Examensarbete
TVVR 09/5002

Submarine Groundwater Discharge Estimation from Kikuchi River Basin to the Ariake Bay, Japan

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Avdelningen för Teknisk
Vattenresurslära
ISRN LUTVDG/TVVR-09/5002+48p
ISSN-1101-9824

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January 2009

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January 2009
Report TVVR 09/5002
Master of Science Thesis in Water Resources
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Abstract

Submarine groundwater discharge (SGD) affects environmental conditions in semi-enclosed sea areas. Semi-enclosed areas often experience eutrophication caused by excess nutrient transport from agricultural areas. However, it is often unclear how much the nutrients that are transported through the groundwater discharge. Therefore, it is necessary to quantify groundwater discharge to the sea. For this quantification, a methodology to estimate SGD is presented. A distributed groundwater recharge model (GRM) and a groundwater flow model (GFM) were developed and coupled to estimate SGD from Kikuchi River basin into the Ariake Bay, Kumamoto, Kyushu, Japan. The river basin located in Kumamoto prefecture was studied as a representative area for the entire Ariake Bay catchment. The GRM separates rainfall into direct runoff, evapotranspiration, and groundwater recharge. Parameters are set based on land use. Groundwater level was calculated by the GFM to estimate subsurface water runoff, base flow to the river, and evaporation from the shallow groundwater table. The SGD was calculated using a water balance approach. The result of calculation shows that SGD accounts for 47 mm year^{-1}, corresponding to 3.6 % of the river discharge and 2.3% of the average annual rainfall. The results are in the same range as earlier reported in the research literature and thus appear reasonable.

Keywords
Groundwater flow model, groundwater recharge, hydrological model, numerical simulation, submarine groundwater discharge, water balance analysis.

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Acknowledgement

This work was carried out at the Department of Water Resources Engineering, Lund University. I would like to thank Prof. Ronny Berndtsson for giving me this opportunity to do research at Department of Water Resources Engineering, Lund University and continuous support and advice.

From Kyushu University, Prof. Kenji Jinno gave me a lot of advice especially for the approach methods.

Thanks to all my colleagues for all discussions and help.

The present study was financed by the International Training Program (ITP) of Japan Society for the Promotion of Science (JSPS) and the Scandinavia-Japan Sasakawa Foundation (SJSF).

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Abbreviations, Acronyms, and Symbols

AE	Actual Evapotraspiration
AIST	National Institute of Advanced Industrial Science and Technology
FDM	Finite Difference Method
GF	Groundwater Flow
GFM	Groundwater Flow Model
GRM	Groundwater Recharge Model
GSJ	Geological Survey of Japan
JMA	Japan Meteorological Agency
MILT	Ministry of Infrastructure, Land and Transport, Japan
PE	Potential Evapotranspiration
SGD	Submarine Groundwater Discharge
SMHI	Swedish Meteorological and Hydrological Institute
SOR	Successive Over Relaxation
USGS	United States Geological Survey, US
WBA	Water Balance Analysis

GRM

a_L	Outlet flow coefficient
D	Daily sunshine hours in unit of 12 hours
$EVT_1(t)$	Evapotranspiration from the tank
$F(r)$	Direct runoff coefficient
F_∞	Maximum value of direct runoff coefficient
$h_w(t)$	Storage water depth
$PE(t)$	Potential evapotranspiration
P_t	Saturated water vapor density
q_d	Direct runoff
$q_w(t)$	Groundwater recharge
R_0	Outlet level
$r(t)$	Effective rainfall
$r_{int}(t)$	Rainfall interception at forest area
$r_{total}(t)$	Total rainfall
$r_{(1/2)}$	Rainfall when $F(r)$is equal to $F_\infty/2$
$Y[h_w(t)-R_0]$	Step function equal to 1 for $h_w(t)> R_0$ and 0 for $h_w(t)< R_0$

GFM

$b(x,y,t)$	Impermeable base elevation
$EVT_2(x,y,t)$	Evaporation from groundwater table
$GL(x,y)$	Ground surface elevation

$h_f(x,y,t)$	Fresh groundwater head
$h_s(x,y,t)$	Salt groundwater head
h_g^*	Extinction depth of groundwater table for EVT_2
k	Permeability
n_e	Porosity of the groundwater aquifer
$q_m(x,y,t)$	Groundwater pumping rate from wells
$q_l(x,y,t)$	Base flow from groundwater aquifer to river
u_f	Velocity in x-direction of fresh groundwater
u_s	Velocity in x-direction of salt groundwater
v_f	Velocity in y-direction of fresh groundwater
v_s	Velocity in y-direction of salt groundwater
ϕ_f	Piezometric head of fresh groundwater
ϕ_s	Piezometric head of salt groundwater
ρ_f	Density of fresh groundwater
ρ_s	Density of salt groundwater
$\Delta\rho$	Difference of densities between fresh and salt groundwater

WBA

AE_i	Actual evapotranspiration in basin no.i
GF_i	Groundwater outflow in basin no.i
Q_{outi}	River Discharge in basin no.i
ΔS_i	Change of water storage in basin no.i

Chapter 1 – Introduction

1.1 Introduction to Submarine Groundwater Discharge

Coastal environmental deterioration caused by nutrient (i.e., nitrogen and phosphorous) discharge from land areas is a serious problem in many parts of the world. Excess nutrient input often results in eutrophication that can damage the marine ecosystem in a bay or estuary. Recent research has shown that submarine groundwater discharge (SGD, see Figure 1.1 and 1.2) is a significant pathway of water and nutrients from land to sea (e.g., Moore 1996).

According to USGS (2007), SGD is defined as "An ubiquitous coastal process that is driven by a composite of climatologic, hydrogeologic, and oceanographic processes". More concrete and detailed explanation of SGD is shown in Figure 1.3. Recently, SGD is recognized as being consisted by three groundwater components, which are freshwater, brackish water and recirculated seawater. Since those waters are mixed and discharged as brackish water in the field, electric conductivity (EC) or often measured for separation of freshwater components. Besides, radioactive isotope (e.g., ^{222}Rn) is also observed as a tracer, which can investigate the origins or travel time of groundwater flow.

The SGD often contains high amounts of fertilizers from agricultural and urban areas (e.g., Taniguchi *et al*. 2002) that may be assumed to be connected to eutrophication (e.g., Figure 1.1) and in turn to the ecosystem and fishery production. Therefore, SGD is an important component of the hydrological cycle to quantify.

Much research has been done to estimate SGD based on hydrological and oceanographic approaches. A water balance analysis is often used as a simple but efficient method to understand the hydrological cycle, which mainly considered freshwater component (e.g., Berner & Berner 1987, Zektser & Loaiciga 1993). To understand saltwater intrusion and transport to coastal aquifers, modeling studies have utilized numerical simulation for groundwater flow (e.g., Thompson *et al*. 2007). Hydrological runoff models can be combined with a water balance approach to quantify SGD (e.g., Destouni *et al*. 2003, Jarsjö *et al*. 2007). On the other hand, field surveys using, e.g., seepage meter have been attempted to estimate SGD for regional scale studies. As such research approaches isotope tracer analysis (e.g., Hussain *et al*. 1999, Mcoy *et al*. 2007) or direct piezometric head measurement (e.g., Simmons 1992) was applied to investigate flux and origin of SGD.

However, in spite of the above approaches, efficient SGD estimation methods have not yet been established especially at the catchment scale. The hydrological processes at catchment scale are complicated since both surface-subsurface water interaction and land-ocean water interaction need to be considered simultaneously. Consequently, an efficient approach may be necessary in order to couple numerical simulation and water balance for the estimation of SGD at the catchment scale.

In the present paper, a methodology to estimate SGD, which is considered as freshwater flow from land area to ocean, using a numerical simulation coupled with water balance analysis was developed. The study area is situated in the Kikuchi River basin which discharges to the Ariake Bay. In the Ariake Bay the red tide phenomenon is assumed to be induced by eutrophication and this has seriously damaged the marine environment and fishery industry (Yanagi & Abe 2005). Very little information on the potential effect caused by groundwater discharge to the Ariake Bay has been reported. Quantitative assessment of the SGD for the area is needed to analyze the possible impact of groundwater discharge to the marine environment. In the present study, a simple but efficient water balance approach was used to estimate SGD from the Kikuchi River basin. For this, a groundwater recharge model coupled with a groundwater flow model developed by Tsutsumi *et al*. (2004) was applied.

Figure 1.1 Example of submarine groundwater discharge (SGD) in Rishiri Island, Hokkaido, Japan (GSJ)

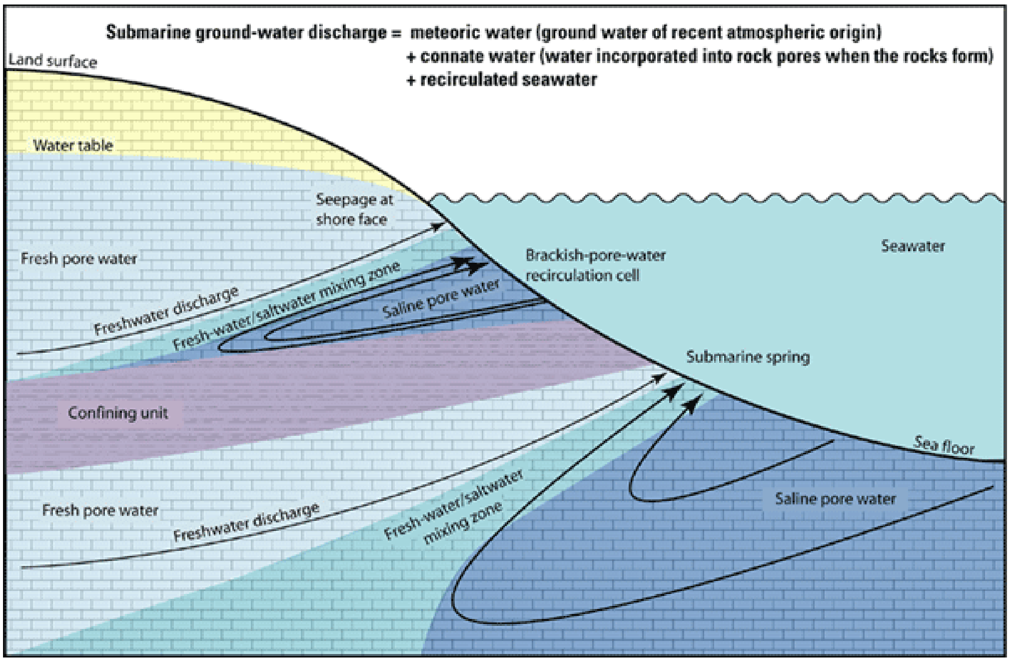

Figure 1.2 Schematic image of Submarine Groundwater *Discharge (USGS 2007)*

Figure 1.3 Example of eutrophication (red tide) in Ariake Bay, Saga, Japan (Saga Shinbun Co., Ltd. 2008)

1.2. Study Area

1.2.1. The Ariake Bay

Ariake Bay is located at the northwest of Kyushu Island, Japan (Figure 1.4). It has a water surface area of 1,700 km^2. Because of the shallow depth of the bay, which is 20 m on average, the difference of the seawater levels between high tide and low tide is about 3-5 m. The area affected by the high tidal changes has an unique habitat for plants and animals (Figure 1.5a and 1.5b).

As seen from Figure 1.4, the bay is of a semi-closed shape which small sea water exchange between inside and outside of the bay. Therefore, eutrophication is often a result especially during summer (e.g., Figure 1.4) because of excess nutrients inputs from the catchment area. This phenomenon can give serious damages to the marine environment, which is related to the fishery industry such as seaweed production (Figure 1.5c). However, the detailed mechanism of this eutrophication occurrence has not been studied well yet. A hydrological approach is one suggested method of the study of this problem for basin water management.

