Grid based rainfall-runoff model User's manual

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History

The Grid-based rainfall-Runoff Model (GRM) is a grid-based and physically based distributed rainfall-runoff model developed by the Korea Institute of Civil Engineering and Building Technology (KICT). The development history of the GRM is as follows.

- The GRM was first developed in 2008. It could simulate overland flow, channel flow, subsurface flow, and controlled flow by stream facilities. The model was developed as HyGIS-GRM, an add-on for Hydro Geographic Information System (HyGIS).

- In 2010, the base flow simulation was added. Moreover, a real-time flow analysis module using real-time rainfall data was developed.

- In 2012, a multi-site calibration method for single watersheds was developed.

- In 2014, infiltration, subsurface flow, and base flow simulation methods were improved and the MW-GRM plug-in that could run on MapWindow GIS (v.4.8.8), an open source GIS, was developed.

- In 2015, the sensitivity of the calculation time step (dt) was improved. Moreover, the real-time flow analysis module was improved to allow simulations of the real-time flow control. A multi-site calibration method that allowed coupled analysis of multiple watershed systems was developed.

- In 2017, the GRM was separated from GIS and graphic user interfaces (GUIs) and was developed into an independent executable file. In addition, a parallel computation method using .NET and a method that could change the calculation time step (dt) during simulation were adopted.

- In 2018, the GUI of the GRM model was developed as QGIS plug-in (QGIS-GRM, QGRM from 2023). The GRM model codes were converted from Visual Basic .NET into C#.

- In 2020, the model was improved to enable setting of multiple channel information. An option for real-time simulation was added. The GRM model using C/C++ was developed.

- In 2021, the model was improved to enable more detailed simulation of reservoir operation.

- In 2022, interception, evapotranspiration, and snow melt simulation modules were added for continuous runoff simulation.

- In 2023, the methods for simulating detension pond and initial loss of precipitation were added.

The GRM is continuously being developed by the KICT.

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Table of Contents

1. Overview of the GRM

1.1 Model structure

The Grid-based rainfall–Runoff Model (GRM) is a physically based distributed rainfall–runoff model used for simulating rainfall–runoff events and continuous runoff processes. The GRM simulates plant canopy interception, evapotranspiration, snow melt, infiltration, percolation, overland flow, return flow, subsurface flow, base flow, and stream flow. In vertical direction, the control volume is composed of a land surface layer and two soil layers(soil layer A and B). Overland flow, subsurface flow, return flow, lateral flow from the upstream control volumes, rainfall, and snow melt contribute to increasing the mass of a control volume. Overland flow, subsurface flow, base flow to a downstream control volume and evapotranspiration contribute to decreasing the mass of a control volume. Infiltration and percolation are the vertical flow components in a control volume.

Precipitation is partially intercepted the canopy of plants and divided into rainfall or snow by temperature. Snow increases snow pack, and snow pack contributes to direct runoff by snow melt. Rainfall contributes to direct runoff after infiltration loss. Evapotranspiration occurs in leafs, land surface, soil, and streams. Surface flow occurs in surface layer and consists of overland flow and stream flow. In the control volumes, the surface layers are classified into those in which only overland flow occurs, only stream flow occurs, and both overland flow and stream flow occur. Direct runoff consists of overland flow and subsurface flow. Overland flow is caused by infiltration excess flow (Horton, 1933) and saturation excess flow (Dunne and Black, 1970). The infiltration process and subsurface flow are simulated in the soil layer A, which means soil water zone (Bras, 1990), and the infiltrated water contributes to subsurface flow. Subsurface flow becomes a lateral inflow of the downstream control volume if there is a stream. If the downstream cell is a saturated overland flow control volume, the subsurface flow contributes to overland inflow through return flow (Beven and Kirkby, 1979). Base flow is simulated In the soil layer B which includes unconfined aquifer.

In the schematic diagram of the model, x is the flow direction, y is the direction perpendicular to the x direction, and h is the water depth. p is precipitation, e_t is evapotranspiration, s_p is snow pack, s_m is snow melt, c is interception, f is infiltration, q_r is return flow, q_L lateral flow, q_{ss} is subsruface flow, q_b is base flow, and Q is stream discharge.

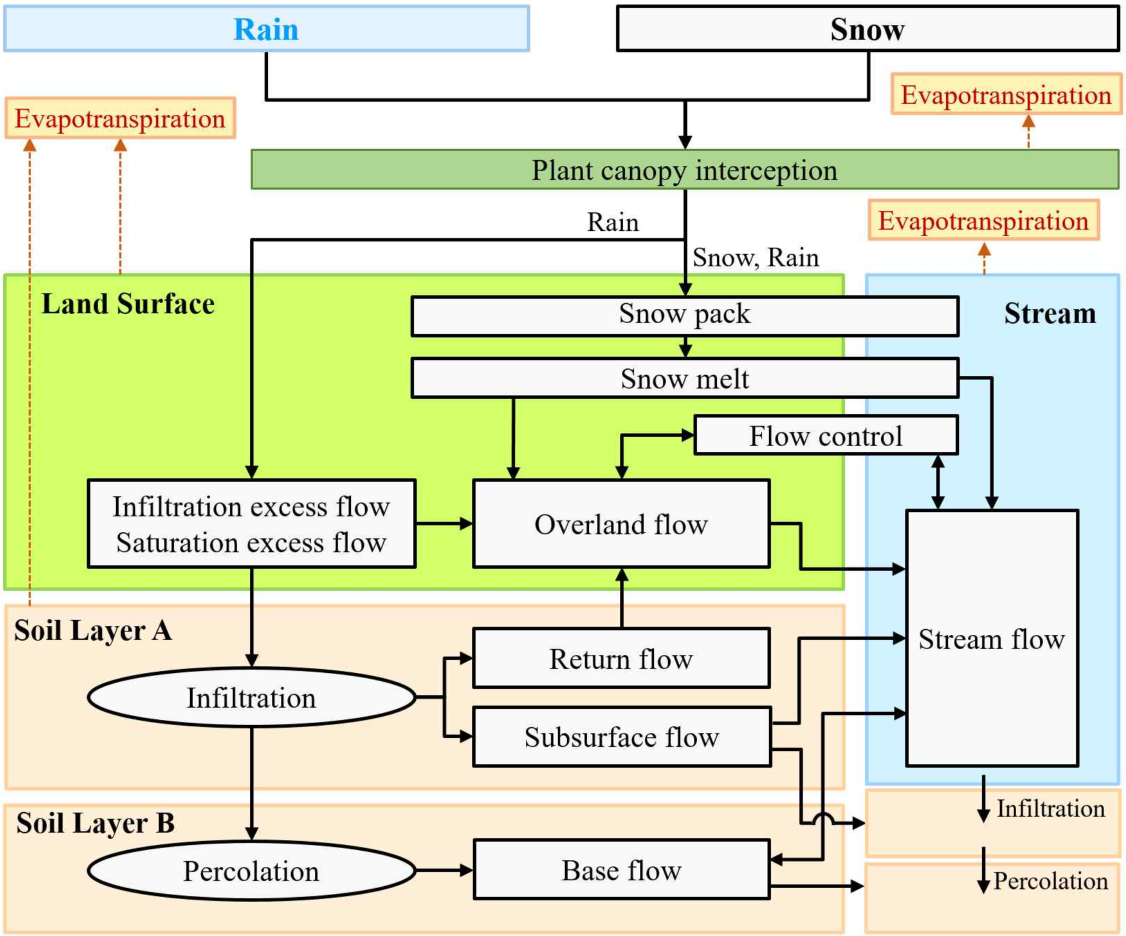


Fig. 1.1 Schematic diagram of hydrological components

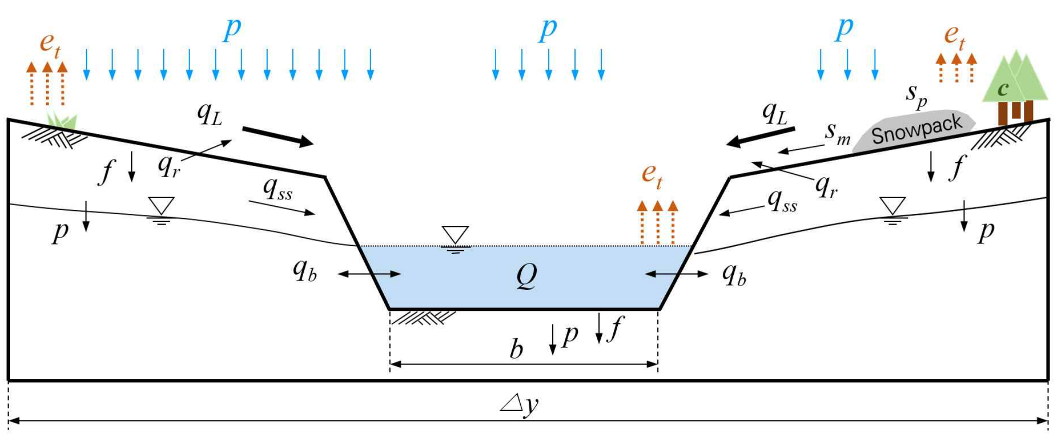


Fig 1.2 Schematic diagram of cross-sectional hydrological components

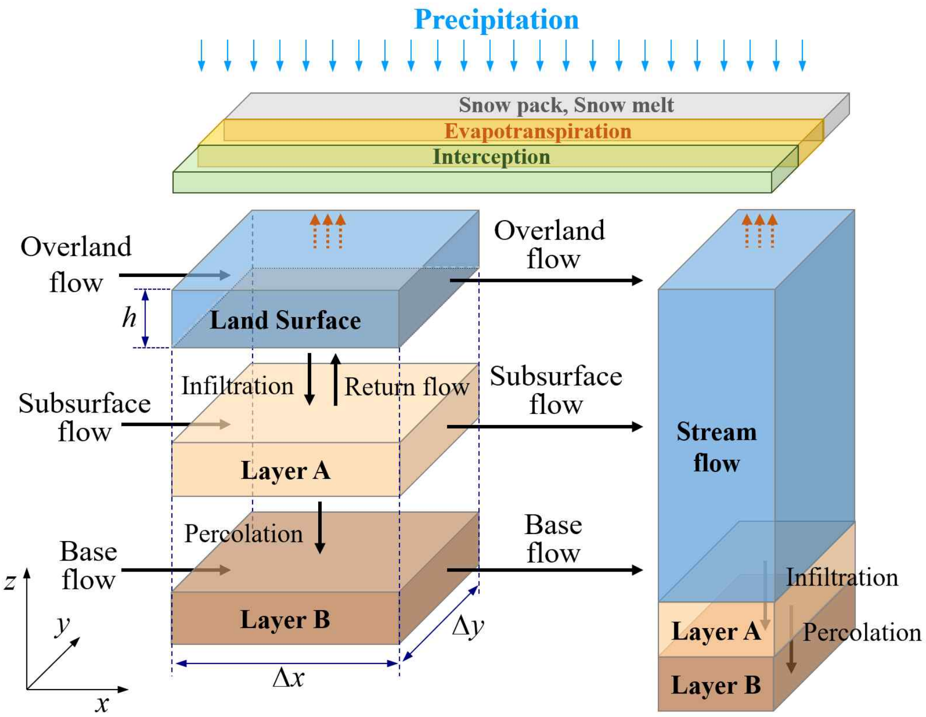


Fig. 1.3 Input and output of hydrological components within a control volume

1.2 Interception

Interception is the loss of precipitation contributing to runoff by plant canopy. Interception can be calculated by using maximum possible interception by plant canopy and vegetation health. The vegetation health is expressed by the ratio of LAI (Leaf Area Index) of the target plant in the month to the maximum value of the LAI (LAI_{mx}) (Neitsch et al., 2005). The precipitation exceeding the daily possible maximum interception passes through the leaves of the plant and reaches the ground. In the GRM, the ratio of vegetation coverage to each grid cell is used to calculate interception and precipitation reaching the ground for each cell.

$$c_{mx\_day} = c_{mx} \frac{LAI}{LAI_{mx}} \tag{1.2.1}$$

$$p_g = p \times (1 - R_{cnpy}) + p_{cg} R_{cnpy} \tag{1.2.2}$$

Here, c_{mx_day} is is the maximum amount of interception per day (mm/day), c_{mx} is the maximum amount of interception for each vegetation (mm), p_g is the precipitation reaching the ground, p is the precipitation without interception, p_{cg} is the precipitation reaching the ground in excess of the maximum interception potential, and R_{cnpy} is the vegetation coverage ratio in a control volume.

1.3 Evapotranspiration

Evapotranspiration is simulated in plant leaves, ground, and water surface. Potential evapotranspiration is calculated by using Blaney-Criddle (Blaney and Criddle, 1950), Hamon (Hamon, 1961), Hargreaves (Hargreaves and Samani, 1985), and Priestly-Taylor (Priestley and Taylor, 1972; Ponce, 1989) methods. Actual evapotranspiration is calculated by multiplying potential evapotranspiration by the evapotranspiration coefficient.

Evapotranspiration from vegetation targets the moisture intercepted by the vegetation, and the evapotranspiration exceeds in the moisture is calculated as the evapotranspiration from ground or water surface. Evapotranspiration from the ground is calculated as the loss of the surface water depth if land surface water exists, or as loss of the soil moisture if surface water does not exist. Evapotranspiration in water bodies such as streams and reservoirs uses potential evapotranspiration values.

1.3.1 Blaney-Criddle method

The Blaney-Criddle method calculates potential evapotranspiration using the daily average temperature and the ratio of daytime hours to total annual daytime hours.

$$e_{tp} = kR_{sr}\,(0.457\,T_a + 8.128) \tag{1.3.1}$$

Here, e_{tp} is the potential evapotranspiration (mm/day), T_a is the daily average temperature (℃), R_{sr} is the ratio of daily daytime hours to total annual daytime hours (%), and k is the monthly crop coefficient (0.45 ~ 1.2), 0.85 during the growing season (usually April ~ September), 0.45 otherwise.

