Appication of MODFLOW to Jun stream basin in Donghae city

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1. Introduction

Groundwater refers to water in a saturated zone of geologic stratum. Groundwater constitutes the largest available source of fresh water far greater than all the lakes, reservoirs, and streams. In order to utilize a groundwater as water resource, it is necessary to understand the properties of groundwater flow. The characteristic of groundwater flow is very complex and it is usually modeled as a simplified mathematical form for the practical applications. MODFLOW is one of the simplified mathematical groundwater flow model.

MODFLOW has been widely used for groundwater simulations and practical applications. After the birth of MODFLOW, many researchers have been applied the model to real groundwater basins. Eberts and Bair (1990) simulated effects of quarry dewatering near a municipal well field in the city of Columbus, Ohio. Cherkauer and McKereghan (1991) examined seepage of groundwater to Green Bay and Lake Michigan from a fractured dolomite aquifer beneath the Door Peninsula of Wisconsin to determine the influences of embayments on the relative amount of groundwater discharge. Reynolds and Spruill (1995) used MODFLOW to estimate the effects of groundwater withdrawals by a phosphate mining operation and a public water-supply well field on a regulated aquifer system. Christensen et al (1998) predicted regional groundwater flow to streams in the Gjern catchment in eastern Jutland, Denmark. In Korea, Chung et al (1994) analyzed groundwater flow in Bugok hot spring area using the MODFLOW model which can simulate three dimensional groundwater flow both in confined and unconfined aquifers.

The purpose of this study is for the applications of a three-dimensional ground water flow model to the aquifer system in Jun stream watershed in Donghae city. The model is calibrated based on the existing data for the groundwater simulation and analysis in Jun stream basin. The specific objectives of this study include that simulation and calibration of a natural steady-state which has no well stresses, Comparison of superiority of solution package in simulate complex groundwater basin, simulation study for the design wells provided for satisfying water shortage in Donghae city and, sensitivity analysis of the model parameters in the packages.

2. A Modular Three-Dimensional Finite-Difference Groundwater Flow Model

Infancy of the study, Trescott (1975), Trescott and Larson (1976), and Trescott, Pinder, and Larson (1976) constructed the two- and three-dimensional finite-difference model. U.S. Geological Survey and others have studied the computer simulation of groundwater flow based on their previous work. The major purpose in designing a new groundwater flow model were to produce a program that could be readily modified, was simple to use and maintain, could be executed on a variety of computers with minimal changes, and was relatively efficient with respect to computer memory and execution time. In this study, majority of the explanation of MODFLOW is referenced to McDonald and Harbaugh (1988).

MODFLOW uses a modular structure wherein similar program functions are grouped together. New options can be added without the necessity of changing existing subroutines because of this structure. The program was originally written using FORTRAN 66 (McDonald and Harbaugh, 1984). It has subsequently been modified to use FORTRAN 77. This report documents the FORTRAN 77 version. The program is highly portable; it will run, without modification, on most computers. On some computers, minor modification may be necessary or desirable.

The major packages that are presently available include procedures to simulate the effects of wells, recharge, rivers, drains, evapotranspiration, and "general-head boundaries". The solution algorithms available included two iteration techniques, the Strongly Implicit Procedure (SIP) and the Slice-Successive Overrelaxation method (SSOR).

The three-dimensional movement of ground water of constant density through porous earth material may be described by the partial-differential equation :

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)-W=S_s\frac{\partial h}{\partial z}$$

where K_{xx}, K_{yy} and K_{zz} are values of hydraulic conductivity along the x, y, and z coordinate axes, which are assumed to be parallel to the major axes of hydraulic conductivity (Lt^{-1}); h is the potentiometric head (L); W is a volumetric flux per unit volume and represents sources and/or sinks of water (t^{-1}); S_s is the specific storage of the porous material (L^{-1}); and T is time (t).

Basic Package, Block-Centered Flow Package, River Package, Recharge Package, Well Package, Evapotranspiration Package, General Head Boundary Package are used in this study.

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3. Applications

1) Study Area

Jun stream located at Donghae city in Kangwon province is a small size stream. The surface water basin area is 123.0km^2, the length of the stream is 18.42km, and the shape of the basin is a branching type. The surface water basin of Jun stream is located at 128° 5′ 33″ of east longitude and 37° 25′ 24″ of north latitude. The stream is generated from Samwhua Dong, flows to northeast side, joins with Shinhung stream, and flows to the East Sea in Donghae city. Precipitation of the site is 1,237mm. The slope of the stream bed is approximately 1/250 from the estuary to the point of the confluence and 1/50 at upstream.