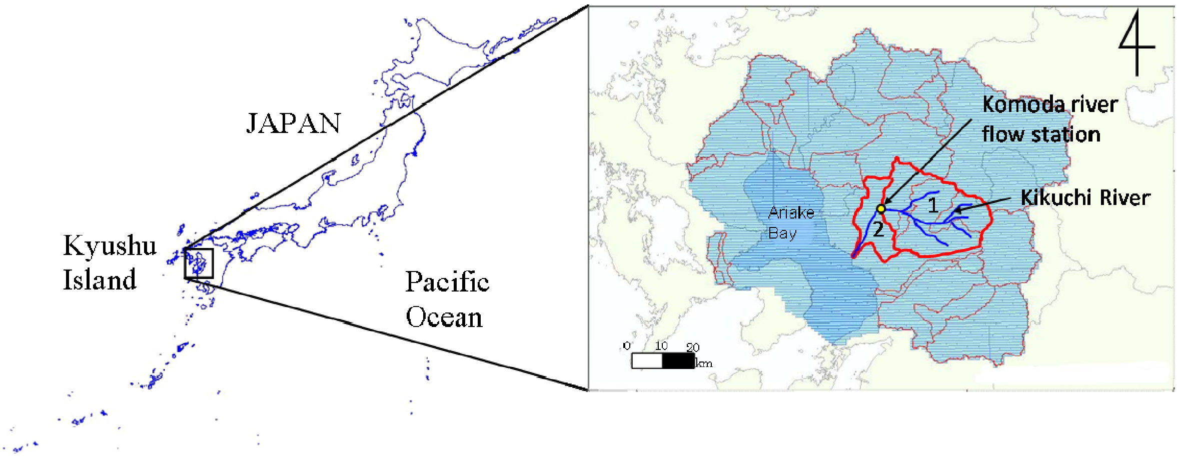

Figure 1.4 Locations of Ariake Bay and Kikuchi River Basin in Kyushu Island, Japan (no.1: upstream Komoda station, no.2: downstream Komoda station)

Figure 1.5a Tidal landscape at low tide in Ariake Bay (Farmers net 2008)

Figure 1.5b A goby fish named "Mutsugorou", which is typical for the tidal land in Ariake Bay (Unoki 2006)

Figure 1.5c Seaweed cultivate fields in Ariake Bay (Saga Prefectural Government 2007)

1.2.2. The Kikuchi River Basin

The study area, Kikuchi River basin, is located in Kumamoto Prefecture, Japan (Figure 1.4). The river basin is divided into two areas: sub-basin no. 1 for the upstream of Komoda discharge station and sub-basin no. 2 representing the downstream of Komoda discharge station. The total basin area is 1,004 km^2, which constitute 12% of the entire river catchment area discharging into the Ariake Bay. Land use distribution data were supplied by the Ministry of Infrastructure, Land and Transport (MILT). Land use was used to assign model parameters in the hydrological cycle, forest interception, direct runoff, and groundwater recharge. Figure 1.6 shows the land use distribution in the basin. Most of the upstream area is covered with forest, paddy field and other agriculture field which may have effect to hydrological cycle and nutrients cycle in the area. Precipitation and temperature data collected from Japan Meteorological Agency (JMA) were used as model input. As seen from figure 1.7, the Thiessen method was applied to assign observed data from 5 stations (Aso-Otohime, Kahoku, Kikuchi, Kumamoto, Minami-Oguni and Taimei) to each calculation grids. River discharge observed at Komoda station was used for model validation. All model inputs were prepared in a regular two-dimensional 500 m grid system. The study period covered 10 years from 1995 to 2004.

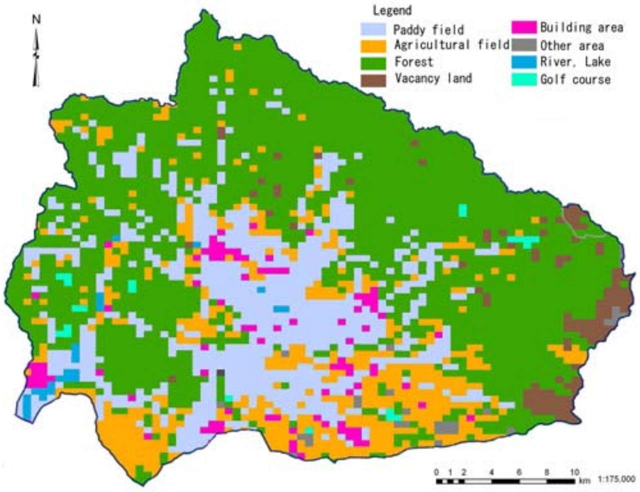

Figure 1.6 The land use distribution in Kikuchi River Basin by Ministry of Infrastructure, Land and Transport of Japan (MILT)

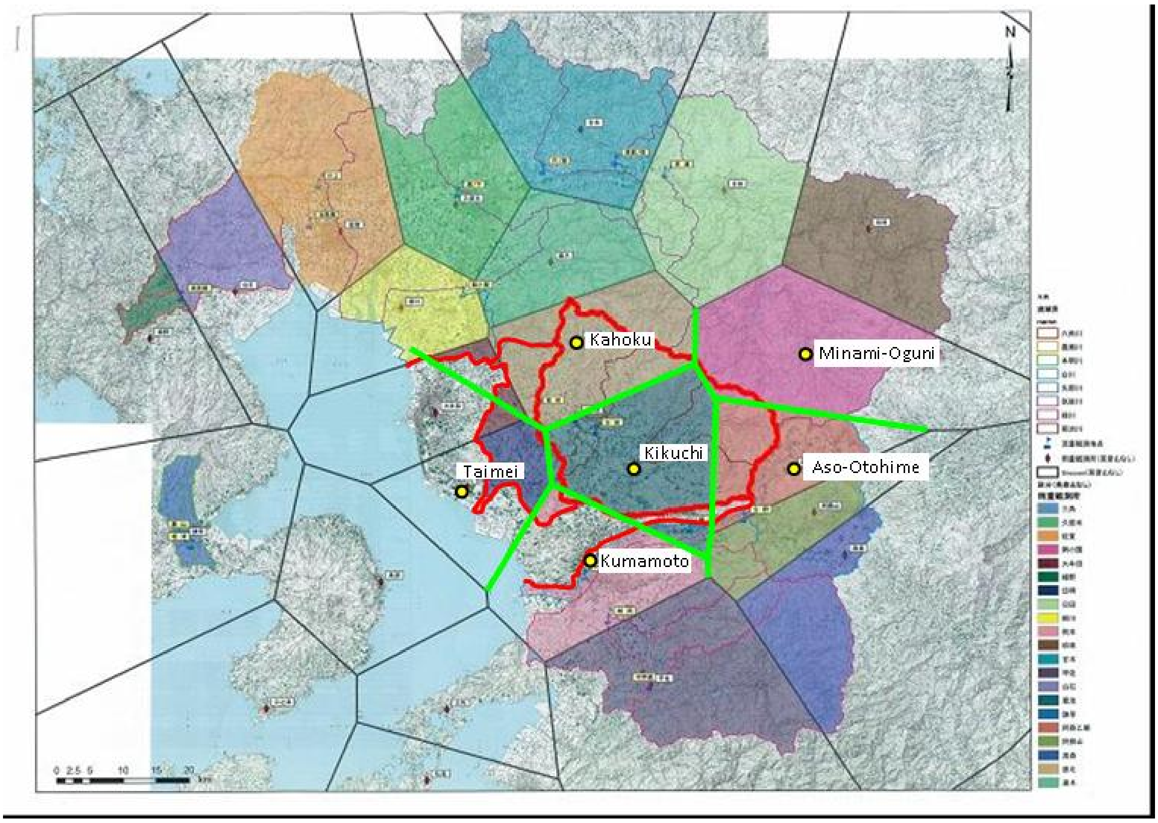

Figure 1.7 Thiessen method for rainfall and temperature data inputs from five stations of Japan Meteorological Agency (JMA)

Chapter 2 Methodology

2.1 General Procedure

In the present study, a simplified SGD estimation method is proposed as outlined in Figure 2.1. A groundwater recharge model (GRM) and a groundwater flow model (GFM) were developed to calculate surface and subsurface hydrological components. The resolution of the models is a 500 m x 500 m distance grid net. The GRM separates rainfall into groundwater recharge, evapotranspiration from a conceptual soil water storage tank, and direct runoff. The calculated groundwater recharge was used as the input data to the GFM which simulates the interface elevation between surface and subsurface water. The GFM also considers direct evapotranspiration from the groundwater table when groundwater is shallow. The groundwater discharge to the river is also calculated after the groundwater level is obtained. This GFM was developed using FORTRAN programming which employed Finite Difference Method (FDM) and Successive Over Relaxation (SOR) method. The flow chart of calculation processes and source code are shown in Appendix 1 and 2 respectively. The freshwater discharge directly to the Ariake Bay (SGD) was calculated by adapting a two-dimensional immiscible fresh and salt water interface model which is described below.

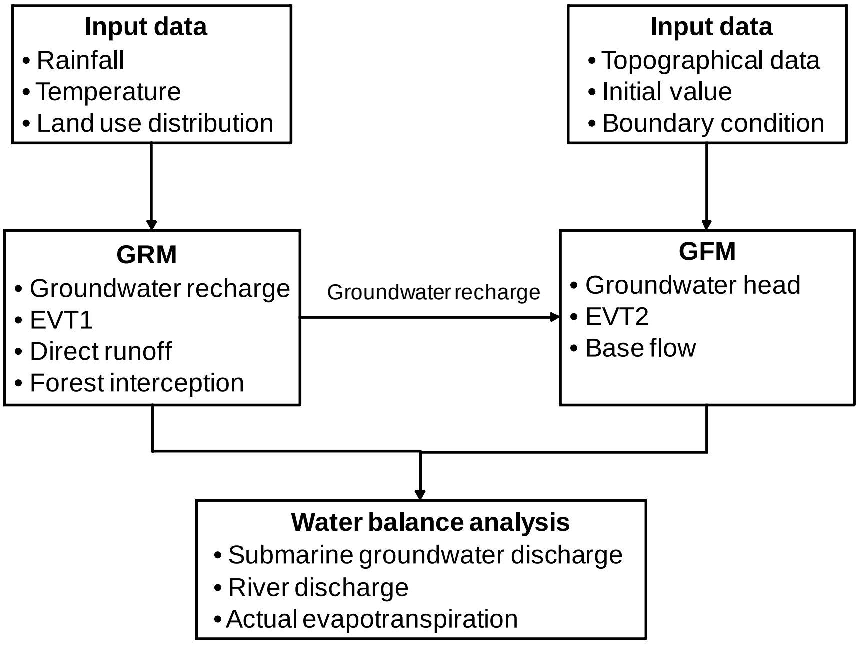

Figure 2.1 Flow chart of the analysis for submarine groundwater discharge estimation (EVT1=Evaporation from storage tank of GRM, EVT2=Evapotranspiration from groundwater table.)

2.2 Groundwater Recharge Model (GRM)

The conceptual groundwater recharge model (SRM) is illustrated in Figure 2.2. The model is coupled to each grid node for the catchment. The assigned models at each grid node functions calculate direct runoff, groundwater recharge, and evapotranspiration. For the forest area, rainfall interception $r_{\mathrm{int}}(t)$ is subtracted from total rainfall $r_{\mathrm{total}}(t)$. The rate of rainfall interception in the study area was taken from Kondo *et al.* (1992). Rainfall $r(t)$ was separated into direct runoff $q_{\mathrm{d}}=r(t)\cdot F(r)$ and infiltration $\{1-F(r)\}\cdot r(t)$, respectively. Here, $F(r)$ represents the direct runoff coefficient as a function of rainfall intensity given by:

$$F(r)=\frac{r(t)}{r(t)+(r)_{1/2}}\cdot F_{\infty} \tag{1}$$

where F_{∞} denotes the maximum value of $F(r)$, and $(r)_{1/2}$ is the value of $r(t)$ when $F(r)$ is equal to $F_{\infty}/2$.

The infiltrated water is stored in a conceptual storage tank with an outlet at height R_0 with outlet coefficient a_{L}. The field capacity of the soil is modeled by R_0 in order to consider time lag for groundwater infiltration. The a_L component controls the groundwater recharge $q_w(t)$ from the storage to groundwater table as follows:

$$q_w(t)=a_L\cdot\{h_w(t)-R_0\}\cdot Y[h_w(t)-R_0] \tag{2}$$

where $h_{\mathrm{w}}(t)$ is the water depth in the storage tank, and $Y[h_{\mathrm{w}}(t) - R_0]$ represents a step function equal to 1 for $h_{\mathrm{w}}(t) > R_0$ and 0 for $h_{\mathrm{w}}(t) < R_0$. Evapotranspiration occurs from the stored water in the tank if $h_{\mathrm{w}}(t) > 0$, representing evaporation from land surface and transpiration from vegetation. Potential evapotranspiration was estimated based on the Hamon (1961) method according to:

$$EVT_1(t)=PE(t)=0.14\cdot D^2\cdot P_t \tag{3}$$

and if the tank is empty ($h_{\mathrm{w}}(t) = 0$), then

$$EVT_1(t)=0 \tag{4}$$

where D denotes the sunshine hours in units of 12 hours and P_{t} is the saturated water vapor density calculated from the daily mean temperature. The stored water level is calculated at each time step using:

$$\frac{dh_w(t)}{dt}=\{1-F(r)\}\cdot r(t)-q_w(t)-EVT_1(t) \tag{5}$$

where dt denotes the time increment step equal to 1 hour. The parameters F_{∞}, $(r)_{1/2}$, R_0, and a_{L} were assigned values depending on land use (Table 1) to represent its effect to direct runoff, infiltration, and groundwater recharge from a previous study by Tsutsumi *et al.* (2004).