1.3.2 Hamon method

The Hamon method calculates potential evapotranspiration using daily average temperature and daytime hours.

$$e_{tp} = 0.55 \times 25.4 \times (\frac{n}{12})^2 (\frac{D_{sv}}{12}) \tag{1.3.2}$$

$$D_{sv} = \frac{216.7 \times e_s}{(T_a + 273.3)} \tag{1.3.3}$$

$$e_s = 6.108 e^{17.26939\,T_a/(T_a + 273.3)} \tag{1.3.4}$$

Here, e_{tp} is the potential evapotranspiration (mm/day), n is the daytime hours (hours), D_{sv} is the saturated water vapor density at temperature T_a (g/m^3), T_a is the daily average temperature (℃), and e_s is the saturated water vapor pressure at temperature T_a (mb)

1.3.3 Hargreaves method

The Hargreaves method calculates potential evapotranspiration using daily maximum temperature, daily minimum temperature, and solar radiation.

$$e_{tp} = k_{RS}\frac{R_a}{0.004184 \times l_v}(T_{\max} - T_{\min})^{e_h} \times \left(\frac{T_{\max} + T_{\min}}{2} + c_t\right) \quad (1.3.5)$$

Here, e_{tp} is the potential evapotranspiration (mm/day), R_a is the daily solar radiation ($MJ/m^2/day$), l_v is the latent heat of vaporization (cal/gr), $T_{\max}$ is the maximum air temperature for a given day (℃), $T_{\min}$ is the minimum air temperature for a given day (℃), k_{RS} is the solar radiation coefficient (0.0023), e_h is the Hargreaves coefficient (0.5), and c_t is the temperature coefficient (17.8).

1.3.4 Priestly-Taylor method

The Priestly-Taylor method calculates potential evapotranspiration using solar radiation and air temperature.

$$e_{tp} = \alpha\frac{\Delta}{\Delta + \gamma}E_r \quad (1.3.6)$$

$$E_r = \frac{R_n}{l_v \rho_w} \quad (1.3.7)$$

Here, e_{tp} is the potential evapotranspiration (cm/day), γ is the psychrometric constant ($kPa/℃$), α is the coefficient (usually 1.28), Δ is the slope of the saturation vapor pressure-temperature curve, E_r is the evaporation rate (cm/day), R_n is the net radiation flux ($cal/cm^2/day$), l_v is the latent heat of vaporization (cal/gr), and ρ_w is the water density (g/cm^3).

1.3.5 Actual evapotranspiration

Actual evapotranspiration is calculated by multiplying potential evapotranspiration by the evapotranspiration coefficient or crop coefficient. At this time, in case of calculating the actual evapotranspiration for a watershed or region, not for a certain crop, an evapotranspiration coefficient of 0.6 to 0.8 can usually be used.

$$e_{ta} = k_c e_{tp} \quad (1.3.8)$$

Here, e_{tp} is the actual evapotranspiration, e_{tp} is the potential evapotranspiration, and k_c is the evapotranspiration coefficient (or crop coefficient) (0.6~0.8).

1.4 Snow melt

Snow melt is generated by melting snow on the ground. Precipitation falling from the sky is divided into snow and rain by the specific air temperature and reaches the ground. The GRM simulate snow melt using the following equation based on the study of Anderson (1976) and Neitsch et al.(2005). Sublimation from the snow pack is assumed to be included in evapotranspiration and is not considered in the snow melt simulation.

$$S_p = S_p + p_{day} - S_{mlt} \tag{1.4.1}$$

$$S_{mlt} = b_{mlt} \cdot S_{cov} \cdot \left[\frac{T_{snow} + T_{mx}}{2} - T_{mlt} \right] \tag{1.4.2}$$

Here, S_p is the moisture content of the snow pack (the height when the height of snow pack is converted to water depth) ($mm\,H_2O$), p_{day} is the daily precipitation (valid when $T_{av} \leq T_{sr}$) ($mm\,H_2O$), T_{av} is the average daily air temperature (℃), T_{sr} is the threshold air temperature for dividing precipitation into snow and rain (℃), S_{mlt} is the daily snow melt ($mm\,H_2O$), b_{mlt} is the snow melt coefficient ($mm\,H_2O$/day-℃), S_{cov} is the snow pack coverage ratio, T_{snow} is the snow pack temperature for the day (℃), T_{mx} is the max air temperature for the day (℃), and T_{mlt} the air temperature at which the snow melt begins (℃).

1.5 Surface flow

Surface flow can be divided into overland flow and channel flow. A kinematic wave equation is used for flow analysis. The kinematic wave equation uses a combination of the continuity equation and momentum equation. Equation (1.5.1) is the continuity equation for overland flow and Eq. (1.5.2) is the equation for stream flow. The momentum equation for the kinematic wave model is defined by Eq. (1.5.3).

$$\frac{\partial h}{\partial t} + \frac{\partial q}{\partial x} = M + \frac{q_r}{\Delta y} \tag{1.5.1}$$

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = M \Delta y + L \tag{1.5.2}$$

$$S_0 = S_f \tag{1.5.3}$$

$$M = r - f - c - e_t - s_p + s_m \tag{1.5.4}$$

$$L = q_o + q_{ss} + q_b \tag{1.5.5}$$

Here, q is the flow per unit width ($q = uh$), u is the flow velocity in x direction, q_r is the return flow, A is the cross-sectional flow area perpendicular to the x direction, Q is the flow, h is the water depth, t is the time, S_0 is the ground surface slope, S_f is the friction slope, M is the source term, r is the rainfall intensity, f is the infiltration rate, c is the interception, e_t is the evapotranspiration, s_p is the snow as water depth add to the snow pack, s_m is the snow melt, L is the lateral inflow, q_o is the overland flow in the control volume including both overland flow and stream flow characteristics, q_{ss} is the subsurface flow, and q_b is the base flow.

From equation (1.5.3), the bed slope can be used instead of the friction slope to calculate the flow velocity with Manning's flow velocity equation. The water depths is used to approximate the hydraulic radius of overland flow with shallow water depths. An asymmetrical trapezoidal cross section can be applied to the hydraulic radius for channel routing.

$$u = \frac{R^{2/3} S_0^{1/2}}{n} \tag{1.5.6}$$

Here, n is the roughness coefficient and R is the hydraulic radius.

$$R = \frac{b_s h}{b_s + 2h} \approx h \tag{1.5.7}$$

Here, b_s is the control volume width for overland flow ($b_s \gg h$)

$$R = \frac{bh + \frac{h^2}{2}\left(\frac{1}{SLB} + \frac{1}{SRB}\right)}{b + h \times \sqrt{1 + \frac{1}{SLB^2}} + h \times \sqrt{1 + \frac{1}{SRB^2}}} \tag{1.5.8}$$

Here, b is the channel base width, $SLB = h/b_{LB}$, and $SRB = h/b_{RB}$.

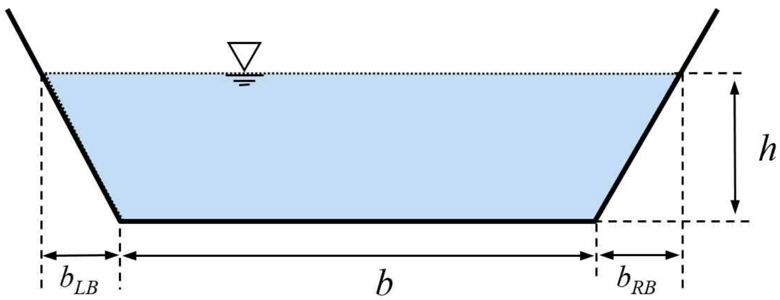


Fig. 1.4 Asymmetrical trapezoidal channel cross section

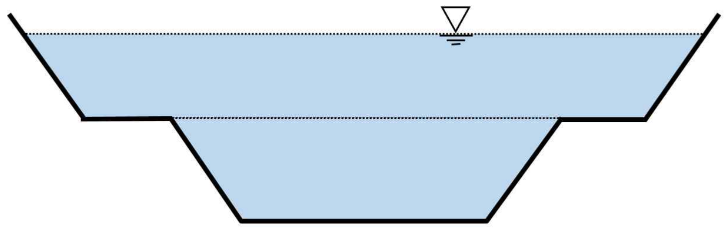


Fig. 1.5 Compound channel cross section

The GRM model uses uniform square grids as control volumes, and the length of the x direction (Δx) of a diagonal flow is larger than the value of rectangular flow. To conserve the mass of the rainfall for the control volumes of different flow directions, the GRM model uses the equation below.

$$r_{app} = r \times \Delta x / \Delta x_{app} \tag{1.5.9}$$

Here, r_{app} is rainfall intensity for a control volume, r is the rainfall intensity calculated from input rainfall data, Δx is the x direction length of a control volume for rectangular flow, and Δx_{app} is the x direction length by the flow direction (rectangular or diagonal) of a control volume

1.6 Infiltration

The GRM can simulate infiltration excess flow, which occurs when the rainfall intensity exceeds infiltration rate, and saturation excess flow, which occurs when soil is saturated. The Green–Ampt Model is used to calculate the infiltration. The Green–Ampt Model calculates cumulative infiltration, as shown the equations below, the infiltration rate is then calculated using the cumulative infiltration.

$$F(t) = Kt + \Delta\theta\psi \ln(1 + \frac{F(t)}{\Delta\theta\psi}) \tag{1.6.1}$$

$$f(t) = K\left(\frac{\psi\Delta\theta}{F(t)} + 1\right) \tag{1.6.2}$$

Here, $F(t)$ is the cumulative infiltration at time t, $f(t)$ is the infiltration rate at time t, $\Delta\theta$ is the change in the soil moisture content ($\Delta\theta = (1 - S_e)\theta_e$), S_e is the effective saturation ($S_e = (\theta - \theta_r)/(\eta - \theta_r)$), θ is the moisture content ($\theta_r \le \theta \le \eta$), θ_r is the residual moisture content ($\theta_r = \eta - \theta_e$), η is the soil porosity, θ_e is the effective soil porosity, ψ is the wetting front soil suction head, and K is the hydraulic conductivity.

1.7 Subsurface flow

Beven (1981) applied the kinematic wave model to simulate subsurface flow at saturated conditions. The subsurface flow from the kinematic wave model is based on the assumption that the hydraulic gradient is equal to the land surface gradient within a control volume. Subsurface flow can be calculated using the equation below.

$$q_{ss} = KD_s \sin(S_a) \tag{1.7.1}$$

Here, q_{ss} is the subsurface flow, D_s is the saturated soil depth, and S_a is the land surface inclination angle.

The simulation of subsurface flow from the kinematic wave model with soil depth D is shown in the figure below (Choi, 2010). The GRM assumes the hydraulic gradient of subsurface flow within a control volume to be equal to the land surface gradient and simulates the subsurface flow for saturated soil depths. In stream flow, the subsurface flow contributes as a component of lateral flow into the stream. In overland flow, subsurface flow from the upstream control volumes (SFUCV) is simulated as a return flow when the soil of the current control volume is saturated. If the soil is not saturated, the increase in soil moisture content due to SFUCV is first calculated, and after saturation, the return flow is calculated.

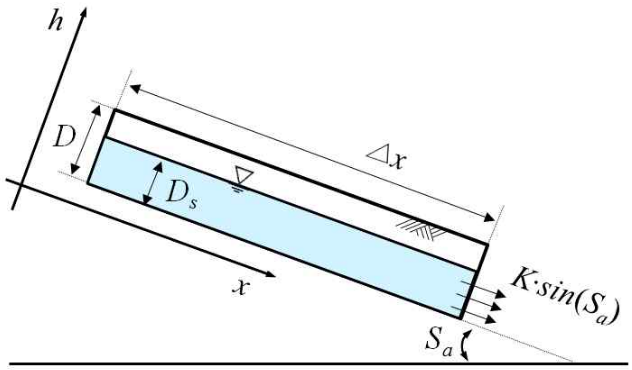


Fig. 1.6 Subsurface flow of a kinematic wave model

Sloan and Moore (1984) suggested the Simple Storage–Discharge Model based on the water budget to calculate flow in an arbitrary segment including completely saturated soil. The equation below shows the saturated excess flow and subsurface flow for completely saturated soil. Each component of the GRM is used to simulate the overland inflow and either lateral inflow or return flow at the downstream control volume. Particularly, when rainfall and runoff occur, the depth of the saturated soil varies. Thus the control volumes in which saturated excess flow (Dunne and Black, 1970) and return flow simulated only for completely saturated soil are occurred also vary (Dunne and Black, 1970; Bras, 1990).

$$q_o = i_s L_s + q_s \tag{1.7.2}$$

Here, q_o is the flow per unit width at the downstream end of an arbitrary segment, L_s is the length of the land surface segment that is saturated up to the land surface, and i_s is the inflow perpendicular to the saturated water surface from an external area.

1.8 Base flow

The GRM divides soil into two layers. Simulations of the infiltration and subsurface flow are done for the upper layer A and the base flow is simulated for the lower layer B. Soil moisture in layer A is moved to layer B by percolation. The equation below is used to calculate the percolation depth.

$$p = K_{Bv} \times \Delta t \tag{1.8.1}$$

Here, K_{Bv} is the vertical hydraulic conductivity of layer B, p is the percolation during time Δt.

The horizontal flow in layer B can be calculated using Eq. (1.8.2) based on Darcy's law (Freeze and Cheery, 1979). Here, the head difference of segment Δx is assumed to be equal to the land surface slope when applying Eq. (1.8.3).

$$q_{Bh} = K_{Bh} D_B \frac{dz_B}{dx} \tag{1.8.2}$$

$$q_{Bh} = K_{Bh} D_B \sin(S_a) \tag{1.8.3}$$

Here, z_B is the water level of layer B, K_{Bh} is the horizontal hydraulic conductivity of layer B, D_B is the water depth of layer B, and q_{Bh} is the horizontal flow per unit width of layer B.