The flow direction at upstream is approximately parallel to the direction of foliation of neighboring strata or strike of cracks. Tributaries are developed to the east-west direction, the upstream is a steep slope, and the longitudinal cross section shows its irregularity. Hydrogeologic units in this site are mainly formed as a granite, limestone, unconsolidated sediments, half-consolidated sediments, crystalline metamorphic rock, metasedimentary rock, and early sedimentary rock.

As a result of the investigation of hydrogeology in this site, it was proved that there are two fault lines which are lying on the north-south direction in parallel and there are apparent differences in stratal distribution. Two fault lines divide the area into three sites which have the different hydraulic characteristics.

2) Discretization and Boudnary Conditions

The grid is composed of 85 rows by 104 columns and it has a 50m wide by 50m long. The model vertically divide the study area into five layers. Layer 1 represents a unconfined aquifer. It contains continental deposit, fluvial deposit and surface layers. Layer 2 represents marine deposite layer that contains fine-grid silty sand and clay under the continental deposit layer near the East Sea. It plays role of a confining layer to the Bukpyung pudding layer. Layer 3 represents the Bukpyung pudding layer which is confined by the upper layer. Layer 4 represents thick mudstone layer which is impermeable. It has confining effect on the layer 5. Layer 5 is confined Pungchon limestone layer. Drill logs shows discrete geologic structures in this site. Based on the elevation and bottom elevation data from field drill log in each layer, the bottom elevations in whole basin are interpolated by using the Kriging method. The closer to the east coast, the deeper bottom elevation of each layer is and the thicker each layer is. Upper layers have the irregular distribution of bottom elevations of layer while lower layers have simple one. In MODFLOW, a layer cannot simply vanish when a pinchout occurs by the real stratification and limitation of data. Thus, this study uses 0.1m as a minimal thickness of the layer..

Boundary conditions are for the simulation on the effect of external flow in interested area. But it is impossible to determine distinct delineation of a groundwater basin without abundant geologic survey. Therefore, the general head boundary is utilized as a boundary condition to complement those problems. The border of groundwater basin is delineated along 30m-contour line of ground surface, which has small effect of upland, and the resident and drill logs are included within the boundary. Groundwater is assumed to flow from inland to the East Sea, namely, from the west to the east. Therefore, the outer groundwater inflows from the west inland. The northern and southern boundaries are applied as no flow boundaries and the eastern and western boundaries are mainly general head boundaries. Even though the cells are located at the northern and southern boundaries, if they are assumed as orthogonal groundwater flow lines, they may be general head boundary conditions. Initial boundary heads in Gen-eral Head Boundary Package (GHB) were substituted by an initial observed head for steady-state simulation. Constant head boundaries are utilized as a boundary condition of the northeast part of the site where the East Sea bounds.

3) Hydraulic Characteristics

Aquifer tests for determining hydraulic characteristics were performed from 10th of February to 18th of May in 1996 (KOWACO, 1996). MODFLOW needs all hydraulic conductivitics at the center of each model grids. A Kriging method is adopted in order to solve the problem with the limited measurements of hydraulic conductivities. The hydraulic conductivity around northeast side is greater than that of southeast part of the basin.

In MODFLOW, the vertical flow between layers is controlled by the vertical conductance coefficients, *Vcont*. In the process of calibration, it is necessary to change hydraulic conductivities for matching the calculated and observed groundwater levels. It takes a time to convert *Vcont* according to changes of hydraulic conductivities. Because of the inconvenience, Fortran program was developed to convert *Vcont* automatically.

4) Others

Jun stream functions as a source of recharge to the aquifer and a recipient of discharge from the aquifer. The data used in River Package is referenced from "The Report of Channel Improvement Plan for Jun Stream"(1994, Donghae city). Since it is considered that the effect on the aquifer system would be small, the tributaries of Jun stream are excluded.

Recharge rate is estimated as 0.0005m/day from the report by KOWACO(1996). Evapotranspiration estimate is 572mm per year when the equivalent method of soil moisture is used with rainfall data at Samchuk station. This value is referenced from the report by KOWACO (1996).