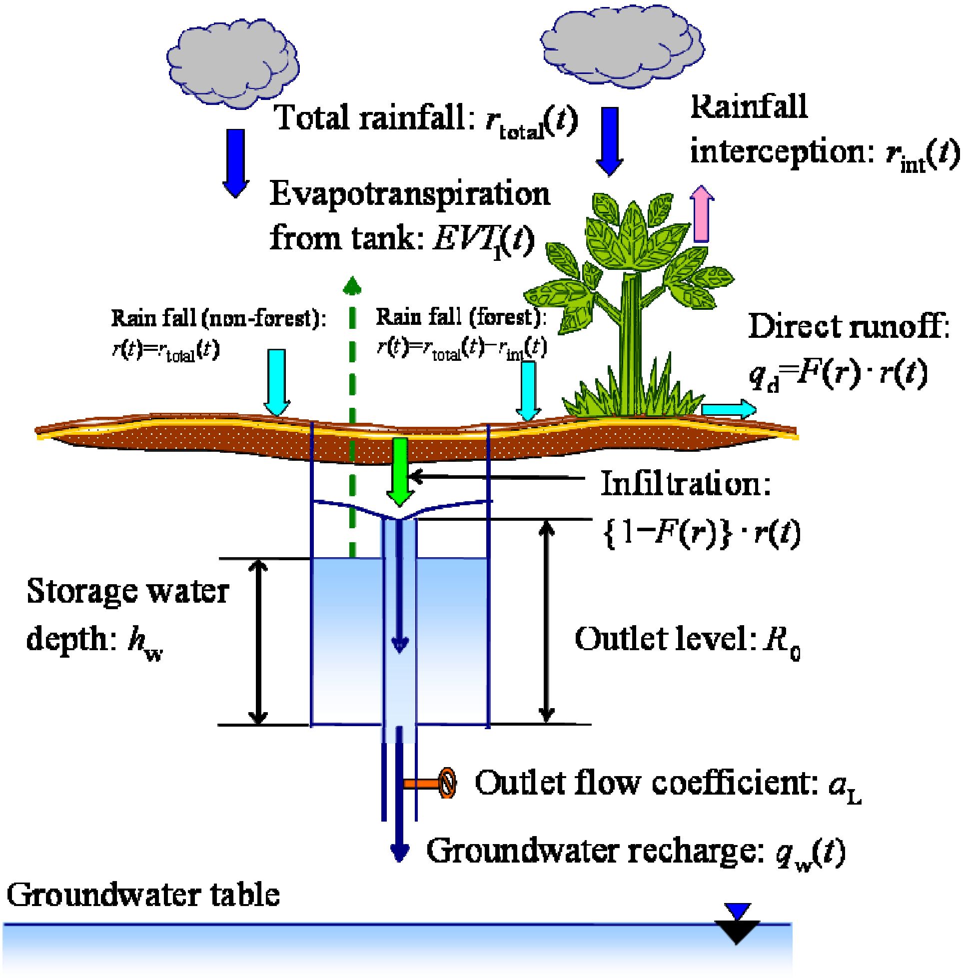

Figure 2.2 Schematic of groundwater recharge model (GRM) (Tsutsumi et al. 2004)

Table 2.1 Parameters of the groundwater recharge model (GRM) depending on land use classification
(F_∞ = maximum value of $F(r)$, $(r)_{1/2}$ = rainfall intensity at $F(r)= F_\infty/2$, R_0 = outlet height of tank , a_L = outlet coefficient of tank)

Land use*	F_∞	$(r)_{1/2}$	R_0	a_L
Paddy field	0.20	7.7	8.7	0.36
Agriculture field	0.20	7.7	8.7	0.36
Forest area	0.30	11.3	17.0	0.14
Vacancy area	0.30	4.4	10.3	0.29
Building area	0.30	3.4	13.0	0.20
Golf field	0.25	6.1	11.2	0.33
Other	0.26	6.7	9.5	0.28

**Classified by Ministry of Infrastructure, Land and Transport (MILT), Japan.*

2.3 Groundwater Flow Model (GFM)

A quasi three-dimensional salt and freshwater two-phase groundwater flow model (GFM) was applied to calculate the groundwater head. Figure 2.3 shows a description of the model concept. Close to the coastal area, not only freshwater but also saltwater head were calculated to simulate saltwater intrusion to the aquifer. The model employs a finite difference method to solve basic groundwater flow equations. Unconfined aquifer conditions are assumed. The equation for the freshwater aquifer is:

$$
\begin{aligned}
n_e \frac{\partial\{h_f(x,y,t)-h_s(x,y,t)\}}{\partial t} &= -\frac{\partial[\{h_f(x,y,t)-h_s(x,y,t)\}\cdot u_f]}{\partial x} - \frac{\partial[\{h_f(x,y,t)-h_s(x,y,t)\}\cdot v_f]}{\partial y} \\
&-\sum_m q_m(x,y,t) + q_w(x,y,t) - EVT_2(x,y,t)
\end{aligned}
\tag{6}
$$

and for the saltwater:

$$
n_e \frac{\partial h_s(x,y,t)}{\partial t} = -\frac{\partial[\{h_s(x,y,t)-b(x,y)\}\cdot u_s]}{\partial x} - \frac{\partial[\{h_s(x,y,t)-b(x,y)\}\cdot v_s]}{\partial y} \tag{7}
$$

where $h_f(x,y,t)$, $h_s(x,y,t)$ and $b(x,y)$ are fresh groundwater elevation, saltwater elevation and impermeable base elevation, respectively, at a point (x,y) and time t,. The n_e denotes the porosity of the aquifer. The term $q_m(x,y,t)$ is groundwater pumping rates. The groundwater recharge $q_w(x,y,t)$ is calculated by the GRM, Eq. (2). The EVT_2 occurs as evaporation from groundwater table, if $h_f(x,y,t) > h_g^*(x,y,t)$ according to:

$$
EVT_2(x,y,t) = PE(x,y,t) - EVT_1(x,y,t) \tag{8}
$$

where h_g^* represents the depth where no evapotranspiration occurs. The $PE(t)$ is potential evapotranspiration calculated by Eq. (3). The term $q_l(x,y,t)$ denotes base flow from aquifer to river which occurs if groundwater table is larger than ground surface, described as:

$$
q_l(x,y,t) = \frac{d}{dt}\{h_f(x,y,t) - GL(x,y)\} \tag{9}
$$

where $GL(x,y)$ is ground surface elevation at (x,y). The terms u_f, u_s, and v_s, v_f are velocity components in x- and y-direction and subscripts s and f are freshwater and saltwater respectively, according to:

$$
\begin{aligned}
u_f &= -k\frac{\partial \phi_f}{\partial x}, v_f = -k\frac{\partial \phi_f}{\partial y}, \phi_f = h_f \\
u_s &= -k\frac{\partial \phi_s}{\partial x}, v_s = -k\frac{\partial \phi_s}{\partial y}, \phi_s = \frac{\rho_f}{\rho_s}\cdot h_f + \frac{\Delta\rho}{\rho_s}\cdot h_s
\end{aligned}
\tag{10}
$$

where k is permeability assumed uniform in the vertical direction. The symbols ϕ_f and ϕ_s represent the piezometric heads, the different density of fresh and salt water is, $\Delta\rho = \rho_s - \rho_f$ at the saltwater intrusion area. The boundary condition was assumed impermeable at a river catchment border.

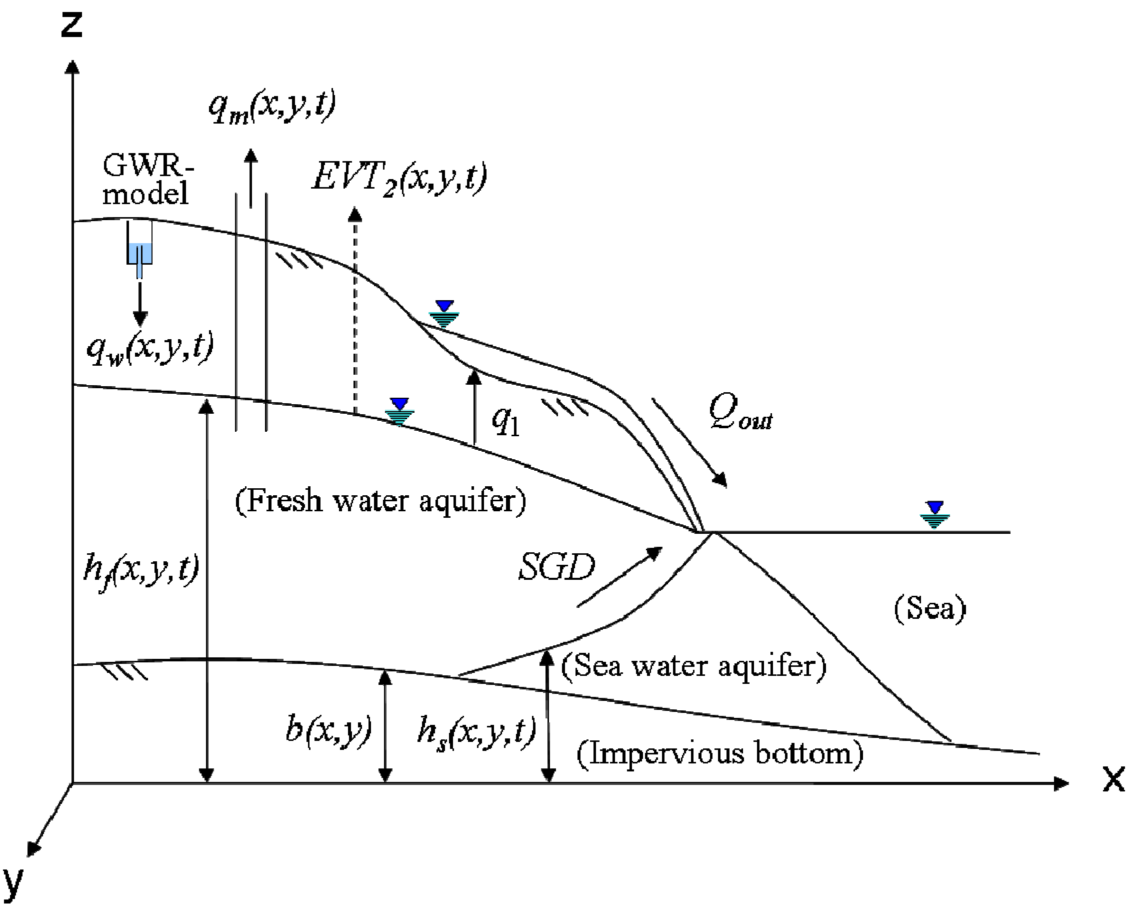

Figure 2.3 Conceptual quasi three-dimensional groundwater flow model (GFM) for an unconfined aquifer

2.4 Water Balance Analysis

Water balance analysis for the experimental basin was conducted based on results from the GRM and GFM to estimate SGD. The hydrological components considered are illustrated in Figure 2.4. The groundwater flow at basin (*GF*) was calculated for two basins, no. 1 and no. 2, using the following equation:

$$\sum_{x,y}\sum_{t} GF_i(x,y,t) = \sum_{x,y}\sum_{t}\left\{r_i(x,y,t) - Q_{out\,i}(x,y,t) - AE_i(x,y,t) - \Delta S_i(x,y,t)\right\} \tag{11}$$

where the subscript *i* is the number of basin and (*x*,*y*,*t*) represents the calculation grid point and increment time. This analysis used the sum of value for the basin and year. The term $\Delta S_i(x,y,t)$ denotes the change of total water storage in the basin, which is negligible for longer time periods. Rainfall r_i (*x*,*y*,*t*) is observed values. The actual evapotranspiration AE_i (*x*,*y*,*t*) and river discharge $Q_{\mathrm{out}\,i}$ (*x*,*y*,*t*) were calculated with the respective equations:

$$\sum_{x,y}\sum_{t} AE_i(x,y,t) = \sum_{x,y}\sum_{t}\left\{EVT_{1i}(x,y,t) + EVT_{2i}(x,y,t) + r_{\mathrm{int}\,i}(x,y,t)\right\} \tag{12}$$

$$\sum_{x,y}\sum_{t} Q_{out\,i}(x,y,t) = \sum_{x,y}\sum_{t}\left\{q_{d\,i}(x,y,t) + q_{l\,i}(x,y,t)\right\} \tag{13}$$

where $r_{int\,i}$ (*x*,*y*,*t*) is the rainfall interception for forest areas. The terms $q_{d\,i}$ (*x*,*y*,*t*) and $q_{l\,i}$ (*x*,*y*,*t*) denote direct runoff and base flow, respectively. The water balance assumes subsurface as well as surface water flow. Besides, groundwater extraction was assumed to be negligible since groundwater is pumped up and used mainly as irrigation water inside the catchment. The total SGD to the Ariake Bay was calculated as the sum of *GF* according to:

$$SGD = \sum_{i=1}^{2} GF_i \tag{14}$$

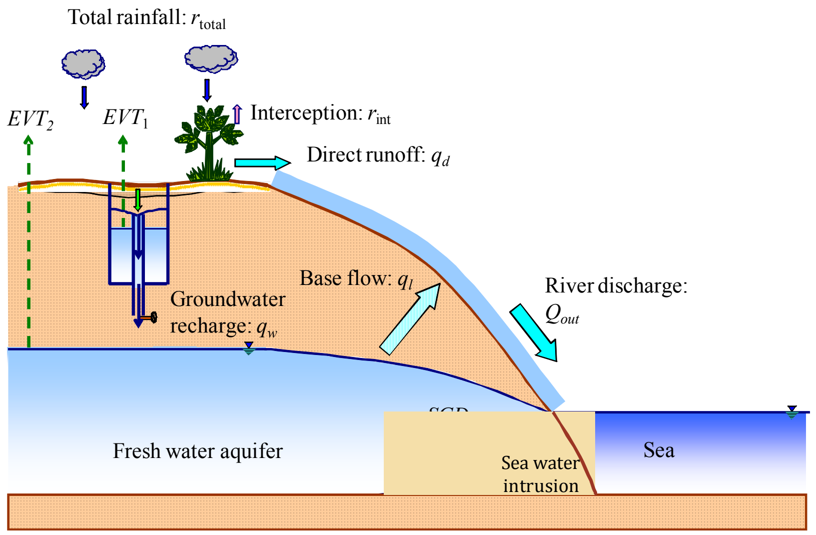

Figure 2.4 Major hydrological components of water balance analysis

Chapter 3 Results and Discussions

3.1 Groundwater Recharge Model (GRM)

Figure 3.1 shows the annual result of GRM. This model separates rainfall into groundwater recharge, direct runoff, evapotranspiration from the tank and rainfall interception. Groundwater recharge was calculated to be 842 to 1708 mm year^{-1} corresponding to 53 to 60% of total rainfall. Fazal *et al*. (2005) estimated groundwater recharge accounting for 39 to 52% of total rainfall in Miyakojima Island, Japan. They used a hydrological model named Soil Moisture Accounting and Routing (SMAR), which is a conceptual rainfall-runoff model. In spite of the difference of meteorological and geological conditions of the study area, our recharge result appears to be similar to those of Fazal et al. As it explained in Chapter 2.3, this calculated groundwater recharge was used as input data for GFM. This means GRM and GFM can be connected with groundwater recharge, which represents interfaces between surface and subsurface water in unsaturated zones in soil.