For the flow exchange between an unconfined aquifer and stream, the base flow into the channel is calculated with Eq. (1.8.4) when the water depth of the unconfined aquifer (h_B) is deeper than the water depth of the channel (h_{ch}). When the water depth of the channel is deeper than the water depth of the unconfined aquifer, Eq. (1.8.5) is used to calculate the flow from the channel into soil layer B.

$$q_b = K_{Bh} \frac{h_B - h_{ch}}{h_{ch}} b \qquad \text{(for} \quad h_B > h_{ch}) \tag{1.8.4}$$

$$q_b = K_{Bh}(h_B - h_{ch}) \qquad \text{(for} \quad h_B < h_{ch}) \tag{1.8.5}$$

Here, h_B is the water depth of the unconfined aquifer, h_{ch} is the water depth of the channel, b is the channel base width, and q_b is the base flow per unit length of the control volume.

1.9 Discretization of governing equations

The GRM uses the finite volume method for the discretization of governing equations. The definition of a control volume for such a process is shown in the following figure. The control volume number is indicated with subscript i, the central point of the control volume with p, the control volume surface in the upstream direction ($-x$ direction) from the inflow into the control volume with w, and the control volume surface in the downstream direction (x direction) with outflow with e (Patankar, 1980).

Equations (1.9.1) and (1.9.2) show the discretization of equations from integrating the continuity equations for overland flow and channel flow analyses with respect to x and t for CV_i. Converging solutions for nonlinear terms are found from the Newton–Raphson iteration method (Choi, 2010). When overland flow and stream flow must be simulated together from one grid, the difference between the length in direction y (Δy) and the channel base width (b) is applied to Δy_i which is used for overland flow analysis in Eq. (1.9.1).

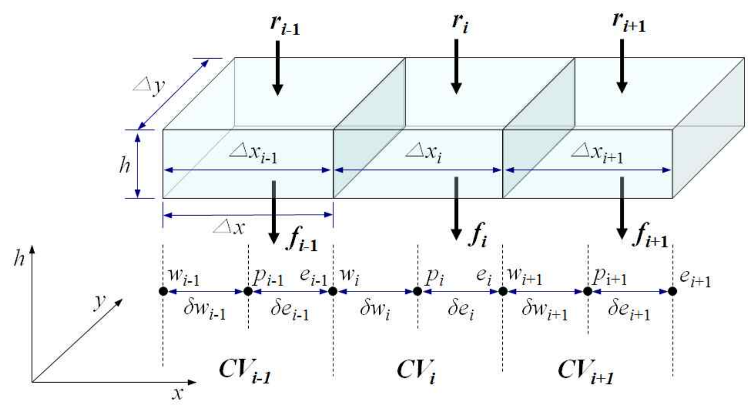


Fig. 1.7 Definition of the control volume for discretization

$$h_{ip}^{j+1} = h_{ip}^{j} - \alpha(\overline{u})_{ie}^{j+1} h_{ie}^{j+1} \frac{\Delta t}{\Delta x_i} + \alpha(\overline{u})_{iw}^{j+1} h_{iw}^{j+1} \frac{\Delta t}{\Delta x_i} - (1-\alpha)\left\{(\overline{u})_{ie}^{j} h_{ie}^{j} - (\overline{u})_{iw}^{j} h_{iw}^{j}\right\} \frac{\Delta t}{\Delta x_i} + \left\{\alpha S_i^{j+1} + (1-\alpha) S_i^{j}\right\} \Delta t \tag{1.9.1}$$

Here, $S_i = M_o + \dfrac{q_{ri}}{\Delta y_i}$, $\Delta y_i = \Delta y - b_i$, b_i is the channel base width defined for the control volume CV_i, and α is the temporal discretization coefficient.

$$A_{ip}^{j+1} = A_{ip}^{j} - \alpha(\overline{u})_{ie}^{j+1} A_{ie}^{j+1} \frac{\Delta t}{\Delta x_i} + \alpha(\overline{u})_{iw}^{j+1} A_{iw}^{j+1} \frac{\Delta t}{\Delta x_i} - (1-\alpha)\left\{(\overline{u})_{ie}^{j} A_{ie}^{j} - (\overline{u})_{iw}^{j} A_{iw}^{j}\right\} \frac{\Delta t}{\Delta x_i} + \left\{\alpha S_i^{j+1} + (1-\alpha) S_i^{j}\right\} \Delta t \tag{1.9.2}$$

Here, $S_i = M_s \Delta y_i + L$.

An arbitrary control volume which have stream properties is divided into two cases according to the channel base width and grid cell size: the case of the channel base width being smaller than the grid cell size and the case of the channel base width being equal to or larger than the grid cell size. When the channel base width is smaller than the grid cell size, all the hydrological components for overland flow and stream flow are simulated with respect to the corresponding control volume. However, when the channel base width is equal to or larger than the grid cell size, only stream flow is simulated.

Here, rainfall at the corresponding control volume either occurs within the channel base width or outside of it. The rainfall occurring within the channel base width contributes to the direct runoff of the stream and the rainfall outside the channel is needed infiltration analysis as it is done for the overland flow control volume.

Consequently, Δy_i in Eq. (1.9.2) for stream flow analysis must be the same as the grid cell size in direction y ($\Delta y_i = \Delta y$) when the channel base width is equal to or larger than the grid cell size. And when the channel base width is smaller than the grid cell size, the channel base width should be applied ($\Delta y_i = b_i$).

1.10 Flow control

The GRM can not only simulate natural runoff but also reflects the changes of artificial flow conditions occurring within a watershed to runoff simulations using a flow control module. The flow conditions that can be simulated with the flow control module are “Reservoir outflow,” “Inlet,” “Reservoir operation,” “Sink flow,” “Source flow”, and ”Detension pond.”

The flow control technique can be applied to all grids with channel flow or overland flow properties. Moreover, multiple flow control conditions can be simultaneously applied to a single watershed to reflect the direct runoff from rainfall and changes of various flow conditions that occur during runoff simulations (KICT, 2011b).

1.10.1 Reservoir outflow

The “Reservoir outflow” function simulates runoff by dividing a watershed into upstream and downstream with respect to grids selected as the reservoir; it does not consider the reservoir operation rule. The discharge from the control volume selected as the reservoir is set using an observed hydrograph of the reservoir entered by the user. The runoff simulation of the control volume located in the immediate downstream of the reservoir is performed by including the reservoir outflow in the upstream boundary conditions.

$$q_{ie} = q_o \tag{1.10.1}$$

Here, q_{ie} is the outflow per unit width from the control volume i selected as the reservoir and q_o is the outflow per unit width calculated from the observed discharge hydrograph of the reservoir.

When “Reservoir outflow” is applied, reservoir specification (RS) can be set as shown in the following table and reservoir operation method (ROM) is not needed to be set. If RS is not entered, the initial and maximum storage amounts are set as “0” and the storage of the cell is not calculated.

When the "/a" option is used in “Reservoir outflow”, the GRM model uses all the data entered by the user (e.g., the dam discharge) in the flow control simulation, and if there is no more flow control data, the AutoROM is applied using the reservoirs specification. Therefore, when applying the "/a" option, specifications of all the reservoirs included in the runoff simulation must be entered.

1.10.2 Inlet

Upstream and downstream are distinguished based on the grid selected as the inlet. This is identical to the “Reservoir outflow” that simulates flow by dividing a watershed based on a particular grid. However, the “Inlet” does not simulate the upstream of inlet grid. Moreover, it does not consider the reservoir operation rule. When a runoff hydrograph for the inlet grid is given, the outflow of inlet grid is calculated with the method shown in Eq. (1.10.1). And data is applied as the upstream boundary condition for the downstream cell of the inlet.

This "Inlet" function excludes the upstream area of a dam and reservoir from simulation area when observed runoff hydrographs of a dam or reservoir are available for large watersheds that include dams and reservoirs. It only simulates the downstream areas and thus allows the reduction of the scope of required spatial data and hydrological time series data. In grid-based distributed models, the number of grids comprising a watershed is reduced when the simulation area decreases. It can reduce the model run time. Moreover, applying equal model run times allows using small-sized grids. This can reduce uncertainties in gridded topographical and hydrological data due to issues with the scales of grid sizes.

1.10.3 Reservoir operation

The "Reservoir operation" function can reflect the effects of storage in a reservoir and reservoir operation in flow simulations. When "Reservoir operation" is applied, reservoir specification (RS) and reservoir operation method (ROM) in the following table have to be entered.

1.10.4 Sink flow / source flow

"Sink flow" simulates the condition of partially omitting flow that was simulated in an arbitrary grid. "Source flow" simulates flow by reflecting flow conditions that were added to the flow simulated in an arbitrary grid. The discharge, either excluded or added due to "Sink flow" and "Source flow," is given by time series data and is applied as source term when simulating overland flow and channel flow. "Sink flow" or "Source flow" can be calculated with other flow control features ("Inlet", "Reservoir outflow", "Reservoir operation") simultaneously in a control volume. In this case, the time step of the flow control timeseries data in a control volume need to be set as the same value.

1.10.5 Detension pond

When there are the observed inflow and outflow data of a detension pond (DP), it is possible to simulate the changes of runoff through the "Sink flow" and "Source flow" methods. If there are no flow data for the DP, "Detension pond" method can be applied to simulate the effect of a DP. In "Detension pond" method, the GRM make a virtual DP by using the reservoir specification in the following table and the parameters related to the inflow and outflow of the DP are used.

When “Detension pond” is assinged to an overland flow cell, all the runoff from the cell is calculated as the inflow of the DP, and the outflow from the cell is not occurred until the maximum storage of the DP. When “Detension pond” is assinged to a stream cell, the following equation is used to calculate the inflow of the DP.

$$Q_{di} = (Q_s - Q_{th}) \times c_{di} \times W_{di} / (W_s + W_{di}) \tag{1.10.2}$$

Here, Q_{di} is the inflow of the DP, Q_s is the stream flow rate at the location of the DP inlet, Q_{th} is the threshold stream flow rate to start flowing between stream and DP, c_{di} is the inflow coefficient, W_{di} is the inlet base width (assuming an open channel with rectangular cross section), and W_s is the stream base width at the location of the DP inlet.

Table 1.1 Reservoir conditions for applying the “Reservoir operation” function (Choi, 2010)

Classification		Description
Specifica-tions	Initial Storage	The reservoir storage at the time of starting simulation
	Maximum Storage	Maximum storage of the reservoir. The capacity corresponding to the project reservoir water level. The maximum storage capacity during the flood season.
	Storage for the normal high water level	The reservoir storage for the normal high water level. The maximum storage during the period excluding flood season.
	Storage for the restricted water level	The reservoir storage for the restricted water level(e.g. flood restricted water level). If there is no observed “Initial Storage”, it can be applied to “Initial Storage” value.
	Period of the restricted water level storage	The period to apply the restricted water level storage. The simulation time except this duration the normal high water level storage is applied.
ROM	Automatic ROM	Reservoir discharge does not occur until the maximum possible storage(Maximum storage, storage for the normal high water level, storage for the restricted water level, etc.) is reached. When the maximum possible storage is reached, all flow into the reservoir is discharged.
	Rigid ROM	If the reservoir inflow is less than the set discharge, the constant ratio of inflow is discharged. If the inflow is equal or greater than the set discharge, set constant flow is discharged. If the reservoir storage exceeds the maximum possible storage, all inflow to the reservoir is discharged.
	Constant Discharge	If the reservoir storage is less than the set discharge, all of it is discharged. If the reservoir storage is more than the set discharge, the constant flow is discharged during specified time regardless of reservoir capacity.
	Storage–Discharge Relationship	The storage–discharge, water level–storage, or water level–discharge relationships are used to calculate the storage and discharge (only supported in source code level).

1.11 Calculation time step

The GRM can either use the same calculation time step (Δt) for the entire simulation process or different calculation time steps according to calculated flow. The first case applies the same calculation time step set by the user repeatedly for the entire simulation process. The second case uses the Courant–Friedrichs–Lewy (CFL) condition to change the calculation time step for each calculation step. The CFL condition is defined by the equation below.

$$\Delta t \leq \frac{\Delta x}{u_{\max}} \tag{1.11.1}$$

Here, $u_{\max}$ is the maximum flow among all grids calculated at time t and Δt is the calculation time step for time $t + \Delta t$.

2. Model parameters

The GRM analyzes the rainfall–runoff relationship physically and consequently physical parameters assigned to each grid are used. Theoretically, physical parameters selected based on the watershed boundaries, stream network, soil, and land cover should be omitted from the list of parameters estimated by the user. However, they can become parameters to be estimated depending on the limitations of governing equations and issues with data creation and scale. The GRM includes the parameters to be estimated by users and each parameter selected according to the soil and land cover properties can be modified by uniform ratio using the parameter calibration coefficient.

2.1 Evapotranspiration parameter

Most of the potential evapotranspiration can be calculated using meteorological data, but the Blaney-Criddle method and the Priestly-Taylor method require additional parameters. The Blaney-Criddle method requires the monthly crop coefficient (k) and the ratio of daily daytime hours to total annual daytime hours (R_{sr}). Generally, monthly crop coefficient is 0.45 ~ 1.2, and 0.85 for the growing season (from April to September) and 0.45 for the non-growing season can be applied. R_{sr} can be set using the table below (Kim, 2012) calculated using the ratio of monthly daytime hours to total annual daytime hours presented by latitude.

The Priestly-Taylor method requires the slope of the saturated vapor pressure curve at a specific temperature, the psychrometric constant, and the latent heat of vaporization. In GRM, it is assumed that the saturated vapor pressure in each temperature period has a linear slope from the saturated vapor pressure data for each temperature, and this slope value is used for evapotranspiration calculation.

The psychrometric constant and latent heat of vaporization are calculated using the following linear regression equation using each reference table.

$$l_v = -0.56 \times T_a + 597.3 \quad (2.1.1)$$

$$\gamma = 0.0006 \times T_a + 0.655 \quad (2.1.2)$$

Here, l_v is the latent heat of vaporization (cal/gr), γ is the psychrometric constant ($mb/℃$), and T_a is the average air temperature (℃).

