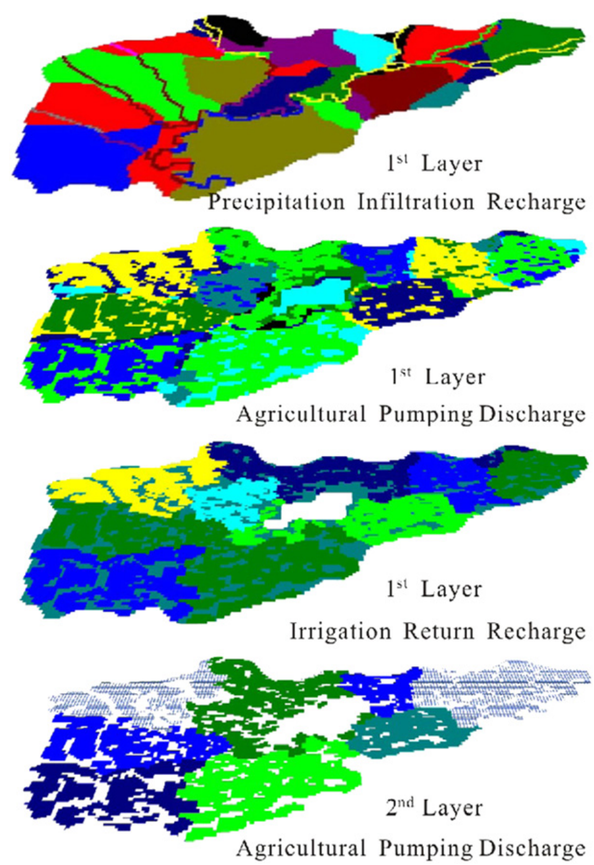

Fig. 1. Map showing the areal distribution of recharge and discharge zones in different aquifers. Each color in the map represents one recharge or discharge zone, corresponding to a serial data during six years (2003–2008).

Table 2
MF2K-ARD namefile of Pinggu Basin model.

Ftype	Numit	Fname
LIST	3	output.dat
DIS	95	discret.dat
BAS6	1	bas6.dat
LPF	33	lpf.dat
WEL	12	wel6.dat[a]
PCG	23	pcg2.dat
OC	22	oc.dat
RCH	18	rch6.dat[b]
ARD1	19	wel-1.dat[c]
ARD2	20	irr-1.dat[d]
ARD3	21	wel-2.dat[e]
DATA(BINARY)	50	budget.dat
DATA(BINARY)	51	heads.dat
DATA(BINARY)	52	ddown.dat

[a] wel6.dat contains the industrial and domestic well pumping discharge, especially pumping in two well fields.
[b] rch6.dat is the input file for RCH represents precipitation infiltration recharge.
[c] wel-1.dat is an ARD input file containing negative rate represents agricultural pumping discharge to the first layer.
[d] irr-1.dat is an ARD input file containing positive rate represents irrigation return recharge to the first layer.
[e] wel-2.dat is an ARD input file containing negative rate represents agricultural pumping discharge to the second layer.

Table 3
Water budgets of groundwater system of Pinggu basin from the MF2K-ARD model during the simulation period from 2003 to 2008.

Budget Items	Quantity(10^6 m^3)	Percentage (%)
Recharge		
Precipitation infiltration	480.01	51.86
Irrigation return	41.74	4.51
Boundary inflow	364.32	39.36
River leakage	39.55	4.27
Total	925.61	
Discharge		
Evapotranspiration	0.1	0.01
Agricultural pumping(1st layer)	289.18	21.82
Agricultural pumping(2nd layer)	416.14	31.40
Industrial and domestic pumping	618.46	46.67
Boundary outflow	1.42	0.11
Total	1325.31	

using the ARD method. In the Pinggu basin the groundwater quantity was recorded by each county. Therefore, it has been possible to compute the areal discharge and recharge rates of the agricultural pumping and irrigation return conveniently. Fig. 1 shows the areal distribution of recharge and discharge zones in the different aquifers.

Using the ARD method, three ARDs were added to the MODFLOW model. Table 2 shows the name file of the model.

The model simulates the groundwater flow from 1 January 2003 to 31 December 2008, calibrated and validated using 26 observation wells. The numerical solution was obtained with the PCG2 solver (Hill, 1990). Table 3 shows the water budgets of groundwater system of Pinggu basin.

With the benefit of the ARD method, water budgets of precipitation recharge, irrigation return recharge, agricultural pumping, industrial and domestic pumping were calculated easily.

4. Summary and Conclusions

By reusing the code of the RCH package, a simple and powerful tool, the ARD method, has been provided for MODFLOW to simulate areally distributed recharge and discharge. The ARD method maintains the integrity of MODFLOW and its input follows the standard RCH convention.

In an application of a regional groundwater flow model in the Pinggu basin, it is demonstrated that the ARD method can efficiently simulate areally distributed precipitation recharge, multilayer pumping wells discharge and irrigation infiltration recharge to the groundwater system simultaneously.

Software Availability

The software may be requested via e-mail from the authors (guominli@mail.iggcas.ac.cn, lemondyh@mail.iggcas.ac.cn).

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.cageo.2011.10.005.

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