Direct runoff was estimated by hydrograph analysis for 57 selected rainfall events occurring from 1995 to 2004. In this method, the direct runoff is separated by drawing a straight line from the beginning of the direct runoff to a point on the recession limb representing the end of direct runoff (Maruyama & Mitsuno 1999). In Figure 3.2, point A marks sharp start of direct runoff and point B is identified by the 2nd inflection of recession limb. The direct runoff was estimated by integrating the river flow graph for the area between A and B, which is shaded area in figure 3.2. The direct runoff estimated by model calculation and results of hydrograph separation are compared in Figure 3.3. Overall there is a linear regression correlation coefficient between observations and model results equal to 0.81. According to this good relationship between hydrograph analysis and model calculation, it is indicated that direct runoff was estimated by GRM in a proper way.

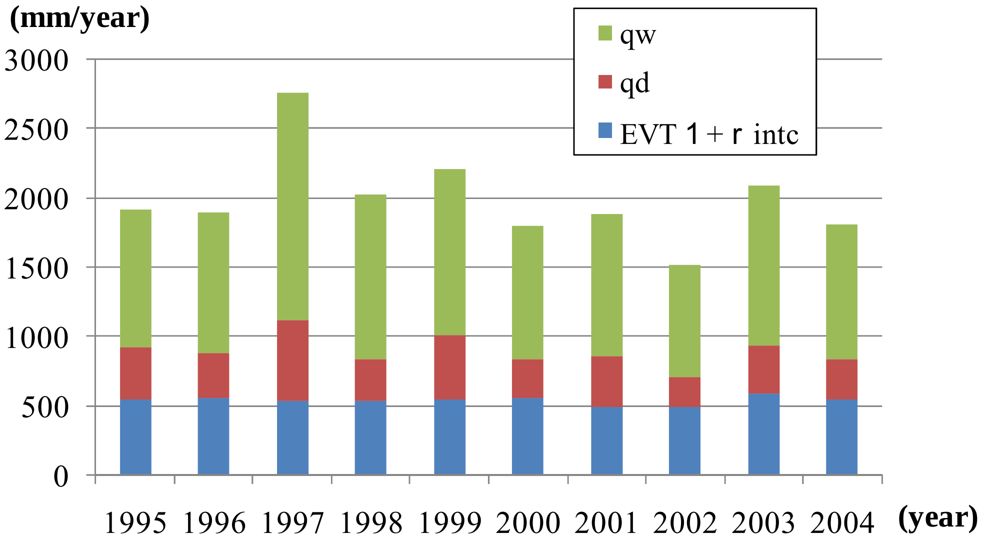

Figure 3.1 Annual result of GRM (q_w=groundwater recharge, q_d=direct runoff, EVT_1=evapotranspiration from the tank, r_{intc}=rainfall interception)

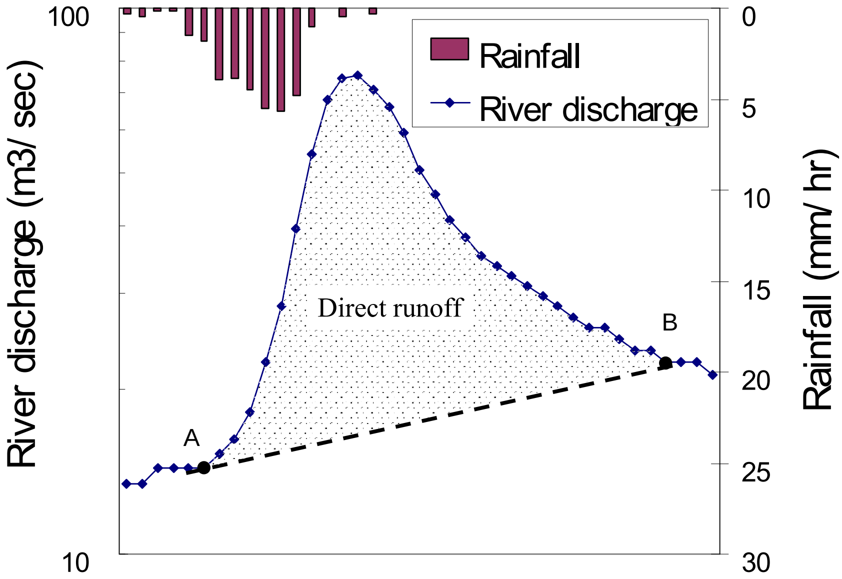

Figure 3.2 Example of semi-logarithmic plotting of hydrograph showing direct runoff separation method (at Komoda station, 2004-03-21 17:00 – 2004-03-23 7:00)

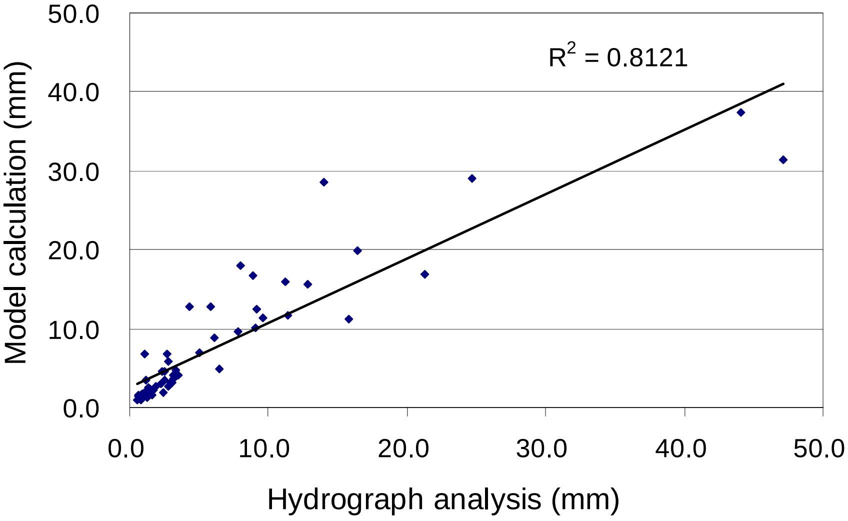

Figure 3.3 Comparison of direct runoffs between hydrograph analyzed and model calculated for 56 rainfall events from 1995-2004

3.2 Groundwater Flow Model (GFM)

Fresh water head and sea water head of groundwater were calculated by GFM. Figure 3.4 shows the calculated fresh groundwater head distribution in the study area. This groundwater distribution appears to be similar to topographic distribution in the basin, which is reasonable considering the assumption of single unconfined aquifer in the model. Using the calculated groundwater head, evapotranspiration (EVT_2) and base flow from the groundwater aquifer were calculated according to equations (8) and (9) respectively. GFM also represent interface between surface and subsurface water by calculating those two hydrological components which are used for water balance analysis. The model does not consider the deep, confined groundwater aquifer which might have very low velocity depending on geological conditions. However, in the present study, the increment calculation was conducted to obtain stable initial condition. Therefore, groundwater flow could be modeled properly in spite of 10 year calculation period.

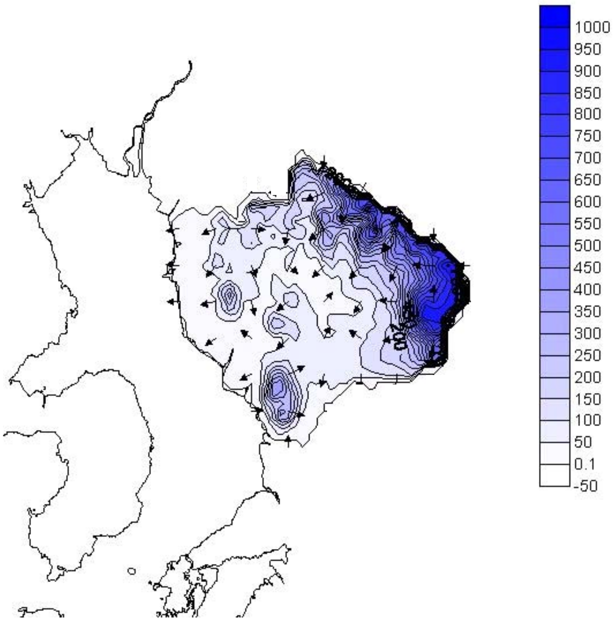

Figure 3.4 Result of groundwater head calculation (unit: meter)

3.3 Water Balance Analysis

3.3.1. Submarine Groundwater Discharge (SGD)

The SGD was estimated by water balance analysis applying the equations presented above. The calculated annual water balance is shown in Figure 3.5. In this figure, rainfall was partitioned into submarine groundwater discharge SGD, river discharge Q_{out}, and actual evapotranspiration *AE*. The total SGD to the Ariake Bay calculated using Eq. (14) accounted for 47 mm year^{-1}, corresponding to 3.6% of the river discharge and 2.3% of the average rainfall for the 10-year period, from 1995 to 2004. Table 3.1 shows the annual groundwater flow rate from the two basins, no. 1 and no. 2. The total groundwater flow to the sea, SGD, is estimated as the sum of these. The results can be compared to previous studies. Zektser & Loaiciga (1993) found that SGD was about 6% of total water flux from land to ocean using the water balance method for the global scale. Church (1996) found SGD to range between 0.01 and 10% of total river discharge. The same author state that SGD can amount to 3 % of total precipitation and 10 % of river discharge. Using modeling methods, the SGD for two river basins located in Sweden was estimated by Jarsjö *et al*. (2008) using a hydrological modeling approach. SGD was calculated to about 20 % of total discharge to the Baltic Sea for a 30-years average (1961-1990). Besides, a tracer observation is used as a method for SGD estimation. Hussain *et al*. (1999) estimated the SGD to be up to 10% of riverine freshwater inputs to the Chesapeake Bay in USA by measuring ^{222}Rn and ^{226}Ra.

In the present study, it was shown that the amount of SGD is much smaller than river discharge in average for 10 years. However, the maximum SGD was estimated to be 310 mm year^{-1}, accounting for 17% of total rainfall in 1997. Therefore, it is indicated that SGD can be important discharge component from the basin quantitatively, at some years which have large rainfall.

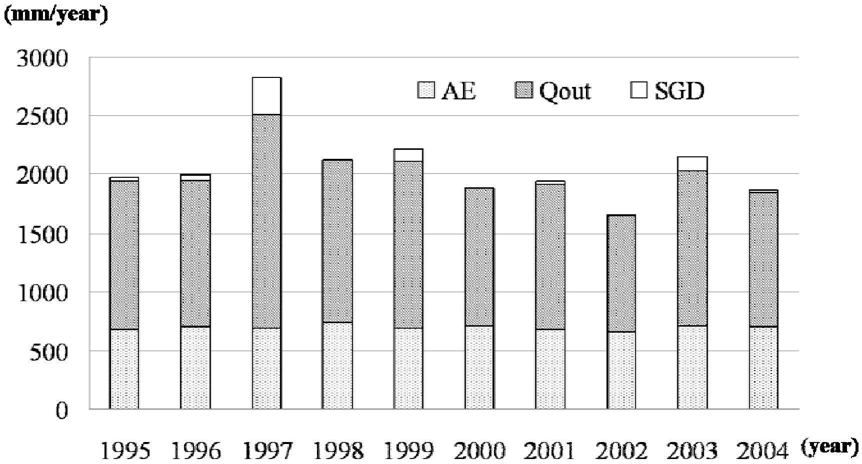

Figure 3.5 Annual water balance from equation (11) and (14) for the total basin area (no.1 and 2)

Table 3.1 Mean groundwater flow and comparison between rainfall and river discharge for the two basins for 10years, 1995-2004 (GF=groundwater flow, Q_{out}=river discharge, r=rainfall)

Basin number	*GF* (10^6 m^3/year)	Q_{out} (10^6 m^3/year)	*r* (10^6 m^3/year)	GF/Q_{out} (%)	GF/r (%)
1	41	1031	1610	4.0	2.5
2	6.4	274	442	2.3	1.5
Total	47*	1305	2052	3.6	2.3

***** SGD calculated as the sum of GF_1 and GF_2.***

3.3.2. Actual Evapotranspiration (AE)

According to equation (12), actual evapotranspiration *AE* was calculated to be 697 mm year^{-1} on average for the investigated period, which accounts for 34% of the total rainfall. Shimizu *et al.* (2003) found that for a similar basin, the evapotranspiration accounted for 39 to 40% and 43% using the latent heat balance method and water balance method, respectively. These results appear to be somewhat larger than our results. In this study, a simple water balance equation without groundwater discharge was used, $E = P - Q$, where E, P and Q represent evapotranspiration, precipitation, and river discharge, respectively. Besides, their experimental watershed had an area of 3.69 ha, which is much smaller than that of the present study. Therefore, it appears reasonable that our actual evpotranspiration is somewhat smaller. Figure 3.6 shows comparison between AE and potential evapotranspiration (PE). The AE accounts for 79 to 85% of PE. It is said that AE corresponds to 60 to 80% of PE in Japan when the Penman method is applied (JSIDRE, 1989).