Table 2.1 The ratio of daily daytime hours for each month to total annual daytime hours

월 / 북위	1	2	3	4	5	6	7	8	9	10	11	12
64도	0.12	0.19	0.26	0.33	0.40	0.45	0.43	0.36	0.29	0.21	0.14	0.10
62도	0.14	0.20	0.26	0.33	0.39	0.43	0.41	0.35	0.29	0.22	0.16	0.12
60도	0.15	0.20	0.26	0.32	0.38	0.41	0.40	0.34	0.28	0.22	0.17	0.13
58도	0.16	0.21	0.26	0.32	0.37	0.40	0.38	0.34	0.28	0.23	0.18	0.15
56도	0.17	0.21	0.26	0.32	0.36	0.39	0.38	0.33	0.28	0.23	0.18	0.16
54도	0.18	0.22	0.26	0.31	0.36	0.38	0.37	0.33	0.28	0.23	0.19	0.17
52도	0.19	0.22	0.26	0.31	0.35	0.37	0.36	0.33	0.28	0.24	0.20	0.17
50도	0.19	0.23	0.27	0.31	0.34	0.36	0.35	0.32	0.28	0.24	0.20	0.18
48도	0.20	0.23	0.27	0.31	0.34	0.36	0.35	0.32	0.28	0.24	0.21	0.19
46도	0.20	0.23	0.27	0.30	0.33	0.35	0.34	0.32	0.28	0.24	0.21	0.20
44도	0.21	0.23	0.27	0.30	0.33	0.35	0.34	0.31	0.28	0.25	0.22	0.20
42도	0.21	0.24	0.27	0.30	0.33	0.34	0.33	0.31	0.28	0.25	0.22	0.21
40도	0.22	0.24	0.27	0.30	0.32	0.34	0.33	0.31	0.28	0.25	0.22	0.21
38도	0.22	0.24	0.27	0.30	0.32	0.33	0.33	0.31	0.28	0.25	0.23	0.22
36도	0.23	0.24	0.27	0.30	0.32	0.33	0.32	0.30	0.28	0.25	0.23	0.22
34도	0.23	0.25	0.27	0.29	0.31	0.32	0.32	0.30	0.28	0.25	0.23	0.22
32도	0.23	0.25	0.27	0.29	0.31	0.32	0.32	0.30	0.28	0.26	0.24	0.23
28도	0.24	0.25	0.27	0.29	0.31	0.31	0.31	0.30	0.28	0.26	0.24	0.23
26도	0.24	0.25	0.27	0.29	0.30	0.31	0.31	0.29	0.28	0.26	0.25	0.24
24도	0.24	0.26	0.27	0.29	0.30	0.31	0.30	0.29	0.28	0.26	0.25	0.24
22도	0.25	0.26	0.27	0.29	0.30	0.30	0.30	0.29	0.28	0.26	0.25	0.24
20도	0.25	0.26	0.27	0.28	0.30	0.30	0.30	0.29	0.28	0.26	0.25	0.25
18도	0.25	0.26	0.27	0.28	0.29	0.30	0.30	0.29	0.28	0.26	0.26	0.25
16도	0.26	0.26	0.27	0.28	0.29	0.30	0.29	0.29	0.28	0.27	0.26	0.25
14도	0.26	0.26	0.27	0.28	0.29	0.29	0.29	0.28	0.28	0.27	0.26	0.26
12도	0.26	0.27	0.27	0.28	0.29	0.29	0.29	0.28	0.28	0.27	0.26	0.26
10도	0.26	0.27	0.27	0.28	0.28	0.29	0.29	0.28	0.28	0.27	0.26	0.26
8도	0.26	0.27	0.27	0.28	0.28	0.28	0.28	0.28	0.28	0.27	0.27	0.26
6도	0.27	0.27	0.27	0.28	0.28	0.28	0.28	0.28	0.27	0.27	0.27	0.27
4도	0.27	0.27	0.27	0.28	0.28	0.28	0.28	0.28	0.27	0.27	0.27	0.27
2도	0.27	0.27	0.27	0.28	0.28	0.28	0.28	0.28	0.27	0.27	0.27	0.27
0도	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27

2.2 Snow melt parameter

In order to calculate snow melt, in addition to meteorological data and snow pack temperature time series data, parameters include the threshold air temperature at which precipitation divided into snow and rainfall, the air temperature at which snow melt begins, the snow pack coverage ratio by each cell if there is snow pack, and the snow melt coefficient are required. These parameters are set for each simulation region (watershed, catchment, etc.), assigned for each cell, and estimated by the users.

2.3 Soil parameters

The GRM uses the Green–Ampt model to simulate the infiltration process. The Green–Ampt model parameters according to the soil properties for the simulation of infiltration excess flow and the soil depth for saturation excess flow and subsurface flow must be selected.

Calculating the infiltration using the Green–Ampt model requires the physical soil properties such as porosity, effective porosity, wetting front suction head, and hydraulic conductivity. Such soil properties can be obtained by measuring the soil moisture content (Brakensiek et al., 1981). Rawls et al. (1983) analyzed approximately 5,000 soil samples across the U.S. and suggested average values for the Green–Ampt model parameters according to the soil texture (Rawls et al., 1983; Chow et al., 1988). All parameters used to derive the effective saturation of the soil for the Green–Ampt model, except for the initial moisture content (θ), are defined by the values already set according to the soil texture. Moreover, each parameter can be estimated during the flow simulation process. The initial moisture content (θ) can be derived from measurement or parameter estimation and can vary depending on the hydrological conditions of a watershed such as antecedent rainfall.

※ Typical soil map applicable in Korea is detailed soil map (Kim, 1998). The detailed soil map is based on a detailed soil survey focused on Korea. It categorizes Korean soil into 'soil series' and further according to 'soil type' and 'soil phase'. It also includes the physical properties of the smallest unit, the 'soil phase'. The parameters of the Green–Ampt model are set according to the soil texture. The detailed soil map categorizes the 'soil type' in the same manner as soil texture. Moreover, the soil depths of Korean soil required for the calculation of the saturation excess flow are categorized with respect to the 'soil series' of the detailed soil map. The range of each soil depth category was defined based on the results of a soil survey project and is shown in table 2.4 (National Institute of Agricultural Science and Technology, 1992).

GRM uses unsaturated hydraulic conductivity to calculate percolation from soil layer A to B. From Fredlund et al. (1994), Averjanov (1950) suggested a power function(Eq. 2.1.1) to calculate unsaturated hydraulic conductivity (K). Fredlund et al. (1994) applied 3.5 to the n value, and Noh et al. (2015) used 12 in continuous modelling for long period. The GRM suggests 6.4 as the default n value for the simulation of rainfall-runoff event.

$$K_u = K_s S_r^n \tag{2.3.1}$$

Here, K_u is unsaturated K, K_s is saturated K, S_r is soil saturation ratio {$=(\theta - \theta_r)/(\theta_s - \theta_r)$}, θ_r is residual moisture content, θ_s is saturated moisture content, and n is the coefficient.

In the GRM, below equations as well as the power function can be used. In these equations, the default values of n is 0.2 and m is 0.1.

$$K_u = nK_s S_r \tag{2.3.2}$$

$$K_u = mK_s \tag{2.3.3}$$

Table 2.2 Green–Ampt model parameters according to the soil texture

Soil Texture	Porosity (η)	Effective porosity (θ_e)	Residual moisture content ($\theta_r=\eta-\theta_e$)	Wetting front soil suction head ($\lvert\psi_f\rvert$) (cm)	Hydraulic conduct. (K) [cm/hr]
Sand	0.437 (0.374-0.5)	0.417 (0.354-0.479)	0.02	4.95 (0.97-25.35)	11.78
Loamy sand	0.437 (0.363-0.505)	0.401 (0.329-0.472)	0.036	6.13 (1.35-27.93)	2.99
Sandy loam	0.453 (0.351-0.554)	0.412 (0.283-0.54)	0.041	11.01 (2.67-45.46)	1.09
Loam	0.463 (0.375-0.55)	0.434 (0.334-0.533)	0.029	8.89 (1.33-59.37)	0.34
Silt loam	0.501 (0.42-0.581)	0.486 (0.394-0.577)	0.015	16.68 (2.92-95.38)	0.65
Sandy clay loam	0.398 (0.332-0.463)	0.33 (0.235-0.424)	0.068	21.85 (4.42-108.1)	0.15
Clay loam	0.464 (0.409-0.518)	0.309 (0.279-0.5)	0.155	20.88 (4.79-91.9)	0.1
Silty clay loam	0.471 (0.418-0.523)	0.432 (0.347-0.516)	0.039	27.3 (5.67-131.49)	0.1
Sandy clay	0.43 (0.37-0.489)	0.321 (0.207-0.434)	0.109	23.9 (4.08-140.1)	0.06
Silty clay	0.479 (0.425-0.532)	0.423 (0.334-0.511)	0.056	29.22 (6.13-139.3)	0.05
Clay	0.475 (0.427-0.522)	0.385 (0.269-0.5)	0.09	31.63 (6.39-156.4)	0.03

Table 2.3 Classification of the soil depth for soil series

Soil depth classification	Soil depth (cm)	
	USDA*	Detailed soil map
Very shallow	0 - 10	0 - 20
Shallow	10 - 30	20 - 50
Moderately deep or Moderately shallow	35 - 50	50 - 100
Deep	50 - 60	100 - 150
Very Deep	> 60	> 150

* USDA: United States Department of Agriculture

2.4 Land cover parameters

The land cover of watersheds have influence on determining the roughness coefficient, impervious ratio, and interception to calculate overland flow. The GRM uses roughness coefficients suggested by Engmand (1986) and Vieux (2004), as shown in the table below, to simulate overland flow from rainfall.

"Impermeable areas of land surface" refers to areas without infiltration through soil, even with rainfall. Sagong (2003) classified land cover as permeable or impermeable using IKONOS satellite images with a spatial resolution of 1 m. This classification system was applied to Anyang City in Korea to calculate impervious ratios for different land usage. The GRM uses impervious ratios from the study results by Sagong (2003) that correspond to the 7 classifications of land cover attributes by the Ministry of Environment. Table below shows impervious ratios ranging from 0 – 1. When the ratio is "1," grids with corresponding land cover properties are determined as impermeable areas.

In order to calculate interception, the parameters of the monthly LAI values, the area ratio of canopy by each cell, and the maximum possible interception need to be assigned to each land cover attribute. Monthly LAI for each land cover attribute can be referred to the following table from previous studies (Kim, 2005; KICT, 2004; KICT, 2005). The area ratio of canopy by each cell and the maximum possible interception are user-estimated parameters.

Table 2.4 Monthly LAI for each land cover attribute

Month / Land cover	1	2	3	4	5	6	7	8	9	10	11	12
Urban	0.2	0.2	0.3	0.3	0.3	0.3	0.7	0.7	0.7	0.5	0.5	0.2
Agricultural Area	0.2	0.2	0.3	0.3	0.4	0.4	0.8	0.8	0.8	0.5	0.5	0.2
Forest	0.3	0.3	0.3	0.6	1.0	1.5	2.4	3.8	3.8	1.5	1.0	0.6
Grass	0.2	0.2	0.3	0.3	0.3	0.3	0.7	0.7	0.7	0.5	0.5	0.2
Wetland	0.2	0.2	0.3	0.3	0.6	0.6	1.4	1.4	1.4	0.9	0.9	0.3
Bare	0.2	0.2	0.3	0.3	0.3	0.3	0.7	0.7	0.7	0.5	0.5	0.2
Water	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 2.5 Roughness coefficients, canopy ratio, potential interception according to land cover properties

7 Classifications of land cover (Ministry of Environment, Korea)		Roughness coefficient	Canopy ratio	Maximum possible interception (mm)
Code*	Attributes			
100	Urban/dry area	0.015	0.2	0.3
200	Agricultural area	0.035	0.4	0.3
300	Forest	0.1	0.8	0.4
400	Grass	0.15	0.5	0.3
500	Wetland	0.07	0.4	0.3
600	Bare	0.02	0.2	0.3
700	Water	0.03	0.1	0.1

* May have different values depending on the data used

Table 2.6 Classification of land cover according to the permeability (Sagong, 2003)

Permeable area	Impermeable area
Vegetation	Paved road
Cultivated land	Concrete structure
Vinyl greenhouse	Apartment
Stream	Detached house
Bare land	Town house
Other grassland	Buildings other than houses
Railway	Factory

Table 2.7 Impervious ratios according to land cover map properties (Sagong, 2003)

Land cover map attributes	Land usage type	Impervious ratio	
		Range of values	Average
Urban/dry area	Commercial area	0.641-0.947	0.853
Agricultural area	Rice paddy	0.107-0.456	0.391
	Field	0.053-0.504	
	Vinyl greenhouse	0.422-0.842	
Forest	Greenbelt area, non-urban area, forest	0.001-0.05	0.025
Grass	Grassland	0.14-0.86	0.44
Wetland	-	-	0.1
Bare	Bare land	0.12-0.81	0.442
Water	-	-	0.1

2.5 Channel base width

The channel base width is a parameter to simulate the channel flow. The GRM can simulate asymmetrical trapezoidal compound cross sections. Here, the channel base width is applied to calculate cross-sectional flow areas of channels. Streams in watersheds have irregular compound cross sections and channel base widths; entering such varying channel shapes for every stream grid is very difficult. Therefore, objective parameters must be used when entering channel base widths for flood flow simulations to obtain consistent simulation results for all stream grids. In the GRM model, either the flow accumulation from grids or the design channel base width equation can be used.

2.5.1 Method using flow accumulation

The flow accumulation from watershed grids increases as it approaches downstream grids. The channel base width is typically larger in the downstream than upstream. A method using flow accumulation reflects these trends to set the channel base width proportional to flow accumulation. Here, the channel base width for an arbitrary control volume (CV_i) can be calculated using Eq. (2.5.1). The grid at the most downstream of a watershed shows maximum flow accumulation. The channel base width calculated with Eq. (2.5.1) takes a maximum value for the most downstream grid. This value decreases as it approaches grids upstream. When the channel base width is defined based on Eq. (2.5.1), the measured channel base width from the most downstream location can be applied and used to define the channel base width for upstream grids with the consistent method (Choi, 2010).

$$b_i = \frac{FA_i \times b_{\max}}{FA_{\max}} \tag{2.5.1}$$

Here, b_i is the channel base width for CV_i, $FA_{\max}$ is the flow accumulation for the most downstream control volume, FA_i is the flow accumulation for CV_i, and $b_{\max}$ is the channel base width for the most downstream control volume.