5)Well

Stresses from well are not considered in the first simulation condition in which model is calibrated because there is no dewatering in natural state. Though there is a personal small well, it is ignored because its effect is very slight and there is no exact data. Second simulation condition is to add the existing wells to the first calibrated steady-state simulation to represent the natural state. This simulation is inevitable since it makes it possible to examine the pure effect of third simulation of the design wells on groundwater flows at the basin. Row and column numbers and the discharge of existing wells are presented in table 1. Third simulation condition is for the prediction of the availability of groundwater by using design wells. Its objective is to investigate the change of groundwater system by the design wells. The location of wells are assumed based on the following considerations for Donghae city. First, Avoid the distributions of the densely grouped wells. Second, pumping discharge rate sould be fine. Third, where it is easy to secure the site of pumping facility. Fourth, Groundwater should not be contaminanted.

Table 1. Existing Wells

Well Point	Row	Col	Discharge (m^3/day)	Stressed Layer	Distributed Discharge(m^3/day)
JCW-1	44	77	3000	3	2500
				5	500
JCW-2	51	66	2500	3	2000
				5	500
JCW-4	48	34	2000	3	700
				5	1300
JCW-5	55	32	2000	1	500
				3	300
				5	1200
W-1	48	56	2500	3	1000
				5	1500
W-2	48	57	2000	3	900
				5	1100

4. Calibration

Even though we simulate the packages in MODFLOW with the data sets obtained by field survey, the uncertainty of groundwater flow always exits due to the limitations of geologic distribution data, the heterogeneous characteristics of aquifer and so on. Therefore, the calibration process is inevitable for the reasonable simulation of groundwater basin. After the calibration, the changes of groundwater flow caused by the pumping of design wells can be simulated. This study assumes that the hydraulic conductivity and boundary condition may have the largest uncertainties in the simulation. The calibrations for these two characteristics are mainly accomplished. The calibration for hydraulic conductivities is performed in a physically proper range based on the hydraulic conductivities interpolated with Kriging method. The reasonable result of calibration is evaluated from the comparisons of the calculated and observed groundwater heads and the groundwater budget in the basin.

Table 2. The target and calculated heads for layer 1

Well Point	X	Y	Target Head(m)	Calculated Head(m)	Residual (m)	Squared Residual(m)
MW-9	208.9096	441.8291	7.43	7.34	0.09	0.008
MW-14	209.4111	441.7066	5.56	5.72	-0.16	0.026
MW-16	209.1211	442.0997	6.64	6.70	-0.06	0.004
MW-19	210.1693	442.1123	2.31	2.59	-0.28	0.078
MW-28	210.3627	442.5619	0.94	2.10	-1.16	1.346
MW-29	210.1191	442.5695	0.93	2.51	-1.58	2.496
MW-35	209.2351	442.5474	5.54	5.72	-0.18	0.032
MW-39	208.4535	442.4897	6.83	6.86	-0.03	0.001
MW-45	208.7513	442.6970	7.43	7.19	0.24	0.058
JCW-5	208.5140	442.0030	6.07	5.91	0.16	0.026
JCW-6	209.1800	442.3740	2.29	5.96	-3.67	13.469
JCW-7	209.3500	442.1220	6.26	5.92	0.34	0.116

The layer 2 and 4 are impermeable and the calibration is performed for the layers of 1 and 3. The observations of hydraulic head in layer 5 could not be found in the previous study (KOWACO, 1996) and it is not considered in this study for the calibration purpose. Tables 2 and 3 show the target head used for the calibration and the calculated head by calibration. Table 2 is for layer 1 and table 3 is for layer 3. There are several abnormal large residuals which represent the difference between the target and calculated heads in table 2 and 3 (table 2: MW-28, MW-29, JCW-6 and table 3: JCW-2). There may be two answers for the large residuals. First, the calibration is not enough to represent the characteristics of the basin.

Second, the hydraulic characteristics of this abnormal point are so different that the additional field survey of aquifer may be needed. RMSE of the target and calculated heads at layer 1 is 0.20m with removing abnormal points and that at layer 3 is 0.35m. Approximately 1ft (30.48cm) is acceptable error of groundwater elevation in other researches (Restrepo at al., 1992).

Table 4 shows water budget related to each package used in the calibration process. Inflow of 'Constant Head' is zero. It means that there is no inflow of salty water from the East Sea. The water budget is mainly dependent on 'Head Dependent Bounds'. That is to say, most of groundwater flow occurs around the border of groundwater basin. The steady-state calibration is accomplished relatively well, since 'Percent Discrepancy' is -0.01, near to zero.