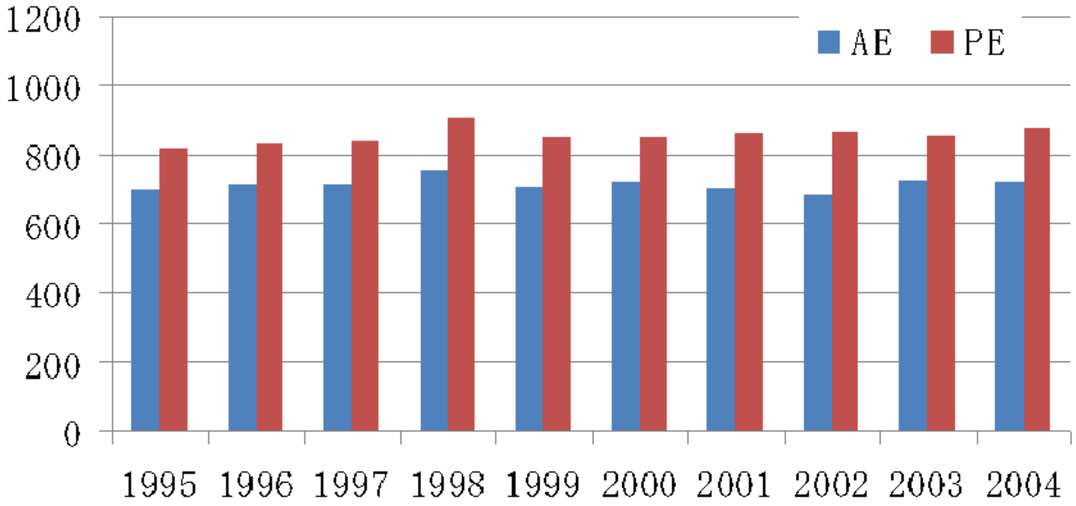

Figure 3.6 Yearly comparison between actual evapotranspiration (AE) and potential evapotranspiration (PE) (unit: mm year^{-1})

3.3.3. River Discharge

The annual river discharge Q_{out} at Komoda station was 1300 mm year^{-1} on average according to equation (13). The Q_{out} is correlated to annual rainfall which appears logical. The calculated and observed monthly river discharge was compared for the Komoda station. As seen from Figure 3.7, a good agreement was obtained between the calculated and observed river discharge. These results indicate that monthly river discharge was estimated reasonably well with the present methodology applied for the upstream basin no.1 of the Kikuchi River.

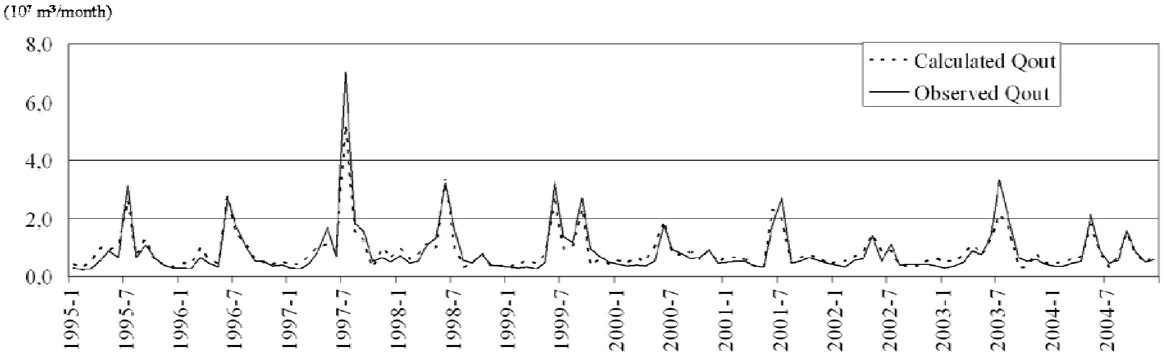

Figure 3.7 Comparison between calculated and observed monthly river flow discharge at Komoda station (basin no.1)

3.4 Summary of the Results

According to the discussions, the results of the present study are summarized as follows:

- The calculation of hydrological components, such as groundwater recharge, direct runoff and base flow using GRM and GFM appear to be corresponding well to representative and observed values.

- SGD was estimated properly using water balance analysis by comparison to representative values as well as examinations of other components of the water balance equation, which are river discharge and AE.

From the above, it seems that the SGD in the study area is a minor component of the total discharge to the Ariake Bay. However, the maximum yearly SGD was calculated to be 310mm year^{-1} accounting for 11% of total rainfall and 17% of river discharge. This indicates that SGD can be a significant component quantitatively sometimes. Besides, in terms of nutrient content the SGD may still play an important role for the total nutrient load (e.g., Moore 1996). Therefore, the SGD may still be an important component for the enclosed water environments such as the Ariake Bay. In order to better understand the role of SGD, it is important to establish reliable methods to estimate SGD and nutrient load to the targeted area by the combining SGD with nutrient concentration. Besides, considering the yearly variation of the calculated SGD, more accurate estimation can be conducted with a longer study period than that of the present study.

Chapter 4 Conclusions

The SGD to the Ariake bay was estimated using a distributed groundwater recharge and flow model combined with a water balance analysis. The calculated SGD appears to be in the same range as reported in other studies. The general methodology presented in this paper can be used to in a simple and straightforward way to estimate SGD at the catchment scale. The results can be used to better manage eutrophic sea areas and bays which are experiencing high nutrient load. Future studies will involve upscaling of results to account for the total SGD into the Ariake Bay which has serious eutrophication problems.

Chapter 5 Suggestions for Future Study

In the present study, using GRM, GFM and WBA were proposed as a straightforward way to estimate SGD in a river basin scale. According to these results, some future studies are indicated, which are interesting to better understand SGD as follows:

- In order to estimate nutrient inputs load to the Ariake Bay, water quality should be considered such as Nitrogen, Phosphorus and Sulfate which may have a large effect to the marine environment (e.g., eutrophication).

- Considering recent climate change occurring all over the world, it may be important to compare the SGD as well as surface runoff in different regions and countries which have various meteorological and hydrological conditions.

According to these indications, the author will work on projects such as:

- In the Ariake Bay Basin, water quality data from groundwater observation wells or field measurements will be analyzed and used to estimate nutrients input, which is transported by SGD. This study will be significant for hydrological and nutrients management in the basin.

- As a collaboration work with Swedish Meteorological and Hydrological Institute (SMHI), the proposed method will be applied for Ljungbyån Basin located at the south part of Sweden along the Baltic Sea (Figure 5.1). Input data for the model, such as meteorological, topographical and geological data will be supplied by SMHI. The methodology will be developed for Swedish conditions, which has much less precipitation and lower temperature than that of Japan. Besides, surface and subsurface water quality data are also obtained for nutrients load estimation. Therefore, this work will involve both climate or location effects to SGD and nutrients input effects to the marine environment in the Baltic Sea which cause an eutrophication.

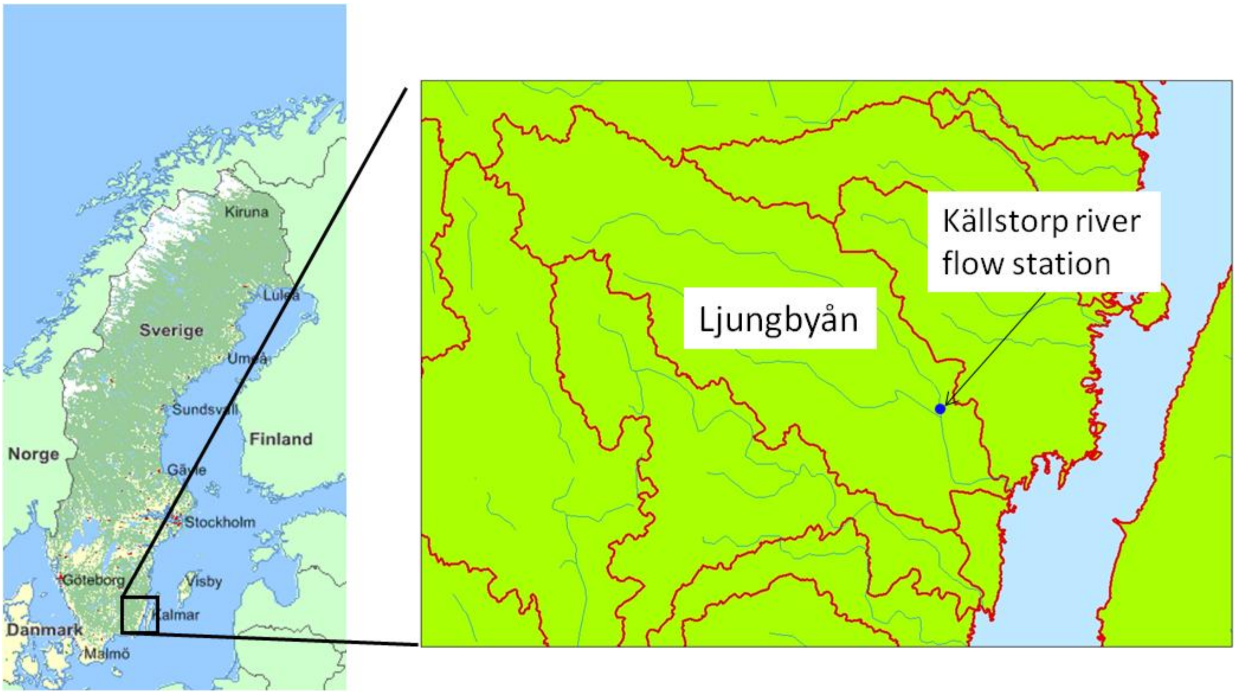

Figure 5.1 Location of Ljungbyån Basin in the south part of Sweden

References

Berner, E.K. & Berner, R.A. 1987 *The global water cycle, chemistry and environment*. Prentice-Hall: Englewood Cliffs, NJ, 12-24.

Church, M. Thomas. 1996 An underground route for the water cycle, *Nature***,** **380**, 579-580.

Destouni, G. & Prieto, C. 2003 On the possibility for generic modeling of submarine groundwater discharge. *Biogeochemistry*, **66**, 171-186.

Farmers net. 2008 Explanation of Ariake Bay:
http://www.farmersnet.net/product/070315110606/070315110606_070328125241.html.
(in Japanese)

Fazal, M.A., Imaizumi, M., Ishida, S., Kawachi, T. & Tsuchihara, T. 2005 Estimating groundwater recharge using the SMAR conceptual model calibrated by genetic algorithm. *Journal of Hydrology*, **303**, 56-78.

Hamon, W.R. 1961 Estimating potential evapotranspiration. *Journal of the Hydraulics Division, ASCE* **87***(HY3)*, 107-120.

Hussain, N., Church, T.M. & Kim, G. 1999 Use of ^{222}Rn and ^{226}Ra to trace groundwater discharge into the Chesapeake Bay. *Marine Chemistry* **65**, 127-134.

Jarsjö, J., Shibuo, T. & Destouni, G. 2008 Spatial distribution of unmonitored inland water fluxes to the sea. *Journal of Hydrology*, **348**, 59-72.

JSIDRE. 1989. *Hand book of Irrigation, Drainage and Rural Engineering*. Japan Society of Irrigation, Drainage and Rural Engineering: 852 (In Japanese).

Kondo, J. Nakazono, S. Watanabe, T. & Kuwagata, T. 1992 Hydrological climate in Japan (3), Evapotranspiration from forest. *Journal of Japan Society of Hydrology and Water Resources* **5**(4), 8–18 (in Japanese).

Maruyama, T. & Mitsuno, T. 1999. *Regional environmental hydrology*. Asakura Publishing Co., Ltd.: 62-63. (in Japanese)

McCoy, C.A., Corbett, D.R., McKee, B.A. & Top Zafer. 2007 An evaluation of submarine groundwater discharge along the continental shelf of Louisiana using a multiple tracer approach. *Journal of Geophysical research* **112**, C03013.

Moore, W.S. 1996 Large groundwater inputs to coastal waters revealed by ^{226}Ra enrichments, *Nature* **380**, 612-614.

National Institute of Advanced Industrial Science and Technology (AIST), Geological Survey of Japan(GSJ). Rishiri Island information: http://www.gsj.jp/Info/100mt/rishiri/rishiri.html (in Japanese).

Saga Prefectural Government. 2007 Information page for Seaweed production: http://www.pref.saga.lg.jp/web/noritumitori.html (in Japanese)

Saga Shinbun Co., Ltd. 2008 News page for 2008.08.11: http://www.sagas.co.jp/view.php?pageId=1036&mode=0&classId=0&blockId=1010443&newsMode=article (in Japanese)

Shimizu, A., Shimizu, T., Miyabuchi, Y. & Ogawa, Y. 2003 Evapotranspiration and runoff in a forest watershed, western Japan. *Hydrological Processes* **17**, 3125-3139.

Simmons, G.M. Jr. 1992 Importance of submarine groundwater cycling to material flux across sediment/water interfaces in marine environments. *Marine Ecology Progress Series* **84**, 173-184.

Taniguchi, M., Burnett W.C., Cable J.E & Tuner, J.V 2002. Investigation of submarine groundwater discharge. *Hydrological Process* **16**, 115-2129.

Thompson, C., Smith, L. & Maji, R. 2007 Hydrogeological modeling of submarine groundwater discharge on the continental shelf of Louisiana. *Journal of Geophysical research* **112**, C03014.