2.5.2 Method using the design channel width equation

The Korea Ministry of Construction and Transportation (2005) recommends an empirical equation that adopts topographical properties, such as slope and watershed area, to select the design channel base widths according to design floods when designing channels. Equation (2.5.2) can be used for southern regions (Honam and Youngnam regions, Korea) and Eq. (2.5.3) can be used for central regions (Gyeonggi, Gangwon, Chungnam, and Chungbuk provinces, Korea) of Korea.

$$B = 1.698\frac{A_w^{0.318}}{S_0^{0.5}} \tag{2.5.2}$$

$$B = 1.303\frac{A_w^{0.318}}{S_0^{0.5}} \tag{2.5.3}$$

Here, B is channel width, A_w is the watershed area (km^2), and S_0 is the channel bed slope.

The watershed area of each grid is used as the watershed area (A_w) to calculate the channel base width for each grid applying the design channel base width equation. The watershed area of each grid is calculated using the equation below, by multiplying the flow accumulation of the corresponding grid and grid area. The slope of each grid selected in the slope layer (input data for the model) can be used as the channel bed slope (S_0).

$$A_{wi} = (FA_i + 1) \times (\Delta y)^2 \tag{2.5.4}$$

Here, A_{wi} is the watershed area of an arbitrary control volume.

2.6 Initial saturation ratio

Initial saturation ratio is a parameter used to calculate infiltration and maximum possible infiltration and shows the soil saturation ratio at the time of runoff simulation. The initial saturation ratio is estimated within the range of "0 – 1" during the calibration process of the model and can approach 1 with increasing antecedent rainfall. If there is a soil saturation ratio raster data, it can be applied to flow simulation instead of estimating initial soil saturation ratio parameter.

2.7 Initial loss of precipitation

This parameter is used to apply initial loss of precipitation (ILP) to the runoff simulation. When the cumulative precipitation calculated from the simulation starting time is equal or smaller than the ILP parameter value, precipitation is not applied to the runoff simulation (the source terms of governing equations). The cumulative precipitation is calculated for each grid and ILP parameter is set for each domain area divided by the user.

2.8 Minimum slope

The kinematic wave model uses the land surface slope as friction slope to calculate the flow velocity. The flat area calibration process of a DEM entails a very small elevation modification to minimize changes in the original DEM. Therefore, the surface slope of areas that went through flat area processing can take very small values. When such miniscule surface slopes are applied to the kinematic wave model, the calculated flow velocity and discharge can be close to "0". Various studies were performed to determine minimum values that can be applied to the kinematic wave model as surface slopes (Ponce et al., 1978; Woolhiser and Liggett, 1967); the values mostly ranged from 0.0001–0.01. Moreover, Henderson (1966) and ASCE (1996) suggested that the kinematic wave model was appropriate for streams with a bed slope of 0.002 (10 ft/mi) or more when analyzing flood waves.

Minimum slopes of the channel and overland flow are parameters estimated by users to apply the slope layer including grids with very small slope values that resulted from flat area calibration of a DEM to the kinematic wave model. The minimum slope is part of the flow calculations for flood routing and thus affects discharge and flood wave arrival times. Consequently, it must be estimated by considering the watershed and stream properties and DEM properties applied during flow simulation.

2.9 Channel roughness coefficient

The roughness coefficient of a channel can vary depending on the channel shape, ground composition materials, vegetation, and degree of management (Chow, 1959). Chow (1959) combined existing studies on the roughness coefficient selection for channels to suggest roughness coefficients for various channel conditions. Among these roughness coefficients, those for natural streams are shown in Table below. Chaudhry (1993) suggested roughness coefficients for "clean, straight, full stage, no rifts, or deep pools," "bottom: gravel, cobbles, and few boulders," and "bottom: cobbles with large boulders" for natural streams. However, for actual flow simulations, it is appropriate to estimate roughness coefficients considering the channel conditions that can reflect the properties of a watershed within the range of roughness coefficient for each channel condition.

Table 2.8 Roughness coefficients for natural rivers (Chow, 1959)

Classification		Roughness Coefficient		
		Minimum	Typical	Maximum
Streams on plain	Clean, straight, full stage, no rifts or deep pools	0.025	0.030	0.033
	Same as above, but more stones and weeds	0.030	0.035	0.040
	Clean, winding, some pools and shoals	0.033	0.040	0.045
	Same as above, but some weeds and stones(Ⓐ)	0.035	0.045	0.050
	Same as above, lower stages, more ineffective slopes and sections	0.040	0.048	0.055
	Same as Ⓐ, but more stones	0.045	0.050	0.060
	Sluggish reaches, weedy, deep pools	0.050	0.070	0.080
	Very weedy reaches, deep pools, or floodways with heavy stand of timber and underbrush	0.075	0.100	0.150
Mountain streams, no vegetation in channel, banks usually steep, trees and brush along banks submerged at high stage	Bottom: gravels, cobbles, and few boulders	0.030	0.040	0.050
	Bottom: cobbles with large boulders	0.040	0.050	0.070

2.10 Dry stream order

When the antecedent rainfall is small in natural streams, their upstream tributaries can be dry streams and infiltration may occur first. To take into account early infiltration at dry streams during flow analysis, the GRM uses the dry stream order. When the entered stream network is dense, the dry stream order can be entered by considering antecedent rainfall and stream flow. The stream flow of dry streams is set to 0. The dry stream order is estimated within the range of “0 to maximum stream order.” To apply the dry stream order during flow analysis, stream order data must be entered into the stream network raster data. Hydrological GIS S/W, such as HyGIS, uses the stream order as grid cell value when creating a stream network raster data. The maximum stream order can also be identified based on the entered stream network raster data.

2.11 Parameter calibration coefficients

In the case of calibrating roughness coefficients and parameters of the Green–Ampt model set from land cover and soil properties with a certain ratio, a calibration coefficient corresponding to each parameter can be applied. The parameter calibration coefficient is a value applied to each parameter of the entire grid to be simulated. When 1 is entered, the corresponding parameter takes the value initially set in the flow simulations.

2.12 Parameter estimation

A physically based model assumes that parameters set according to spatial data from field surveys represent true values. Therefore, parameters which are difficult to set observed values for every cell and have relatively high uncertainties and high sensitivities such as initial saturation, channel minimum slope, channel roughness coefficient, permeability, and soil depth, are estimated by users.

The GRM simulates rainfall-runoff events. Consequently, the model calibration mainly reproduces observed hydrographs for peak discharge, peak time, and total discharge. Moreover, the overall trend of the calculated hydrograph can be considered to determine how well it reproduces the trend of the observed hydrograph. The typical trial-and-error method and any other optimization techniques can be used for model calibration.

Goodness-of-fit evaluation of a model can be performed using various objective functions such as relative errors of peak discharge, peak time, and the total discharge and root-mean-square error (RMSE), normalized RMSE (nRMSE), mean absolute percentage error (MAPE), correlation coefficient (CC), and Nash–Sutcliffe model efficiency (ME) of time series data.

3. Multi-site calibration

Most distributed models are set up with uniform grid sizes for single watersheds. Moreover, flow simulations are carried out using one parameter group that was set for each grid. Here, when one parameter group is used for flow simulations of a watershed that is comprised of many subwatersheds with varying runoff properties (Ajami et al., 2004), the physical and hydrological properties of the subwatersheds cannot be reflected properly in the model.

Distributed models have the advantage of easily obtaining flow simulation results from arbitrary sites within a watershed divided by grids (Beven and O'Connell, 1982). To improve the reliability of the flow analysis results for arbitrary cells which are not calibration sites, the model should be set up securing physical and hydrological similarities between the watershed of a cell to get simulation results and the calibrated watershed (Pilgrim, 1983; Dawson et al., 2006). The most intuitive method to secure physical and hydrological similarities between the calibrated watershed and the watershed outputting flow analysis results is to establish the model such that model calibration is possible at a point close to the point of the flow analysis output (Ajami et al., 2004; Merz, R. and Blöschl, 2004; Young, 2006). This requires the calibration of models for multiple sites (multi-site calibration) within a watershed.

The multi-site calibration method can be divided into a method for a single watershed system and a method that connects multiple subwatersheds. If verifiable stream gauges exist within a watershed, the watershed can be divided into subwatersheds according to the gauges. The single watershed multi-site calibration method calibrates a model collectively using the corresponding observed flow for subwatershed areas that were divided according to stream gauges within a watershed. All subwatersheds have a uniform grid size, which restricts applications of varying resolutions for each subwatershed. However, the advantage is the simple model calibration for multiple sites within one watershed.

The multi-site calibration method of connecting subwatersheds connects the flow analysis results from each watershed using the flow control module of the GRM. This method can improve the flow analysis results for an entire area consisting of multiple watersheds. Here, each subwatershed is an independent watershed system and thus different resolutions can be applied and data suitable for the properties of each subwatershed can be applied separately. Therefore, the properties of each subwatershed are reflected as much as possible. Moreover, flow analysis for each subwatershed is carried out by an independent process, which allows parallel computation through separated processes and consequently reduces the calculation time required for an entire watershed. In a typical hydrological event simulation, the multi-site calibration method of connecting subwatersheds takes the entire time series of flow analysis results and applies it to the flow control module of a different watershed. However, a real-time flow analysis system using real-time analysis modules of the GRM (GRM Real Time) requires real-time input of precipitation and flow control data and flow analysis is performed through dynamic connection of each subwatershed.

3.1 Single watershed multi-site calibration

The multi-site calibration method for single watersheds is used to set up a model with a single watershed system with uniform grid size. Moreover, it is used to collectively calibrate a model with respect to numerous stream gauges existing within a watershed. Parameters are set for each subwatershed using watershed raster data divided into subwatersheds and the model is calibrated according to each subwatershed. The basic principle of the multi-site calibration module is the application of the parameter set of an arbitrary watershed to the entire upstream area. If there is no subwatershed upstream with parameters set by user, a single parameter group is applied (Choi et al., 2012).

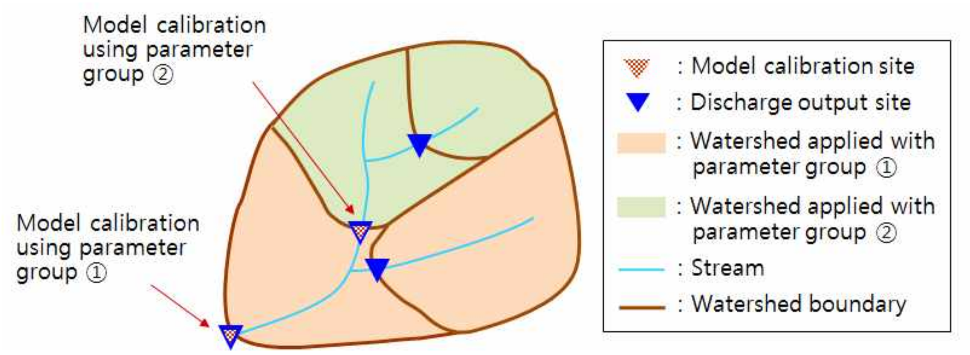


Fig. 3.1 Application method of the single watershed multi-site calibration

Table 3.1 Parameters of the GRM subject to multi-site calibration

Classification	Parameter subject to multi-site calibration	Abbreviation
Topographic	Minimum land surface slope	MinSlopeOF
	Minimum channel bed slope	MinSlopeChBed
	Minimum channel base width	MinChBaseWidth
	Channel roughness coefficient	ChRoughness
	Dry stream order	DryStreamOrder
Land Cover and Soil	Land surface roughness coefficient calibration coefficient	CalCoefLCRoughness
	Porosity calibration coefficient	CalCoefPorosity
	Wetting front soil suction head calibration coefficient	CalCoefWFSuctionHead
	Hydraulic conductivity calibration Coefficient	CalCoefHydraulicK
	Soil depth calibration coefficient	CalCoefSoilDepth
Hydrological conditions	Initial saturation ratio	IniSaturation
	Initial flow	IniFlow

The GRM uses project files in xml format to save the environment and parameters of a modelling project. Multi-site calibration data are saved as a subwatershed parameter table ("SubWatershedSettings") in an xml project file. A subwatershed parameter table takes the subwatershed number as the key code, has parameters entered according to subwatersheds (4.5 Project file).

3.2 Subwatersheds connecting multi-site calibration

To obtain reliable flow analysis using a physical model for watersheds with various hydrological properties and watershed areas, models suitable for each watershed property must be established. Runoff analysis using a distributed model usually builds a model for one watershed with uniform grid size and uses the one parameter group. However, when single-sized grids are used to build a model and a single parameter group is used to calibrate a model for multiple subwatersheds with various hydrological properties, the physical and hydrological properties of subwatersheds are not properly reflected. Therefore, different watershed systems must be established according to different watershed properties and a modeling technique that can integrate each watershed is required.

The subwatersheds connecting multi-site calibration method builds models for each subwatershed using the flow control module of the GRM. Moreover, the flow analysis results for each subwatershed can be connected to perform flow analysis of the entire watershed. Here, flow analysis results from the upstream of a watershed are transferred to a subwatershed downstream using the inlet function of the flow control module (Korea Institute of Civil Engineering and Building Technology, 2015). To execute flow analysis dynamically for each watershed using the subwatersheds connecting multi-site calibration method, the real-time analysis module of the GRM (GRM RT) is used. The GRM RT not only enters precipitation data but also input data of the flow control module, such as dam discharge, in real-time for flow analysis. Therefore, the downstream of a watershed receives simulation results from the upstream in real-time and dynamic simulation can be obtained for the entire watershed. The description of GRM RT is included in the GRM RT section in this user manual.