Table 3. The target and calculated heads for layer 3

Well Point	X	Y	Target Head(m)	Calculated Head(m)	Residual (m)	Squared Residual(m)
W-1	209.7223	442.4102	4.15	3.93	0.221	0.049
W-2	209.7927	442.4199	4.09	3.77	0.325	0.106
W-6	209.7987	442.5022	4.37	3.81	0.564	0.318
JCW-2	210.1940	442.2340	4.20	2.49	1.715	2.941
JCW-3	209.9380	442.6440	3.27	3.41	-0.139	0.019

Table 4. Water budget for each package used in the calibration process

Item	Inflow(m^3/day)	Outflow(m^3/day)
Constant Head	0.0000	112626.2000
River Leakage	1137.0030	5816.9700
ET	0.0000	3656.9390
Head Dependent Bounds	394985.6000	279480.2000
Recharge	5431.2500	0.0000
Total inflow	401553.9000	401580.3000
Inflow-outflow(m^3/day)	26.4375	
Discrepancy(%)	-0.01	

5. Simulation of Design Well

After the calibration for the natural state, the simulation for existing wells should be done before the simulation of design wells for the safe demands of water for domestic and industrial purposes of 20,000m^3/day in Donghea city. The reason why the simulation of existing wells should be done before the simulation of design wells is to examine the pure effect of design wells on the Jun stream basin. Drawdowns caused by existing wells are calculated based on the calibrated results. The maximum drawdowns at layer 1, 3, and 5 are respectively about 0.07, 0.6, and 1.0m. Approximately the maximum 1m-drawdown at layer 5 occurs from the contours of drawdown compared to calibrated natural state. When we simulate for existing wells, there is no dried cell and so groundwater is not drying up for the operation of existing wells. Drawdowns near the east coast area is so insignificant that salty water doesn't intrude into inland.

In order to choose the locations of well field sets, the most important things are the yield capacity and quality of groundwater among the commented conditions as afore mentioned. The data for yield capacity and quality of groundwater is referenced from the report by KOWACO (1996).

Table 5. Aquifer distribution and hydraulic characteristic in Jun stream basin

Observed Well Point	Thickness Rangeof Aquifer(m)	Hydraulic Conductivity (m/day)	Specific Yield Capacity(m^2/day)	Existing Layer
W-1 W-2 JCW-4	4.45 ± α	27.4~400	630~2000	Free surface limestone aquifer and pudding layer
JCW-1 JCW-2 JCW-3	13.9~33.0	0.9~257	24.5	Confined pudding aquifer and alluvial aquifer
JCW-5 JCW-6 JCW-7	7.8~11.5	1.7~1280	50.0~3467	Alluvial aquifer

The existing morphology of groundwater is varying according to the positions. Yielding form of groundwater is divided into three types. The table 5 shows the distribution of aquifers and underground hydraulic characteristics. The specific pumpage in the second row represents that of JCW-3 observation well as a result of pumping test. It is smaller than any other specific pumpage in the basin. Water quality samples from seven drilled observation wells in Jun stream basin shows that water from JCW-3 is not proper.

Since fault belts longitudinally exist from north to south around Jun stream bridge and the site around JCW-3 is excluded for choosing the design well sites. The fields of an design wells are determined in four places in the directions of the east and west sides of the basin. The fields of design wells are planned to be located like figure 3.11.

Each design well is arbitrarily distributed with the similar distance in the selected zones. The wells are sited near the Jun stream in order to put the wells around main stream as the discussed before. The distributed discharges in each layer are calculated based on the transmissivities in assigned cells and the results are shown in the last column of table 6.

Table 6. Characteristics of design wells

Well Point	Row	Col	X	Y	Discharge (m^3/day)	Pumping Layer	Distributed Discharge(m^3/day)
IW-11	49	29	208.9752	442.3472	2000	3	64.35
						5	1935.65
IW-12	48	40	208.9252	442.3972	2000	1	2000.00
IW-13	47	53	209.5752	442.4472	2000	1	2000.00
IW-21	53	35	208.6752	442.1472	2000	1	2000.00
IW-22	53	42	209.0252	442.1472	2000	1	2000.00
IW-23	53	53	209.5752	442.1472	2000	1	2000.00
IW-31	45	71	210.4752	442.5472	2000	1	1519.20
						3	480.80
IW-32	41	81	210.9752	442.7472	2000	1	1687.16
						3	312.84
IW-33	39	86	211.2252	442.8472	2000	1	1787.85
						3	212.15
IW-41	50	72	210.5252	442.2972	2000	1	1580.10
						3	419.90
IW-42	48	80	210.9252	442.3972	2000	1	1599.31
						3	400.69
IW-43	45	86	211.2252	442.5472	2000	1	1774.97
						3	225.03