Tsutsumi, A., Jinno, K. & Berndtsson, R. 2004 Surface and subsurface water balance estimation by the groundwater recharge model and a 3-D two-phrase flow model. *Hydrological Sciences-Journal-des Sciences Hydrologiques* **49**(2), 205-226.

Unoki, Sanae. *2006 Nature of Ariake Sea and its resuscitation*. Tsukiji Shobou, ISBN 4-8067-1330-9. (in Japanese)

U.S. Geological Survey. (USGS) 2007 *Submarine Groundwater Discharge: An Introduction*, Center for Coastal and Watershed Studies website, http://coastal.er.usgs.gov/sgd/

Yanagi, T. & Abe, R. 2005 Increase in water exchange ratio due to a decrease in tidal amplitude in Ariake Bay, Japan. Continental Shelf Research **25**, 2174-2181.

Zektser, I.S. & Loaiciga, H.A. 1993 Groundwater fluxes in the global hydrologic cycle: past, present and future. *Journal of Hydrology* **144**, 405-427.

Appendices

Appendix 1 Flow Chart of the Model Calculation

According to the methodology presented in Chapter 3, the models were developed and coupled as following figure. More detailed calculation process is shown in Appendix 2 as a FORTRAN Source code.

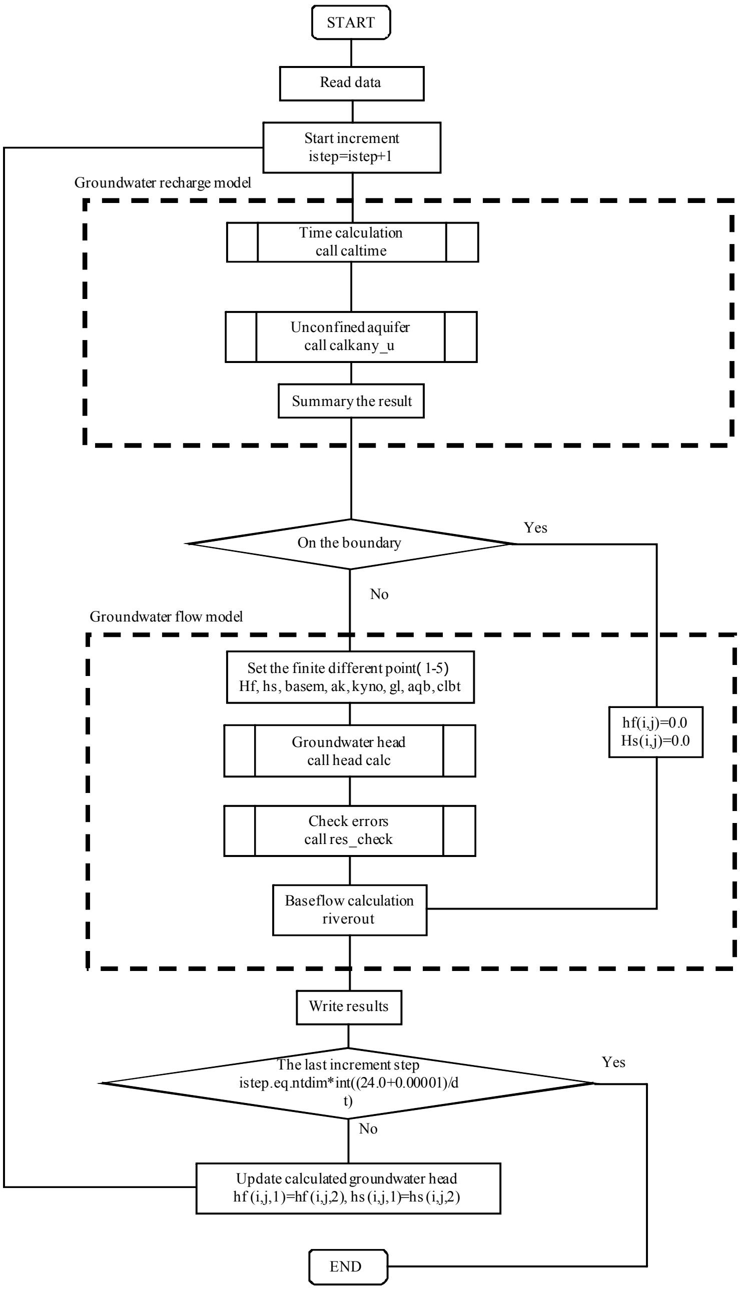

Figure A.1 Flow chart of the models calculation

Appendix 2 FORTRAN Source Code for GRM and GFM

In the present study, the combined model between GRM and GFM was developed using FORTRAN programming. The calculation flow is shown in Figure A.1 at Appendix 1. The parameters for the model and FORTRAN source code are shown as fellows.

List of parameters:

A2	*ROUF/ ROUS*
A3	*(ROUS-ROUF)/ROUS*
AINTC	Rainfall interception at forest area
AK, AKK	Permeability
AL1, AL	Outlet flow coefficient of GRM
ANE	Porosity of groundwater aquifer
BASEM	Elevation of hydrological basement layer
DRUNOFF	Direct runoff
DRUNOFFT,1,2	Total direct runoff for total, no.1 and 2 basin
DT	Increment time (=0.5 hour)
DX	Resolution grid size in *x*-direction (=562.5 m)
DY	Resolution grid size in *y*-direction (=463.5 m)
EMAXF	Maximum value of error for iteration error for fresh groundwater
EMAXS	Maximum value of error for iteration error for salt groundwater
EPSI	Over relaxation coefficient
EVAPO	Potential evapotranspiration from GRM tank
EVT	Evaportranspiration from GRM tank (EVT_1)
EVTFRGW	Evapotranspiration from groundwater aquifer (EVT_2)
FINF1,FINF	Maximum value of direct runoff coefficient
FR	Direct runoff coefficient
GL	Elevation of ground surface
HF	Fresh groundwater head
HGSTAR	Extinction depth between ground surface and groundwater table
HS	Salt groundwater head
HT	Storage water depth in GRM tank
IMAX	Number of resolution grids in *x*-direction (=222)
ISTEP	Number of increments step
JMAX	Number of resolution grids in *y*-direction (=244)
KYNO	ID number for boundary conditions
NDMAX	Number of calculation days (=4018 days)
NGR	ID number of land use data
NGRID1	Number of grids for basin no.1 (=2957)
NGRID2	Number of grids for basin no.2 (=893)
NGRIDT	Number of grid for total basin (=3850)
NLUSE	ID number of land use
NMMAX	Number of calculation months (=132 months)
NOF	Number of successive iterations for fresh groundwater calculation
NOS	Number of successive iterations for salt groundwater calculation

NPMAX	Number of area for groundwater extraction (=19)
NPUMP	ID number of groundwater pumping wells
NRBLOCK	ID number of thiessen distribution
NRIVER	ID number of river line
NRMAX	Number of thiessen method for rainfall and temperature stations
NUMOB	ID number of sub basin
NUTK	ID number of permeability
NWMAX	Number of groundwater observation wells (=13)
PEVTH	Hourly potential evapotranspiration
PUMPH	Hourly groundwater pumping up data
QEVFGWTT,1,2	Total EVT$_2$ for total, no.1 and 2 basin
QEVTT,1,2	Total EVT$_1$ for total, no.1 and 2 basin
QINTT,1,2	Total rainfall interception for total, no.1 and 2 basin
QOUT	Base flow from groundwater aquifer to river water
QPEVTT,1,2	Total potential evapotranspiration for total, no.1 and 2 basin
QPUMPT,1,2	Total groundwater pumping up for total, no.1 and 2 basin
QRET,1,2	Total percolation for total, no.1 and 2 basin
QRGT,1,2	Total actual rainfall for total, no.1 and 2 basin
QW	Groundwater recharge
R01,R0	Outlet level of GRM
RAIND, RAD	Daily rainfall
RAINH,RAH	Hourly rainfall
RAININT, RINT	Rainfall interception rate at forest area
RAINT,1,2	Total rainfall for total, no.1 and 2 basin
RE	Percolation to GRM tank
RECHARGET,1,2	Total groundwater recharge for total, no.1 and 2 basin
RG	Actual rainfall reaching ground surface
RHALF, RHALF1	Rainfall when $F(r)$is equal to $F_\infty/2$
RIVEROUTT,1,2	Total base flow for total, no.1 and 2 basin
ROUF	Density of freshwater
ROUS	Density of saltwater
XX	Coordinate of groundwater observation wells in x-direction
YY	Coordinate of groundwater observation wells in y-direction