Models with different grid sizes can be created using the subwatersheds connecting multi-site calibration and reflecting properties of different subwatersheds. Therefore, the model calibration for each subwatershed can be optimized and the flow analysis results for arbitrary sites within watersheds can be improved compared with the flow analysis results from calibrating only the site at the lowest end of a stream in a single watershed system. However, it is inconvenient because the input data for each watershed must be established separately and model calibration must be performed with individual processes according to the watersheds. Such model calibration is very complex and requires great efforts to maintain a dependable operation of the modeling system and stable analyses of flow preservation between subwatersheds and of flood routing problems.

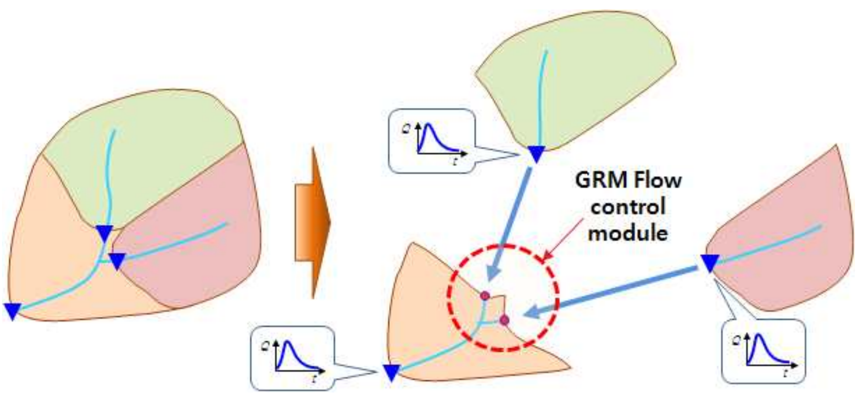


Fig. 3.2 Conceptual diagram of the subwatersheds connecting multi-site calibration

4. Input data

The GRM is executed in project units. Project file of the GRM have .gmp extension and is saved in xml format. The input data required to run the GRM, simulation environment, and parameters are saved in GRM project file. The GRM uses topographical and spatial data established based on a DEM, soil and land cover maps, and rainfall raster file as input data. The watershed, slope, flow direction, flow accumulation, stream network files generated in DEM analyses can be created using the GIS tool, which can also produce hydrological spatial data. The general S/W that includes hydrological spatial data-creating tools based on DEM analyses, such as HyGIS, TauDEM, QGIS Drainage plug-in, and ArcGIS, can be used for the GIS tool, which creates input data. The GRM uses a ASCII raster format. Thus, data of various formats created using the GIS tools have to be converted to ASCII format and applied to the model.

The table below shows the required input data for each hydrologic component simulated in the GRM. Since the GRM can select individual hydrologic components to be simulated, the input data can be configured differently depending on the selection of flood event simulation, continuous simulation, and hydrologic components.

Table 4.1 Input data for the GRM

Original data		Input data	Continuous simulation							Data Format
			Flood event simulation							
			INF	SSF	BF	FC	INTCP	ET	SM	
Geographic data	DEM	Watershed	●	●	●	●	●	●	●	ASCII raster
		Flow direction	●	●	●	●	●	●	●	
		Flow accumulation	●	●	●	●	●	●	●	
		Slope	●	●	●	●	●	●	●	
		Stream	○	○	○	○	○	○	○	
	Channel width		△	△	△	△	△	△	△	
	Land cover map	Land cover	○	○	○	○	●	●	○	
	Soil map	Soil texture	○	○	○	○	○	○	○	
		Soil depth	○	○	○	○	○	○	○	
Weather data		Precipitation	●	●	●	●	●	●	●	ASCII raster Text
		Max. temperature	-	-	-	-	-	●	●	
		Min. temperature	-	-	-	-	-	●	-	
		Daytime length	-	-	-	-	-	●	-	
		Daytime hours ratio	-	-	-	-	-	△	-	Text
		Solar radiation	-	-	-	-	-	●	-	ASCII raster Text
		Snow pack temperature	-	-	-	-	-	-	●	
Hydrological data		Observed flow(stream, dam)	-	-	-	●	-	-	-	Text
		Initial soil saturation ratio	△	△	△	△	△	△	△	ASCII raster
		Initial stream flow	△	△	△	△	△	△	△	
Parameter file		LAI	-	-	-	-	●	-	-	Text
		Blaney-Criddle crop coeff.	-	-	-	-	-	△	-	Text

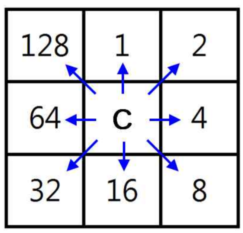
- ● : Required, ○ : Optional (recommended), △ : Optional
- INF : Infiltration, SSF : Subsurface flow, BF : Base flow, INTCP : Interception, ET : Evapotranspiration, SM : Snow melt, FC : Flow control

4.1 Spatial data

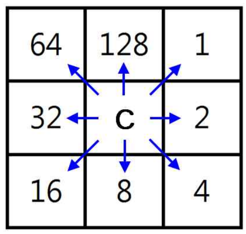
The GRM uses raster data in ASCII format as input data; the raster data required to run the GRM is shown in the table below. The flow direction data used by the GRM is unidirectional, created with the D8 method. The flow direction is determined based on the value in the flow direction raster data (flow direction index). The selections of the 1 o'clock position as 1 (northeast, NE), 12 o'clock position as 1 (north, N), 3 o'clock position as 1 (east, E), or TauDEM flow direction index are applicable in the GRM. When the flow direction data is created from DEM data, the index corresponding the flow direction can be different according to the GIS S/W and thus caution must be needed when applying the flow direction data.

Table 4.2 Spatial input data for the GRM

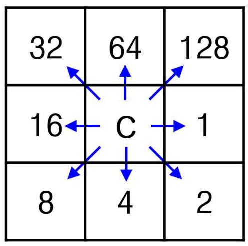
Data	Definition	Data type
Simulation domain (or watershed area)	Raster file with distinguished watershed area or simulation domain	Integer
Slope	Steepest slope data assigned to each grid	Double
Flow direction	Unidirectional flow direction according to the D8 method	Integer
Flow accumulation	Flow accumulation	Integer
Stream	Stream network	Integer
Channel width	Channel base width data for the same location as the stream network grid	Real
Soil texture	Soil texture	Integer
Soil depth	Soil depth	Integer
Land cover	Land cover	Integer



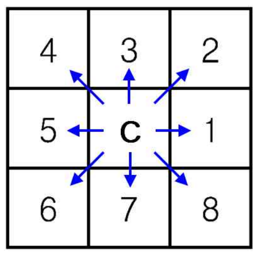
(a) Index starting at north
(StartsFromN)



(b) Index starting at northeast
(StartsFromNE)



(b) Index starting at east
StartsFromE

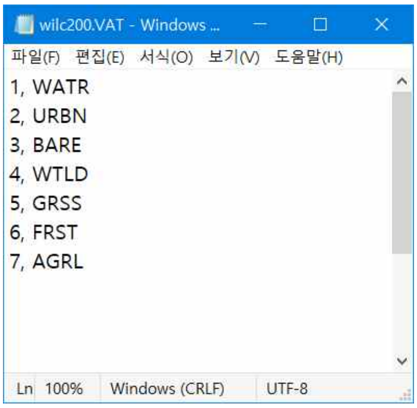


(d) Index by TauDEM
(StartsFromE_TauDEM)

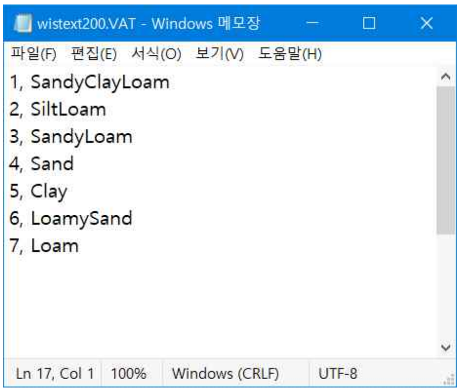
Fig 4.1 Flow direction index

The values of raster files for land cover, soil texture, and soil depth are entered in numbers. Therefore, a response between the numbers in each raster file and the properties to be used for actual flow analysis is required. The QGIS-GRM(GRM model GUI) uses a Value Attribute Table (VAT) text file for this response. The VAT files can be manually created by users with a text editor or automatically created using GIS software.

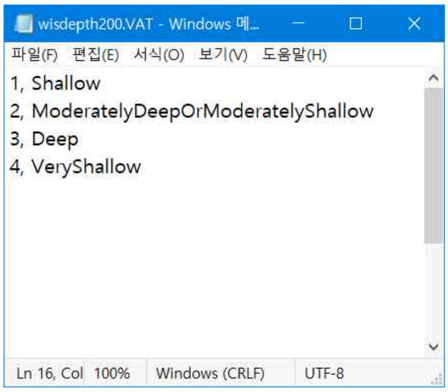
The model parameters related to land cover and soil are saved in the GRM static database (i.e., C:₩GRM₩GRMStaticDB.xml), which can be used to set the parameter default values for each property.



(a) Land Cover VAT File



(b) Soil Texture VAT File



(c) Soil Depth VAT File

Fig. 4.2 Examples of VAT files

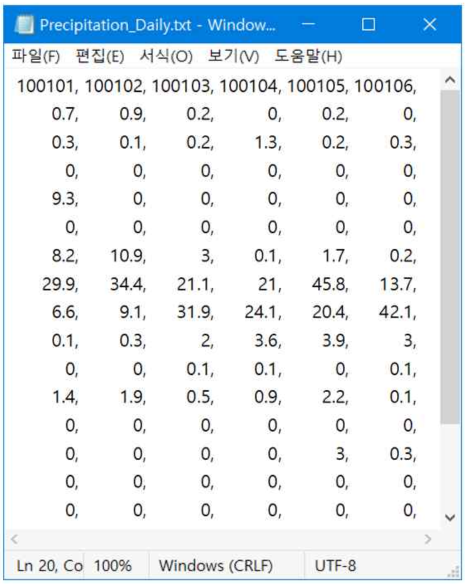
4.2 Meteorological data

The mean areal values or spatially distributed raster files of meteorological data can be applied for the GRM. When the grid-based distributed ASCII raster data file is used, the file path and name of the list of meteorological data files (ACSII files) is saved in the gmp file. The distributed rainfall raster file can be either created from spatial interpolation of point rainfall observed at a rainfall gauge or spatially distributed rainfall data such as radar or numerical prediction data.

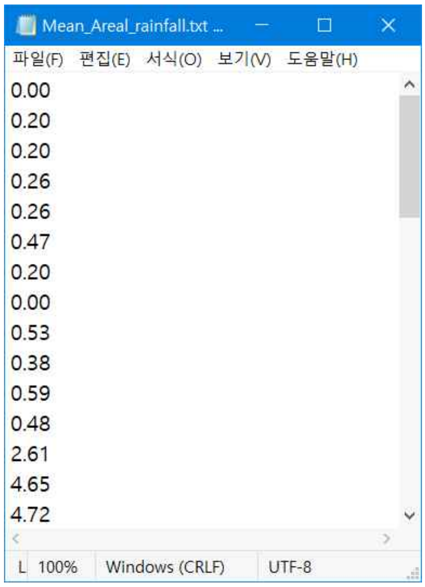
If the mean areal meteorological data is used, the file path and name of the file contains the data is saved in the gmp file. When using one average value time series data for the entire domain, the data is saved as one column to the text file. When dividing the simulated domain into several areas and applying different average values of meteorological data for each area, the raster values that divide the domain area are entered in the first row of the text file, and the meteorological data corresponding to those area are entered from the second row. The data for each area are separated by commas. The ratio of daily daytime hours to total annual daytime hours as monthly value is applied as average value, and the 12 values (from January to December) are sequentially entered into a text file.

Table 4.3 Meteorological input data

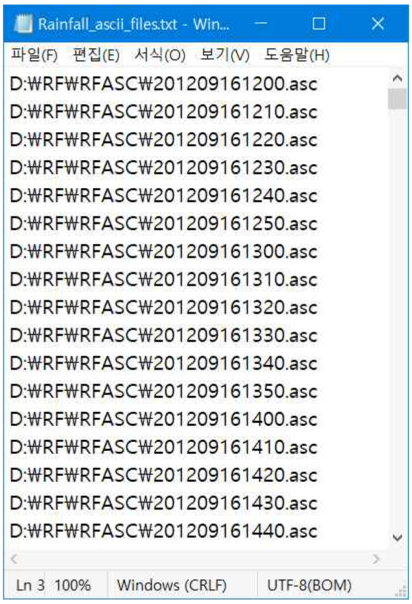
Name	How to write	Data type
Precipitation	Distributed precipitation (mm) ASCII raster file or areal mean precipitation (mm) text file	Real
Maximum temperature	Distributed daily max. temperature (℃) ASCII raster file or areal mean daily max. temperature (℃) text file	Real
Minimum temperature	Distributed daily min. temperature (℃) ASCII raster file or areal mean daily min. temperature (℃) text file	Real
Daytime hours	Distributed daytime hours (hr) ASCII raster file or areal mean daytime hours (hr) text file	Real
Daytime hours ratio	The ratio of daily daytime hours per month to total annual daytime hours. Areal average value.	Real
Solar radiation	Distributed daily solar radiation $(MJ/m^2/day)$ ASCII raster file or areal mean daily solar radiation $(MJ/m^2/day)$ text file	Real
Snow pack temperature	Distributed daily snow pack temperature (℃) ASCII raster file or areal mean snow pack temperature (℃) text file	Real



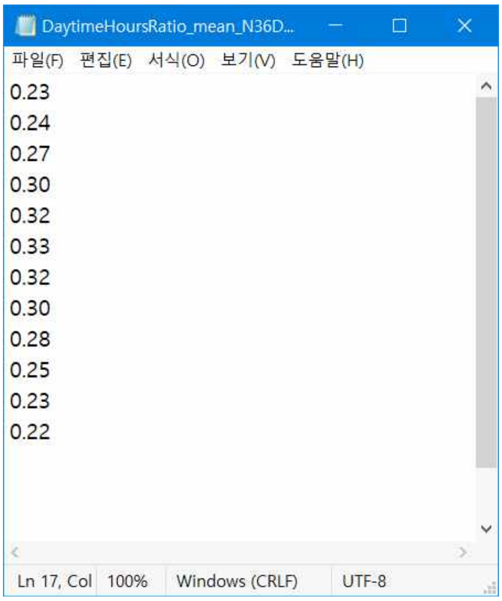
(a) Areal mean meteorological data input file separated by area



(b) Areal mean meteorological data input file using one time series data



(c) Meteorological data input file using ASCII raster files



(d) Daytime hours ratio input file

Fig. 4.3 Examples of meteorological data input files

4.3 Hydrological data

The hydrological data used in the GRM are the observed discharge from stream or dam, the initial soil saturation data for all the grids of the domain, and the initial stream flow for the all the grids of the domain. At the simulation starting time, the observed discharge of the calibration stream point is used as the initial stream flow rate value. In order too apply the dam discharge to the runoff simulation, the observed dam discharge data should be used. If there are ASCII raster files of soil saturation and river flow with values set for the entire grid, the values of each file can be applied as initial conditions in the entire grid. If soil saturation raster file is used, initial soil saturation ratio parameter is not estimated during model calibration.