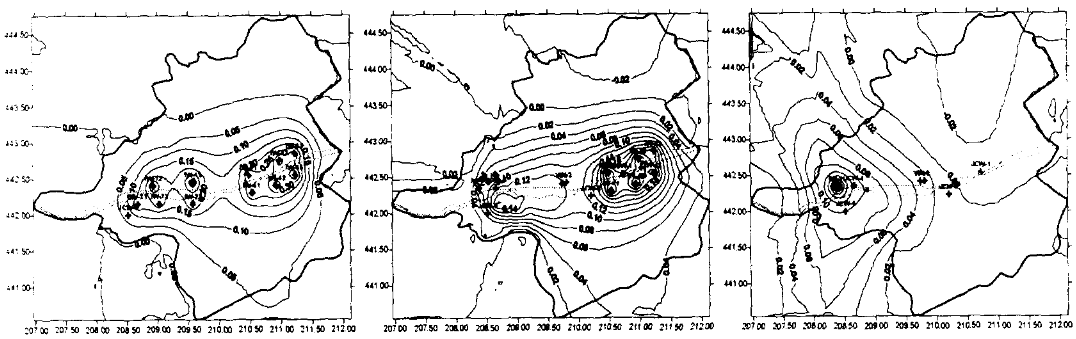

Figure 1. The drawdown of layer 1, 3, 5 caused by the designed wells

The result of simulation for plan to construct desgn well is presented in figures 1 to 3. Contour lines of head drawdown are presented for the assigned layers of each well.

Synthetically judged, there are no severe changes of drawdown contours caused by adding new well (i.e., design wells). Drawdown of southern part of the basin is larger than that of northern part. Drawdown at layer 3 is much smaller than drawdown at layer 1 because layer 3 is confined aquifer. Also, the drawdown affects the hydraulic head at the southern part of the basin comparatively far away. Drawdown occurs only at IW-11 point which is unique in layer 5. So, it can't affect hydraulic head to the east coast. Because there is no dried cell when the design wells are simulated, it is considered that groundwater does not run dry for the simulation. The guess that groundwater does not dry up is supported by the water budget to be generated by MODFLOW, in which the inflow of groundwater at the basin equals the outflow. Additionally, the groundwater budget explains that there is no influx from the east coast caused by the design wells and we can know that there is no inflows in the constant head cells from MODFLOW outputs.

Finally, the plan to install new wells (design wells) near to the downstream of Jun stream can satisfy for predicted water demand, 20,000m³/day, and the groundwater system will not meet serious problem.

6. Conclusion

It was investigated that more water of 20,000m³/day is needed for satisfying water demand in Donghae city. Therefore, this study used MODFLOW to provide sufficient water demands to Donghae city from the groundwater basin through the processes of simulation, calibration, and sensitivity analysis using the design wells. We can obtain the water of 24,000m³/day from 12-design wells and it is sufficient to satisfy the water shortage problem of Donghae city. Also the study provided that the groundwater basin has no effect even though the basin losses the water as much as 24,000m³/day.

First step was to simulate natural steady-state which has no well pumping stresses. Hydraulic characteristics of aquifers were obtained at the points of drill logs for pumping tests. Using these characteristics, the calibration was performed and the simulated heads were compared with observed heads. Second step was to simulate the effect of existing wells and then the effects of design wells were investigated for the hydraulic heads. Third step was to simulate the design added wells for the increased water demand in the future. The required amount of water was assumed as a 24,000m³/day. New wells were distributed in the vicinity of a main stream of Jun stream by considering the condition of a basin. Finally, the sensitivity analysis for the parameters were performed based on the results from the third step.

Based on the results of this study, the following conclusion could be obtained.that the maximum drawdown is approximately 0.35m after simulating the design wells to predict the water demand of 24,000m³/day. Therefore, the new stress will not cause a serious problem in the aquifer system. Data used in this application was not enough and not proper for exact simulation. In order to accomplish more exact simulation of a groundwater basin, it is also important to make a perfect plan to get data and to execute strict field survey.

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