FORTRAN source code:

```
**********************************************************************************************
 GROUNDWATER RECHARGE &
 FLOW MODEL (GRM and GFM)
 WITH EXPLICIT FDM METHOD
 IN KIKUCHI RIVER BASIN
 (KIKUCHI.F)

**********************************************************************************************
   IMPLICIT INTEGER*4(I-N)
   IMPLICIT REAL*8(A-H,O-Z)

    PARAMETER (IMAX=222,JMAX=244,NDMAX=4018,NMMAX=132,NRMAX=6,
   &          NWMAX=13,NPMAX=19,NGRIDT=3850,NGRID1=2957,NGRID2=893)

----DIMENSIONS------------------------------------------------------------------------------------------------------------
    DIMENSION KYNO(IMAX,JMAX),GL(IMAX,JMAX),BASEM(IMAX,JMAX),
   &        NLUSE(IMAX,JMAX),AQB(IMAX,JMAX),NRBLOCK(IMAX,JMAX),
   &        NUMOB(IMAX,JMAX),NRIVER(IMAX,JMAX),CLBT(IMAX,JMAX),
   &        NPUMP(IMAX,JMAX),GEO(IMAX,JMAX),HF(IMAX,JMAX,2),
   &        HS(IMAX,JMAX,2),HG(IMAX,JMAX),HT(IMAX,JMAX),
   &        HT2(IMAX,JMAX),NUTK(IMAX,JMAX),AKK(IMAX,JMAX),
   &        AK(NPERMAX)

   &       RAINH(NRMAX,NDMAX*24),PEVTH(NRMAX,NDMAX*24),
   &        PUMPH(NPMAX),QPUMP(IMAX,JMAX)

   &        RAININT(NMMAX),RAIND(NRMAX,NDMAX)

   &        XX(NWMAX),YY(NWMAX),

   &        DQW(IMAX,JMAX),DQOUT(IMAX,JMAX),QOUT(IMAX,JMAX)

   &        RAH(IMAX,JMAX),RAD(IMAX,JMAX),PEVT(IMAX,JMAX),
   &        RINT(IMAX,JMAX),AINTC(IMAX,JMAX),EVP(IMAX,JMAX),
   &        EVT(IMAX,JMAX),
   &        RG(IMAX,JMAX),RE(IMAX,JMAX),EVAPO(IMAX,JMAX),
   &        FR(IMAX,JMAX),DRUNOFF(IMAX,JMAX),EVTFRGW(IMAX,JMAX),
   &        QW(IMAX,JMAX)

   &        NGR(NLMAX),ANE(NLMAX),AL1(NLMAX),R01(NLMAX),
   &        RHALF1(NLMAX),FINF1(NLMAX)

   &        HF1(5),HS1(5),BA(5),AK1(5),KN(5),GL1(5),AQB1(5),CB(5)

----OPEN FILES------------------------------------------------------------------------------------------------------------
    OPEN(2,FILE='ELEVATION.DAT',STATUS='OLD')
    OPEN(3,FILE='BASEMENT.DAT',STATUS='OLD')
    OPEN(4,FILE='LANDUSE.DAT',STATUS='OLD')
    OPEN(6,FILE='RAIN_TEMP_BLOCK.DAT', STATUS='OLD')
    OPEN(7,FILE='BASIN_BLOCK.DAT',STATUS='OLD')
    OPEN(8,FILE='RIVERLINE.DAT',STATUS='OLD')
    OPEN(10,FILE='PUMP_BLOCK.DAT',STATUS='OLD')
    OPEN(12,FILE='INITIAL_HF.DAT',STATUS='OLD')
    OPEN(13,FILE='INITIAL_HS.DAT', STATUS='OLD')
```

```
    OPEN(14,FILE=’RAIN.DAT',STATUS='OLD')
    OPEN(15,FILE='EVAPORATION.DAT',STATUS='OLD')
    OPEN(16,FILE='PUMP.DAT',STATUS='OLD')
    OPEN(18,FILE='WELL_POINTS.DAT',STATUS='OLD')
    OPEN(19,FILE='GWR_PARAMETER.DAT',STATUS='OLD')
    OPEN(20,FILE='NUMPERM.DAT',STATUS='OLD')
    OPEN(21,FILE='DAYLY_RAIN.DAT',STATUS='OLD')
    OPEN(22,FILE='RAIN_INTERCEPTION.DAT',STATUS='OLD')
    OPEN(23,FILE='PERMEABILITY.DAT',STATUS='OLD')
    OPEN(30,FILE='DAILY_BASIN_T.DAT')
    OPEN(31,FILE='DAILY_BASIN_1.DAT')
    OPEN(32,FILE='DAILY_BASIN_2.DAT')

----READING FILES----------------------------------------------------------------------------------------------------
    !STUDY AREA DATA (222*244)
    DO J=JMAX,1,-1
      READ(1,*)  (KYNO(I,J),I=1,IMAX)
      READ(2,*)  (GL(I,J),I=1,IMAX)
           READ(3,*)  (BASEM(I,J),I=1,IMAX)
           READ(4,*)  (NLUSE(I,J),I=1,IMAX)
           READ(6,*)  (NRBLOCK(I,J),I=1,IMAX)
           READ(7,*)  (NUMOB(I,J),I=1,IMAX)
           READ(8,*)  (NRIVER(I,J),I=1,IMAX)
           READ(10,*) (NPUMP(I,J),I=1,IMAX)
           READ(12,*) (HF(I,J,1),I=1,IMAX)
           READ(13,*) (HS(I,J,1),I=1,IMAX)
           READ(20,*) (NUTK(I,J),I=1,IMAX)

          END DO
   ! INITIAL VALUES
    DO I=1,IMAX
          DO J=JMAX,1,-1
          HFI(I,J)=HF(I,J,1)
          END DO
          END DO

    !METEOROLOTCAL DATA
          !DAYLY DATA
    DO N=1,NDMAX
           READ(21,*) (RAIND(K,N),K=1,NRMAX)
          END DO
    !HOURLY DATA
          DO N=1,NDMAX*24
           READ(14,*) (RAINH(K,N),K=1,NRMAX)
           READ(15,*) (PEVTH(K,N),K=1,NRMAX)
          END DO
    !MONTHLY DATA
    DO N=1,NMMAX
           READ(22,*) RAININT(N)
          END DO
    !HOURLY PUMPING DATA (CONSTANT)
    DO I=1,NPMAX
    READ(16,*) PUMPH(I)
          END DO
    !OBSERVING WELLS POINTS
    DO K=1,NWMAX
```

```
        READ(18,*) XX(K),YY(K)
    END DO

    !GER MODEL PARAMETER
    DO I=1,NLMAX
        READ(19,*) NGR(I),ANE(I),AL1(I),R01(I),RHALF1(I),FINF1(I)
        END DO
  ! PERMEABILITY
    DO I=1,NPERMAX
        READ(23,*) AK(I)
        END DO

    DO I=1,IMAX
        DO J=1,JMAX
        IF (NUMOB(I,J).EQ.999)THEN
         HF(I,J,1)=0.0
         HS(I,J,1)=0.0
        ELSE IF (NUMOB(I,J).EQ.0) THEN
         HF(I,J,1)=0.0
         HS(I,J,1)=0.0
        END IF

        IF (KYNO(I,J).EQ.0.AND.HF(I,J,1).GE.GL(I,J)) THEN
        HF(I,J,1)=GL(I,J)
        END IF
        END DO
        END DO

----CALCULATION CONDITIONS---------------------------------------------------------------------------------
    DX=562.5 !(m)
        DY=463.5 !(m)
        DT=0.50 !TIME INCREMENT (hour)
        ROUF=1.0 !DENSITY OF FRESHWATER
        ROUS=1.025 !DENSITY OF SALTWATER

        A2=ROUF/ROUS
        A3=(ROUS-ROUF)/ROUS
        HGSTAR=1.5 !(m) EXTINCTION DEPTH

        IYS=1995
        IMS=1
        IDS=1
        IYE=2004
        IME=12
        IDE=31
    NUMMON=(IYE-IYS+1)*12

    DO I=1,IMAX
         DO J=1,JMAX
        IF (NUTK(I,J).EQ.999) THEN
        AKK(I,J)=0.0
        ELSE
        AKK(I,J)=AK(NUTK(I,J))/100.0*3600.0 ! (m/hour)
        END IF
         END DO
        END DO
```

```
----SET INITIAL CONDITION OF FRESH & SALT GROUNDWATER LEVEL----------------------------
      DO I=1,IMAX
       DO J=1,JMAX
       IF(KYNO(I,J).NE.999)THEN
                   IF(HF(I,J,1).LT.0.0)THEN
            HF(I,J,1)=0.0
          END IF
                      HG(I,J)=GL(I,J)-HF(I,J,1)
       ELSE IF (KYNO(I,J).EQ.999) THEN
                      HF(I,J,1)=0.0
                      HS(I,J,1)=0.0
                      HG(I,J)=0.0
       END IF
               IF(HG(I,J).LT.0.0)THEN
                HG(I,J)=0.0
               END IF

      IF (KYNO(I,J).EQ.0.OR.KYNO(I,J).EQ.2.OR.KYNO(I,J).EQ.3) THEN
               HS(I,J,1)=BASEM(I,J)
               ELSE IF (KYNO(I,J).EQ.1) THEN
               HS(I,J,1)=0.0
               END IF

       END DO
      END DO

----SET INITIAL VALUES-----------------------------------------------------------------------------------------------
 9980 CONTINUE
      DO I=1,IMAX
      DO J=1,JMAX
        HT(I,J)=0.0
        HF(I,J,2)=HF(I,J,1)
        HS(I,J,2)=HS(I,J,1)
      END DO
      END DO
      EPSI=0.00001

----START INCREMENT CALCULATION-------------------------------------------------------------------------
 1111 CONTINUE
      ISTEP=ISTEP+1
      TIM=TIM+DT
      NOF=0
      NOS=0
      EMAXF=0.0
      EMAXS=0.0

-----SET TIME-------------------------------------------------------------------------------------------------------------
      IF(ISTEP .EQ. 1) THEN
        IY=IYS
        IM=IMS
        ID=IDS
        NMON=NMON+1
        NDAY=NDAY+1
      ELSE IF(MOD(ISTEP,INT((24.0+0.00001)/DT)) .EQ. 1) THEN
        NDAY=NDAY+1
```

```
    CALL CALTIME(IY,IM,ID,NMON,MDIF)
        END IF
   IF(MOD(ISTEP,INT((1.0+0.00001)/DT)) .EQ. 1) THEN
         NHOUR=NHOUR+1
        END IF

----CALCULATION OF EVAPOTRANSPIRATION,RAIN INTERCEPTION----------------------------------
  ! INTERCEPTION EVAPORATION, POTENTIAL EVAPOTRANSPIRATION & DIRECT RUNOFF
   DO 1400 I=1,IMAX
         DO 1500 J=1,JMAX
   IF (NUMOB(I,J).EQ.0.OR.NUMOB(I,J).EQ.999)  GO TO 2222

  ! SET UP OF THE EVAPOTRANSPIRATION RATE AND THE RECHARGE RATE
   IF(MOD(ISTEP,INT((1.0+0.00001)/DT)) .EQ. 1) THEN

  ! HOURLY AND DAYLY RAINFALL
   DO K=1,NRMAX
         IF(NRBLOCK(I,J).EQ.K)THEN
          RAH(I,J)=RAINH(K,NHOUR)
          RAD(I,J)=RAIND(K,NDAY)
         END IF
        END DO

  ! POTENTIAL EVAPOTRANSPIRATION
     DO L=1,NRMAX
      IF(NRBLOCK(I,J).EQ.L)THEN
       PEVT(I,J)=PEVTH(L,NHOUR)
      END IF
     END DO

  ! RAIN INTERCEPTION RATE (KUMAMOTO)
     IF(NRBLOCK(I,J).GE.1.AND.NRBLOCK(I,J).LE.6)THEN
            RINT(I,J)=RAININT(NMON)
     END IF

  ! RAIN INTERCEPTION IN FOREST AREA(NLUSE=3)
   IF(NLUSE(I,J).EQ.3)THEN
           AINTC(I,J)=RINT(I,J)*RAH(I,J)
          IF(AINTC(I,J).GT.PEVT(I,J))THEN
     AINTC(I,J)=PEVT(I,J)
    END IF
           EVP(I,J)=PEVT(I,J)-AINTC(I,J)
    ELSE !NON-FOREST AREA
           AINTC(I,J)=0.0
     EVP(I,J)=PEVT(I,J)
         END IF
  ! SET DIRECT RUNOFF COEFFICIENT
    IF(NLUSE(I,J).EQ.0) GO TO 2222
       K=NLUSE(I,J)
       RHALF=RHALF1(K)
       FINF=FINF1(K)
       AL=AL1(K)
            R0=R01(K)
       IF(NLUSE(I,J).EQ.3) THEN
         RG(I,J)=RAH(I,J)-AINTC(I,J)
        EVAPO(I,J)= EVP(I,J)
```

```
      ELSE
       RG(I,J)=RAH(I,J)
           EVAPO(I,J)= EVP(I,J)
      END IF

       ! CONSIDER THE PADDY FIELD IRRIGATION DURING IRRIGATION PERIOD
      IF(RG(I,J)+RHALF.EQ.0.0)THEN
           FR(I,J)=0.0
           DRUNOFF(I,J)=FR(I,J)*RG(I,J)
          ELSE IF(NLUSE(I,J).EQ.1)THEN
                IF((IM.EQ.6.AND.ID.GE.20).OR.IM.EQ.7.OR.IM.EQ.8.OR.
   &          IM.EQ.9.OR.(IM.EQ.10.AND.ID.LE.10))THEN ! IRRIGATION PERIOD
           FR(I,J)=0.7
           DRUNOFF(I,J)=FR(I,J)*RG(I,J)
          ELSE
                 FR(I,J)=FINF*RG(I,J)/(RG(I,J)+RHALF) !DIRECT RUNOFF COEFFICIENT
           DRUNOFF(I,J)=FR(I,J)*RG(I,J)
          END IF
                ELSE
                 FR(I,J)=FINF*RG(I,J)/(RG(I,J)+RHALF) !DIRECT RUNOFF COEFFICIENT
           DRUNOFF(I,J)=FR(I,J)*RG(I,J)
          END IF

       RE(I,J)=RG(I,J)-DRUNOFF(I,J) !INFILTRATION
      HW1=HT(I,J)

------Groundwater Recharge Model (GRM)--------------------------------------------------------------------------------
            CALL CALKANY_U(HW1,HW2,RE(I,J),EVAPO(I,J),R0,QWX,AL,
   &                             EVT2X,EVTX)
          IF(GL(I,J)-HF(I,J,1) .GT. HGSTAR) THEN
       EVTFRGW(I,J)=0.0
      ELSE IF(NLUSE(I,J).NE.7)THEN
                 IF(RAD(I,J) .EQ. 0.0) THEN
         EVTFRGW(I,J)=EVT2X
        ELSE IF(RAD(I,J) .GT. 0.0.AND.RAD(I,J) .LT. 5.0) THEN
         EVTFRGW(I,J)=0.0
        ELSE
        EVTFRGW(I,J)=0.0
           END IF
          ELSE
        EVTFRGW(I,J)=0.0
      END IF
   QW(I,J)=QWX
   HT(I,J)=HW2
   EVT(I,J)=EVTX

   END IF !IF(MOD(ISTEP,INT((1.0+0.00001)/DT)) .EQ. 1) THEN