Table 4.4 Hydrological input data

Name	Definition	Data type
Discharge	- One flow rate value (CMS) measured at a specific point on the stream - Reservoir discharge time series data (CMS)	Real
Soil saturation raster file	Soil saturation data in all grids saved as an ASCII raster file	Real
Stream flow rater file	Flow rate data in all stream grids saved as an ASCII raster file	Real

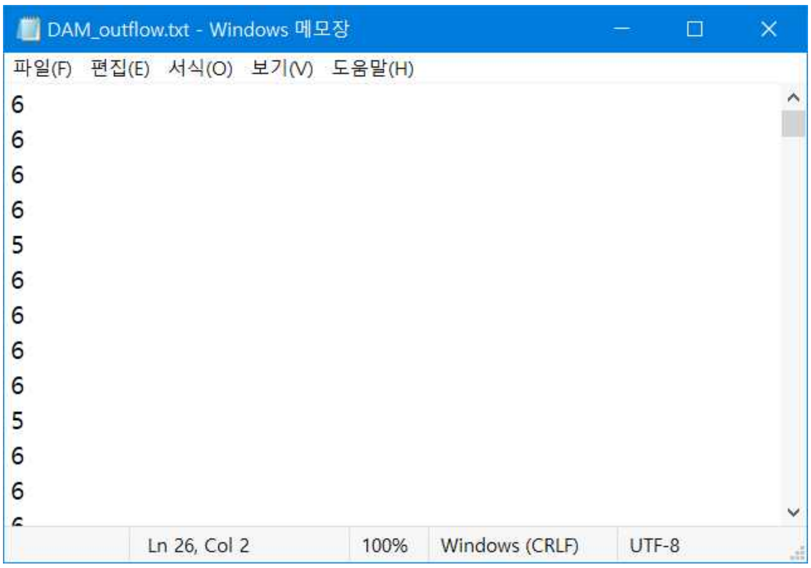
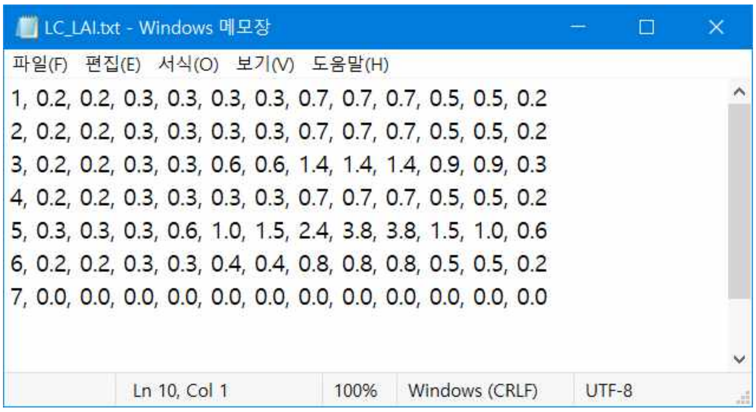


Fig. 4.4 Example of discharge input file

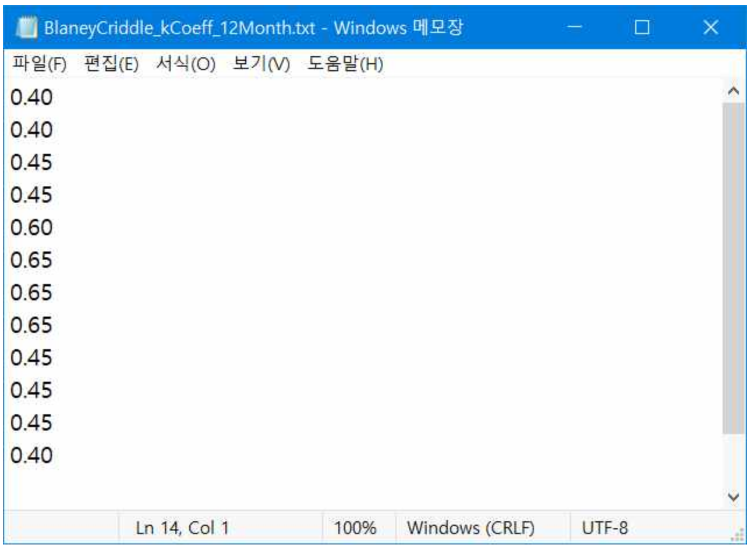
4.4 Model parameter file

Among the parameters used in the GRM model, the parameters entered into the model as a file are the LAI value used for interception simulation and the crop factor used in the Blaney-Criddle method for the calculation of potential evapotranspiration. For LAI values, monthly LAI values for each land cover attribute are saved in a text file. Each value is separated by a comma, and as the first item, the value of the raster file that classifies the land cover attribute is entered, and the LAI values from January to December corresponding to the land cover attribute are entered in order. For the Blaney-Criddle crop coefficients, the values corresponding to January to December are sequentially saved into a text file.




```
1, 0.2, 0.2, 0.3, 0.3, 0.3, 0.3, 0.7, 0.7, 0.7, 0.5, 0.5, 0.2
2, 0.2, 0.2, 0.3, 0.3, 0.3, 0.3, 0.7, 0.7, 0.7, 0.5, 0.5, 0.2
3, 0.2, 0.2, 0.3, 0.3, 0.6, 0.6, 1.4, 1.4, 1.4, 0.9, 0.9, 0.3
4, 0.2, 0.2, 0.3, 0.3, 0.3, 0.3, 0.7, 0.7, 0.7, 0.5, 0.5, 0.2
5, 0.3, 0.3, 0.3, 0.6, 1.0, 1.5, 2.4, 3.8, 3.8, 1.5, 1.0, 0.6
6, 0.2, 0.2, 0.3, 0.3, 0.4, 0.4, 0.8, 0.8, 0.8, 0.5, 0.5, 0.2
7, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0
```

Fig. 4.5 Example of the LAI input file




```
0.40
0.40
0.45
0.45
0.60
0.65
0.65
0.65
0.45
0.45
0.45
0.40
```

Fig. 4.6 An Example of Blaney-Criddle crop coefficient input file

4.5 GRM project file

The GRM runs using project file (.gmp). Running the GRM on a console window requires setting the gmp file as the switch.

(i.e., D:₩grm.exe "projectFilePathAndName.gmp")

The gmp file is saved in xml format. The tables, contents of tables, field names and description for each table, and settings for each field included in the gmp files are shown in the following table. Users can create gmp file with a text editor; however, it is difficult to intuitively determine certain parameters (grid location, etc.). Thus, it is convenient to automatically create gmp files using GUI S/W (QGIS plug-in QGIS-GRM, etc.) of the GRM.

If gmp file includes Korean, it must be saved as UTF-8 format. If gmp file dose not include Korean, it can be saved as ANSI or UTF-8 format.

Table 4.5 Descriptions of the tables in the GRM project xml file

Table name	Description	Required
ProjectSettings	Environment settings, input files, and global parameters to run the model	Required
SubWatershedSettings	Parameters set for each subwatershed	Required
WatchPoints	Grid information subjected to output selected by user	Required
FlowControlGrid	Grids subjected to flow control selected by user, flow control type, data properties, reservoir specifications, and ROM data	Required
ChannelSettings	Channel shape parameters for each watershed	Required
GreenAmptParameter	Soil texture data properties and Green–Ampt parameters values applied to flow simulations	Required
SoilDepth	Soil depth data properties and soil depth values applied to flow simulations	Required
LandCover	Land cover data properties and roughness coefficient and impervious ratio applied to flow simulations	Required

Table 4.6 ProjectSettings table

Field name	Description	Data type	Required
GRMSimulationType	Modeling type (Normal or RealTme)	String	Required
DomainFile	Simulation domain(or watershed) ASCII file path and name	String	Required
SlopeFile	Slope ASCII file path and name	String	Required
FlowDirectionFile	Flow direction ASCII file path and name	String	Required
FlowAccumFile	Flow accumulation ASCII file path and name	String	Required
StreamFile	Stream ASCII file path and name	String	Required
ChannelWidthFile	Channel base width ASCII file path and name	String	Optional
InitialChannelFlowFile	Initial stream flow ASCII file path and name. Values are set only for stream cell	String	Optional
InitialSoilSaturationRatioFile	Initial soil saturation ratio ASCII file path and name	String	Optional
LandCoverDataType	Land cover data type (File or Constant)	String	Required
LandCoverFile	Land cover ASCII file path and name, only used when 'File' is selected for LandCoverDataType	String	Optional
LandCoverVATFile	Land cover ASCII file VAT file path and name, only used if 'File' is selected for LandCoverDataType (If Korean is included, it must be saved as UTF-8 format)	String	Optional
ConstantRoughnessCoeff	Land cover roughness coefficient, only used if 'Constant' is selected for LandCoverDataType	Real	Optional
ConstantImperviousRatio	Impervious ratio, only used if 'Constant' is selected for LandCoverDataType	Real	Optional
LAIFile	Path and name of the file where LAI values for each land cover attribute and month are stored, only used for interception simulation	String	Optional
BlaneyCriddleCoefDataFile	Path and name of the Blaney-Criddle crop coefficient file, only used for evapotranspiration simulation	String	Optional
SoilTextureDataType	Soil texture data type (File or Constant)	String	Required
SoilTextureFile	Soil texture ASCII file path and name, only used if 'File' is selected for SoilTextureDataType	String	Optional
SoilTextureVATFile	Soil texture ASCII file VAT file path and name, only used if 'File' is selected for SoilTextureDataType (If Korean is included, it must be saved as UTF-8 format)	String	Optional
ConstantSoilPorosity	Soil porosity, only used if 'Constant' is selected for SoilTextureDataType	Real	Optional
ConstantSoilEffPorosity	Effective soil porosity, only used if 'Constant' is selected for SoilTextureDataType	Real	Optional

<ProjectSettings table (continued)>

Field name	Description	Data type	Required
ConstantSoilWetting-FrontSuctionHead	Wetting front soil suction head, only used if 'Constant' is selected for SoilTextureDataType	Real	Optional
ConstantSoilHydraulic-Conductivity	Hydraulic conductivity. only used if 'Constant' is selected for SoilTextureDataType	Real	Optional
SoilDepthDataType	Soil depth data type (File or Constant)	String	Required
SoilDepthFile	Soil depth ASCII file path and name, only used when 'File' is selected for SoilDepthDataType	String	Optional
SoilDepthVATFile	Soil depth ASCII file VAT file path and name, only used when 'File' is selected for SoilDepthDataType (If Korean is included, it must be saved as UTF-8 format)	String	Optional
ConstantSoilDepth	Soil depth, only used when 'Constant' is selected for SoilDepthDataType (cm)	Real	Optional
PrecipitationDataFile	Path and name of the precipitation data file	String	Required
PrecipitationInterval_min	Precipitation data interval (min)	Integer	Required
TemperatureMaxDataFile	Path and name of the daily max temperature data file	String	Optional
TemperatureMax-Interval_min	Daily max temperature data interval(min, 1440)	Integer	Optional
TemperatureMinDataFile	Path and name of the daily min temperature data file	String	Optional
TemperatureMin-Interval_min	Daily min temperature data interval(min, 1440)	Integer	Optional
DaytimeLengthDataFile	Path and name of the daytime length data file	String	Optional
DaytimeLength-Interval_min	Daytime length data interval(min, 1440)	Integer	Optional
DaytimeHoursRatio-DataFile	Path and name of the file where the ratio of daily daytime hours per month to total annual daytime hours are stored.	String	Optional
SolarRadiationDataFile	Path and name of the daily solar radiation data file	String	Optional
SolarRadiation-Interval_min	Daily solar radiation data interval(min, 1440)	Integer	Optional
SnowPackTemperature-DataFile	Path and name of the daily snow pack temperature data file	String	Optional
SnowPackTemperature-Interval_min	Daily snow pack temperature data interval(min, 1440)	Integer	Optional

<ProjectSettings table (continued)>

Field name	Description	Data type	Required
FlowDirectionType	Flow direction data type (StartsFromN, StartsFromNE, StartsFromE, or StartsFromE_TauDEM)	String	Required
MaxDegreeOfParallelism	Limit of Parallelism using CPU, maximum value is applied when '-1' or no value are set	Integer	Optional
SimulationStartingTime	Simulation start time. Set date time format string when time format is selected (i.e., 2012-09-16 12:00 LST). If date time format is not selected, set to '0'.	String	Required
SimulationDuration	Simulation duration (h)	Integer	Required
ComputationalTimeStep_min	Computational time step (min)	Integer	Required
IsFixedTimeStep	Fixed calculation time step used (true or false), 'true' is applied when nothing is selected	String	Optional
OutputTimeStep_min	Output time step (min)	Integer	Required
SimulateInfiltration	Infiltration simulation (true or false)	String	Required
SimulateSubsurfaceFlow	Subsurface flow simulation (true or false)	String	Required
SimulateBaseFlow	Base flow simulation (true or false)	String	Required
SimulateInterception	Interception simulation (true or false)	String	Required
SimulateEvapo-transpiration	Evapotranspiration simulation (true or false)	String	Required
SimulateSnowMelt	Snow melt simulation (true or false)	String	Required
SimulateFlowControl	Flow control simulation (true or false)	String	Required
MakeIMGFile	Raster image file creation (true or false)	String	Required
MakeASCFile	ASCII raster file creattion (true or false)	String	Required
MakeSoilSaturationDistFile	Write soil saturation distribution file (true or false) (either MakeIMGFile or MakeASCFile must be true for it to be applied)	String	Required
MakePRCPDistFile	Write precipitation distribution file (true or false) (either MakeIMGFile or MakeASCFile must be true for it to be applied)	String	Required
MakePRCPaccDistFile	Write precipitation accumulation distribution file (true or false) (either MakeIMGFile or MakeASCFile must be true for it to be applied)	String	Required
MakeFlowDistFile	Write flow distribution file (true or false) (either MakeIMGFile or MakeASCFile must be true for it to be applied)	String	Required