----SUM UP RESULTS OF GRM---------------------------------------------------------------------------
----TOTAL BASIN-------------------------------------------------------------------------------------------------
     RAINT=RAINT+RAH(I,J)*DT
     RECHARGET=RECHARGET+QW(I,J)*DT
     QEVFGWT=QEVFGWT+EVTFRGW(I,J)*DT
     QINTT=QINTT+AINTC(I,J)*DT
     DRUNOFFT=DRUNOFFT+DRUNOFF(I,J)*DT
     QPEVTT=QPEVTT+PEVT(I,J)*DT
```

```
         QEVTT=QEVTT+EVT(I,J)*DT
         QRGT=QRGT+RG(I,J)*DT
         QRET=QRET+RE(I,J)*DT
         QPUMPT=QPUMPT+QPUMP(I,J)*DT

----BASIN No.1 (KOMODA)------------------------------------------------------------------------------------------
      IF(NUMOB(I,J).EQ.1)THEN
         RAIN1=RAIN1+RAH(I,J)*DT
         RECHARGE1=RECHARGE1+QW(I,J)*DT
         QEVFGW1=QEVFGW1+EVTFRGW(I,J)*DT
         QINT1=QINT1+AINTC(I,J)*DT
         DRUNOFF1=DRUNOFF1+DRUNOFF(I,J)*DT
         QPEVT1=QPEVT1+PEVT(I,J)*DT
         QEVT1=QEVT1+EVT(I,J)*DT
         QRG1=QRG1+RG(I,J)*DT
         QRE1=QRE1+RE(I,J)*DT
         QPUMP1=QPUMP1+QPUMP(I,J)*DT

----BASIN No.2 (TAMANA)------------------------------------------------------------------------------------------
       ELSE IF(NUMOB(I,J).EQ.2)THEN
         RAIN2=RAIN2+RAH(I,J)*DT
         RECHARGE2=RECHARGE2+QW(I,J)*DT
         QEVFGW2=QEVFGW2+EVTFRGW(I,J)*DT
         QINT2=QINT2+AINTC(I,J)*DT
         DRUNOFF2=DRUNOFF2+DRUNOFF(I,J)*DT
         QPEVT2=QPEVT2+PEVT(I,J)*DT
         QEVT2=QEVT2+EVT(I,J)*DT
         QRG2=QRG2+RG(I,J)*DT
         QRE2=QRE2+RE(I,J)*DT
         QPUMP2=QPUMP2+QPUMP(I,J)*DT

----CALCULATION OF THE FRESHWATER AND THE INTERFACE LEVEL--------------------------------
----(GROUNDWATER FLOW MODEL)----------------------------------------------------------------------------------
      DO I=1,IMAX
      DO J=1,JMAX
      IF(KYNO(I,J).EQ.999 .OR. KYNO(I,J).EQ.1 ) THEN
          GO TO 3333
      ELSE IF (NUMOB(I,J).EQ.1.OR.NUMOB(I,J).EQ.2.OR.KYNO(I,J).EQ.2) THEN
          HF1(1)=HF(I-1,J,1)
          HF1(2)=HF(I,J,1)
          HF1(3)=HF(I+1,J,1)
          HF1(4)=HF(I,J-1,1)
          HF1(5)=HF(I,J+1,1)
          HS1(1)=HS(I-1,J,1)
          HS1(2)=HS(I,J,1)
          HS1(3)=HS(I+1,J,1)
          HS1(4)=HS(I,J-1,1)
          HS1(5)=HS(I,J+1,1)
          BA(1)=BASEM(I-1,J)
          BA(2)=BASEM(I,J)
          BA(3)=BASEM(I+1,J)
          BA(4)=BASEM(I,J-1)
          BA(5)=BASEM(I,J+1)
          AK1(1)=AKK(I-1,J)
          AK1(2)=AKK(I,J)
          AK1(3)=AKK(I+1,J)
```

```
        AK1(4)=AKK(I,J-1)
        AK1(5)=AKK(I,J+1)
        KN(1)=KYNO(I-1,J)
        KN(2)=KYNO(I,J)
        KN(3)=KYNO(I+1,J)
        KN(4)=KYNO(I,J-1)
        KN(5)=KYNO(I,J+1)
        GL1(1)=GL(I-1,J)
        GL1(2)=GL(I,J)
        GL1(3)=GL(I+1,J)
        GL1(4)=GL(I,J-1)
        GL1(5)=GL(I,J+1)
        AQB1(1)=AQB(I-1,J)
        AQB1(2)=AQB(I,J)
        AQB1(3)=AQB(I+1,J)
        AQB1(4)=AQB(I,J-1)
        AQB1(5)=AQB(I,J+1)
        CB(1)=CLBT(I-1,J)
        CB(2)=CLBT(I,J)
        CB(3)=CLBT(I+1,J)
        CB(4)=CLBT(I,J-1)
       CB(5)=CLBT(I,J+1)

       CALL HEAD_CALC(HF1,HF2,HS1,HS2,BA,AK1,KN,A2,A3,QW(I,J)/1000.0,
    &  QPUMP(I,J)/1000.0,EVTFRGW(I,J)/1000.0,DX,DY,QOUTX,GL1,DT,
    &  ANE(NLUSE(I,J)),I,J,CB,NRIVER(I,J))

       HS(I,J,2)=HS2
       HF(I,J,2)=HF2
          QOUT(I,J)=QOUTX

       CALL RES_CHECK(BASEM(I,J),HF(I,J,1),HF(I,J,2),HS(I,J,1),
    &        HS(I,J,2),IFNUM,JFNUM,ISNUM,JSNUM,NOF,NOS,EPSI,EMAXF,
    &        EMAXS,I,J)

   ! BASE FLOW CALCULATION
      RIVEROUTT=RIVEROUTT+QOUT(I,J)*DT
    IF(NUMOB(I,J).EQ.1)THEN
      RIVEROUT1=RIVEROUT1+QOUT(I,J)*DT
           ELSE IF(NUMOB(I,J).EQ.2)THEN
      RIVEROUT2=RIVEROUT2+QOUT(I,J)*DT
   END IF

3333 CONTINUE
    END DO
          END DO

----WRITE DAILY RESULTS-----------------------------------------------------------------------------------------------
    IF (MOD(ISTEP,INT((24.0+0.00001)/DT)).EQ.0) THEN
   !TOTAL BASIN
          WRITE(30,100) NDAY,RAINT/NGRIDT,RECHARGET/NGRIDT,DRUNOFFT/NGRIDT,
    &         QEVTT/NGRIDT,QINTT/NGRIDT,QEVFGWT/NGRIDT,QPEVTT/NGRIDT,
    &         QRGT/NGRIDT,QRET/NGRIDT,AHTT,
    &        RIVEROUTT*1000.0/(DX*DY*NGRIDT)
   !BASIN1(KODODA)
          WRITE(31,100) NDAY,RAIN1/NGRID1,RECHARGE1/NGRID1,DRUNOFF1/NGRID1,
```

```
  &       QEVT1/NGRID1,QINT1/NGRID1,QEVFGW1/NGRID1,QPEVT1/NGRID1,
  &       QRG1/NGRID1,QRE1/NGRID1,AHT1,
  &       RIVEROUT1*1000.0/(DX*DY*NGRID1)
  !BASIN2(TADANA)
       WRITE(32,100) NDAY,RAIN2/NGRID2,RECHARGE2/NGRID2,DRUNOFF2/NGRID2,
  &       QEVT2/NGRID2,QINT2/NGRID2,QEVFGW2/NGRID2,QPEVT2/NGRID2,
  &       QRG2/NGRID2,QRE2/NGRID2,AHT2,
  &       RIVEROUT2*1000.0/(DX*DY*NGRID2)
END IF
100 FORMAT(I5,1X,11F30.10)

  ! UPDATE FRESH & SALTWATER GROUNDWATER HEAD
    DO I=1,IMAX
    DO J=1,JMAX
     HF(I,J,1)=HF(I,J,2)
     HS(I,J,1)=HS(I,J,2)
    END DO
    END DO
   IF((NOS.EQ.0.AND.NOF.EQ.0).OR.
  &  (ISTEP.EQ.NDMAX*INT((24.0+0.00001)/DT))) GO TO 9999

       GO TO 1111

 9999 CONTINUE
   STOP
       END
----SUBROUTINES----------------------------------------------------------------------------------------------------
----CALCULATION OF DATE------------------------------------------------------------------------------------------
   SUBROUTINE CALTIME(IY,IM,ID,NMON,MDIF)
   IMPLICIT INTEGER*4(I-N)
       IMPLICIT REAL*8(A-H,O-Z)
   ID=ID+1
   IF(IM.EQ.2) THEN
    IF(MOD(IY,4) .EQ. 0) THEN
     IF(ID.GT.29) THEN
      IM=IM+1
      ID=1
      NMON=NMON+1
     END IF
    ELSE
     IF(ID.GT.28) THEN
      IM=IM+1
      ID=1
      NMON=NMON+1
     END IF
    END IF
   ELSE IF(IM.EQ.12) THEN
    IF(ID.GT.31) THEN
     IY=IY+1
     IM=1
     ID=1
     NMON=NMON+1
    END IF
   ELSE IF(IM.EQ.4 .OR. IM.EQ.6 .OR. IM.EQ.9 .OR. IM.EQ.11) THEN
    IF(ID.GT.30) THEN
     IM=IM+1
```

```
        ID=1
        NMON=NMON+1
      END IF
    ELSE
      IF(ID.GT.31) THEN
        IM=IM+1
        ID=1
        NMON=NMON+1
      END IF
    END IF
    RETURN
    END

----GROUNDWATER RECHARGE AT UNCONFINED AQUIFER---------------------------------------------
    SUBROUTINE CALKANY_U(H1,H2,RE,EVT1,R0,QW,AL,EVT2,EVT)
    IMPLICIT INTEGER*4(I-N)
            IMPLICIT REAL*8(A-H,O-Z)
            DT=1.0
    H2=H1+RE*DT-EVT1*DT
    IF(H2.GT.R0) THEN
      QW=(H2-R0)*AL
      H2=H2-QW*DT
      EVT2=0.0
              EVT=EVT1
    ELSE
      QW=0.0
      IF(H2.GE.0.0) THEN
        EVT2=0.0
                EVT=EVT1
      ELSE IF (H2.LT.0.0) THEN
        EVT2=-H2
                EVT=EVT1-EVT2
            IF (EVT.LT.0.0) THEN
            WRITE(*,*) EVT
            PAUSE
            END IF
        H2=0.0
      END IF
   END IF

    IF (H2.LT.0.0.OR.EVT2.LT.0.0.OR.QW.LT.0.0) THEN
            WRITE(*,*) H2,EVT2,QW
            PAUSE
            END IF

    RETURN
    END
----Groundwater Flow Model (GFM)-----------------------------------------------------------------------------------
    SUBROUTINE HEAD_CALC(F1,F2X,S1,S2X,B,AK,KN,A2,A3,QX,QM,EVGW,
   &                DX,DY,QOUT,GL,DT,ANE,IC,JC,CB,NRIVER)
    IMPLICIT INTEGER*4(I-N)
            IMPLICIT REAL*8(A-H,O-Z)
    DIMENSION F1(5),S1(5),B(5),AK(5),KN(5),GL(5),
  &          TF(5),TS(5),TF2(5),TS2(5),AK2(5),CB(5)

    EPSIRON=0.00001
```

```
 SS=0.0005
     SOKOTK=1.0E-6/100.0*3600.0
! SET THE THICKNESS OF ARUIFER
     DO I=1,5
  END IF
     IF (F1(I).LT.0.0) THEN
      F1(I)=0.0
     END IF

! UNCONFINED AQUIFER
       IF(F1(I).GT.B(I))THEN
        IF(S1(I).GT.B(I))THEN
         IF(F1(I).EQ.S1(I))THEN
           TF(I)=0.0
         ELSE
           TF(I)=F1(I)-S1(I)
         END IF
           TS(I)=S1(I)-B(I)
        ELSE
          TF(I)=F1(I)-B(I)
          TS(I)=0.0
    END IF
   ELSE
        TF(I)=EPSIRON
        TS(I)=0.0
       END IF
     END DO

! SET THE HYDRAULIC CONDUCTIVITY
 DO I=1,5
  IF(I .NE. 2) THEN
       TS2(I)=(TS(2)+TS(I))*0.5
       TF2(I)=(TF(2)+TF(I))*0.5
   IF(AK2(2)+AK(I) .EQ. 0.0) THEN
    AK2(I)=0.0
   ELSE
    AK2(I)=2.0*AK(2)*AK(I)/(AK(2)+AK(I))
   END IF
  END IF
 END DO
! CALCULATION OF SALTWATER HEAD (CONFINED & UNCONFINED)
 SX=AK2(3)*TS2(3)*(A2*(F1(3)-F1(2))+A3*(S1(3)-S1(2)))
&  -AK2(1)*TS2(1)*(A2*(F1(2)-F1(1))+A3*(S1(2)-S1(1)))
 SY=AK2(5)*TS2(5)*(A2*(F1(5)-F1(2))+A3*(S1(5)-S1(2)))
&  -AK2(4)*TS2(4)*(A2*(F1(2)-F1(4))+A3*(S1(2)-S1(4)))
 S2X=S1(2)+DT/ANE*(SX/DX**2.0+SY/DY**2.0)

 IF(S2X.GT.-40.0*F2X) THEN
  S2X=-40.0*F2X
 END IF

 IF(S2X .LE. B(2)) THEN
  S2X=B(2)
 END IF

! CALCULATION OF FRESHWATER HEAD
```

```
   FX=AK2(3)*TF2(3)*(F1(3)-F1(2))-AK2(1)*TF2(1)*(F1(2)-F1(1))
   FY=AK2(5)*TF2(5)*(F1(5)-F1(2))-AK2(4)*TF2(4)*(F1(2)-F1(4))

  ! SET THE COEFFICIENT OF RIVER WIDTH BASE ON ELEVATION
   IF(NRIVER.EQ.1)THEN
          GL22=GL(2)+3.0
          IF(GL(2).GT.50.0)THEN
           BB=0.1
          ELSE IF(GL(2).GT.30.0)THEN
           BB=0.2
          ELSE IF(GL(2).GT.10.0)THEN
           BB=0.4
          ELSE IF(GL(2).GT.0.0)THEN
           BB=1.0
          END IF
         END IF

         GL22=GL(2)

         IF (GL22.LT.0.00000) THEN
         GL22=0.0
         END IF

  ! UNCONFINED FRESHWATER DEAD & BSEFLOW TO RIVER
         F2X=F1(2)+S2X-S1(2)+DT/ANE*(FX/DX/DX-QM+FY/DY/DY+QX-EVGW)

     IF(F2X .GT. GL22) THEN
      QOUT=ANE/DT*(F2X-GL22)*DX*DY
      F2X=GL22
     ELSE
      QOUT=0.0
          END IF

   IF(F2X-B(2) .LT. EPSIRON) THEN
     F2X=B(2)+EPSIRON
   END IF
   IF(S2X.GT.F2X) THEN
     S2X=F2X
   END IF

   RETURN
   END

----CHECK STABLE CONDITION OF INCREMENT CALCULATION (SOR method)----------------------
   SUBROUTINE RES_CHECK(BASE,HF1,HF2,HS1,HS2,IFNUM,JFNUM,ISNUM,
  &                  JSNUM,NOF,NOS,EPSI,EMAXF,EMAXS,I,J)
   IMPLICIT INTEGER*4(I-N)
         IMPLICIT REAL*8(A-H,O-Z)
   IF(HF2.LE.BASE) THEN
     GO TO 4444
   ELSE
     ERRORF=ABS(HF2-HF1)
     IF(ERRORF .GT. EPSI) THEN
       IF(ERRORF .GT. EMAXF) THEN
         EMAXF=ERRORF
         IFNUM=I
```

```
          JFNUM=J
        END IF
        NOF=NOF+1
      END IF
    END IF
 4444 CONTINUE
C
    IF(HS2.LE.BASE) THEN
      GO TO 5555
    ELSE
      ERRORS=ABS(HS2-HS1)
      IF(ERRORS.GT.EPSI) THEN
        IF(ERRORS.GT.EMAXS) THEN
          EMAXS=ERRORS
          ISNUM=I
          JSNUM=J
        END IF
        NOS=NOS+1
      END IF
    END IF
 5555 CONTINUE
C
    RETURN
    END
```