<ProjectSettings Table (continued)>

Field name	Description	Data type	Required
PrintOption	Print out option (All, DischargeFile, DischargeAndFcFile, AverageFile DischargeFileQ, AverageFileQ, AllQ) - All : Print all simulation results - DischargeFile : Write just "*_Discharge.out" file - DischargeAndFcFile : Write just "*_Discharge.out" file and flow control simulation results - AverageFile : Write just "*_Ave.out" file - DischargeFileQ : Write just "*_Discharge.out" file with discharge value only - AverageFileQ : Write just "*_Ave.out" file with discharge value only - AllQ : Write all output files with discharge value only	String	Required
PrintAveValue	Print the average values during the print interval (Writing "*_Ave.out" file included) (true or false)	String	Required
AveValueTimeInterval-_min	The time step of the calculation and writing average values (min). If this value is not set, the same value of OutputTimeStep is applied.	Integer	Optional
ValueSeparator	Separator of output values in the output file (Tab, Space, or Comma)	String	Required
WriteLog	Write detail log file (true or false)	String	Required
AboutThisProject	Project description entered by user	String	Optional
AboutWatershed	Watershed description entered by user	String	Optional
AboutLandCoverMap	Land cover map description entered by user	String	Optional
AboutSoilMap	Soil texture map description entered by user	String	Optional
AboutSoilDepthMap	Soil depth map description entered by user	String	Optional
AboutPRCP	Precipitation data description entered by user	String	Optional

Table 4.7 SubWatershedSettings table

Field name	Description	Data type	Required
ID	Sub-domain (e.g. sub-watershed) number. Integer greater than 0 is entered as a identifier.	Integer	Required
IniSaturation	Initial saturation parameter, if soil saturation ratio ASCII file is applied, this parameter is not used. Default values are 0.3 if dry season, or 0.8 if wet season.	Real	Required
IniLossPRCP_mm	Initial loss of precipitation (mm). Default value is 0.	Real	Required
MinSlopeOF	Minimum bed slope condition parameter for overland flow. Default value is 0.0001.	Real	Required
MinSlopeChBed	Minimum bed slope condition parameter for channel flow. Default value is 0.0001.	Real	Required
MinChBaseWidth	Minimum channel base width condition (m). Default value is 1/10 of the grid size.	Real	Required
ChRoughness	Channel roughness coefficient parameter. Default value is 0.045	Real	Required
DryStreamOrder	Dry stream order condition parameter. In case of entering 0, the dry stream order is not applied. Default value is 0.	Integer	Required
IniFlow	Initial stream flow parameter (m^3/s). The flow observed at the simulation start time at the most downstream cell of the watershed is entered. If initial stream flow ASCII file is applied, this parameter is not used.	Real	Required
UnsaturatedKType	Unsaturated hydraulic conductivity calculation method (Constant, Linear, or Exponential). If not set, 'Linear' is applied. If 'Constant' is set, the fixed hydraulic conductivity value of Green-Ampt parameter multiplied by the 'CoefUnsaturatedK' coefficient is applied. Default value is 'Linear'.	Real	Required
CoefUnsaturatedK	The coefficient for calculating unsaturated hydraulic conductivity. For UnsaturatedKType is 'Linear', 'Exponential', 'Constant', 0.2, 6.4, 0.1 are applied as default values for each method.	Real	Required
CalCoefLCRough-ness	Roughness coefficient calibration parameter selected according to land cover. Default value is 1.	Real	Required
CalCoefPorosity	Soil porosity calibration parameter. Default value is 1.	Real	Required
CalCoefWFSuction-Head	Wetting front soil suction head calibration parameter. Default value is 1.	Real	Required
CalCoefHydraulicK	Soil hydraulic conductivity calibration parameter. Default value is 1.	Real	Required
CalCoefSoilDepth	Soil depth calibration parameter. Default value is 1.	Real	Required

Table 4.7 SubWatershedSettings table (continued)

Field name	Description	Data type	Required
InterceptionMethod	Interception simulation method (LAIRatio)	String	Optional
PETMethod	Potential evapotranspiration method (BlaneyCriddle, Hamon, PriestleyTaylor, or Hargreaves)	String	Optional
ETCoef	Coefficient to calculate actual evapotranspiration. Default value is 0.6.	Real	Optional
SnowmeltMethod	Snow melt method (Anderson)	String	Optional
TempSnowRain	The threshold air temperature at which precipitation divided into snow and rainfall (℃). Default value is 0	Real	Optional
SnowmeltingTemp	The air temperature at which snow melt begins (℃). Default value is 3 ℃.	Real	Optional
SnowCovRatio	Snow pack coverage ratio by each cell. Default value is 0.7.	Real	Optional
SnowmeltCoef	Snow melt coefficient. Default value is 1.	Real	Optional
UserSet	If parameters of the current watershed were selected by the user or not (true or false)	String	Required

Table 4.8 ChannelSettings table

Field name	Description	Data type	Required
WSID	Most downstream sub-watershed ID(raster value). Integer value greater than 0	Integer	Required
CrossSectionType	Channel cross section type (CSSingle or CSCompound)	String	Required
SingleCSChannel-WidthType	Channel base width calculation method (CWGeneration or CWEquation)	String	Optional
ChannelWidthEQc	Coefficient of the channel base width equation, only used if 'CWEquation' is selected for SingleCSChannelWidthType	Real	Optional
ChannelWidthEQd	Coefficient of the channel base width equation, only used if 'CWEquation' is selected for SingleCSChannelWidthType	Real	Optional
ChannelWidthEQe	Coefficient of the channel base width equation, only used if 'CWEquation' is selected for SingleCSChannelWidthType	Real	Optional
ChannelWidthMost-DownStream	Channel base width at the lowest downstream end of stream (m). Only used if 'CSCompound' is selected for CrossSectionType	Real	Optional
LowerRegionHeight	Low-water area height of compound cross section. Only used if 'CSCompound' is selected for CrossSectionType	Real	Optional
LowerRegionBaseWidth	Channel base width of low-water area of compound cross section. Only used if 'CSCompound' is selected for CrossSectionType	Real	Optional
UpperRegionBaseWidth	Channel base width of high-water area of compound cross section. Only used if 'CSCompound' is selected for CrossSectionType	Real	Optional
CompoundCSChannel-WidthLimit	Range of the channel base width limit applicable to channel compound cross section (Single cross section is applied for stream sections with a channel base width smaller than this limit). Only used if 'CSCompound' is selected for CrossSectionType	Real	Optional
BankSideSlopeRight	Right bank slope	Real	Required
BankSideSlopeLeft	Left bank slope	Real	Required

Table 4.9 WatchPoints table

Field name	Description	Data type	Required
Name	Watch point name	String	Required
ColX	Watch point grid column number, numbering starts from top left corner (0,0). Max. value is 'column count – 1'	Integer	Required
RowY	Watch point grid row number, numbering starts from top left corner (0,0). Max. value is 'row count – 1'	Integer	Required

Table 4.10 FlowControlGrid table

Field name	Description	Data type	Required
Name	Name of FlowControlGrid	String	Required
ColX	Column number for FlowControlGrid, entered with the same method as for ColX in the WatchPoints table	Integer	Required
RowY	Row number for FlowControlGrid, entered with the same method as Row Y in the WatchPoints table	Integer	Required
ControlType	Flow control type (1 chosen from ReservoirOutflow, Inlet, SinkFlow, SourceFlow, ReservoirOperation, and DetensionPond)	String	Required
DT_min	Flow data time interval (min)	Integer	Required
FlowDataFile	Flow data file path and name. Not used when 'ControlType' is ReservoirOperation.	String	Optional
IniStorage	Reservoir initial storage (m^3), only used when 'ControlType' is 'ReservoirOutflow' using the /a option, 'ReservoirOperation', or 'DetensionPond'	Real	Optional
MaxStorage	Reservoir maximum storage (m^3), only used when 'ControlType' is 'ReservoirOutflow' using the /a option or 'ReservoirOperation'	Real	Optional
NormalHighStorage	Reservoir storage for the normal high water level (m^3), only used when 'ControlType' is 'ReservoirOutflow' using the /a option, 'ReservoirOperation', or 'DetensionPond'	Real	Optional
RestrictedStorage	Reservoir storage for the restricted water level (e.g. flood restricted water level) (m^3). If there is no observed "IniStorage", it can be applied to "IniStorage" value. Not used within the model.	Real	Optional
RestrictedPeriod_Start	The starting time of applying restricted water level storage. If the simulation uses 'DateTime' format, set this value as 'mmMddD'(e.g. 06M21D) format, if not use 'DateTime' format, set this value as the time (e.g. 120) after starting simulation(00) by hours unit.	String	Optional
RestrictedPeriod_End	The ending time of applying restricted water level storage. The period of restricted water level storage includes this time. If the simulation uses 'DateTime' format, set this value as 'mmMddD'(e.g. 06M21D) format, if not use 'DateTime' format, set this value as the time (e.g. 120) after starting simulation(00) by hours unit	String	Optional
ROType	Reservoir operation type, only used when 'ControlType' is 'ReservoirOperation' (AutoROM, RigidROM, or ConstantQ) ** Storage and discharge relation equation can be applied by source code writing	String	Optional
AutoROMmax-Outflow_CMS	The limit of reservoir outflow (CMS) when AutoROM is applied. If '0' there is no limit of reservoir outflow. Only used when 'ROType' is AutoROM	Real	Optional
ROConstRatio	Constant discharge ratio, only used when 'ROType' is RigidROM	Real	Optional
ROConstDischarge	Constant discharge value (CMS), only used when 'ROType' is ConstantQ or RigidROM	Real	Optional

<FlowControlGrid table *(continued)* >

Field name	Description	Data type	Required
ROConstDischarge-Duration_hr	Constant discharge duration (h) from simulation starting, only used when 'ROConstQ' is selected.	Integer	Optional
DP_QT_StoD_CMS	Threshold stream flow rate to start flowing between stream and detension pond (DP) (m^3/s). Only used when DP is set at the grid of stream attribute	Real	Optional
DP_Qi_max_CMS	The maximum inflow limit of DP (m^3/s). Only used when DP is set at the grid of stream attribute	Real	Optional
DP_Qo_max_CMS	The maximum outflow limit of DP (m^3/s). Only used when DP is set at the grid of stream attribute	Real	Optional
DP_Wdi_m	DP inlet base width (assuming an open channel with rectangular cross section) (m). Only used when DP is set at the grid of stream attribute	Real	Optional
DP_Ws_m	Stream base width at the location of the DP inlet (m). Only used when DP is set at the grid of stream attribute	Real	Optional
DP_Cr_StoD	DP inflow coefficient. Only used when DP is set at the grid of stream attribute	Real	Optional

Table 4.11 GreenAmptParameter table

Field name	Description	Data type	Required
GridValue	Grid value in soil texture raster file	Integer	Required
USERSoil	Name of soil texture attribute selected by user	String	Optional
GRMCode	Soil texture code (refer to "GRMCode" field value in GreenAmptSoilParameter table of the static DB)	String	Required
GRMTextureE	Soil texture English name (refer to "SoilTextureE" field value in GreenAmptSoilParameter table of the static DB)	String	Optional
GRMTextureK	Soil texture Korean name (refer to "SoilTextureK" field value in GreenAmptSoilParameter table of the static DB)	String	Optional
Porosity	Porosity	Real	Required
EffectivePorosity	Effective porosity	Real	Required
WFSoilSuctionHead	Wetting front soil suction head	Real	Required
HydraulicConductivity	Hydraulic conductivity	Real	Required

Table 4.12 SoilDepth table

Field name	Description	Data type	Required
GridValue	Grid value in the soil depth raster file	Integer	Required
UserDepthClass	Soil depth attributey name selected by user	String	Optional
GRMCode	Soil depth code (refer to 'GRMCode' field value in the SoilDepthParameter table of the static DB)	String	Required
SoilDepthClassE	Soil depth English name (refer to 'SoilDepthClassE' field value in the SoilDepthParameter table of the static DB)	String	Optional
SoilDepthClassK	Soil depth Korean name (refer to 'SoilDepthClassK' field value in the SoilDepthParameter table of the static DB)	String	Optional
SoilDepth_cm	Soil depth value (cm)	Real	Required

Table 4.13 LandCover table

Field name	Description	Data type	Required
GridValue	Grid value in land cover raster file	Integer	Required
UserLandCover	Land cover attribute name selected by user	String	Optional
GRMCode	Land cover code (refer to 'GRMCode' field value in the LandCoverParameter table of the static DB)	String	Required
GRMLandCoverE	Land cover English name (refer to 'LandCoverE' field value in the LandCoverParameter table of the static DB)	String	Optional
GRMLandCoverK	Land cover Korean name (refer to 'LandCoverK' field value in the LandCoverParameter table of the static DB)	String	Optional
RoughnessCoeff-icient	Roughness coefficient	Real	Required
ImperviousRatio	Impervious ratio	Real	Required
CanopyRatio	Canopy area ratio by the control volume grid	Real	Optional
InterceptionMax-WaterCanopy_mm	Maximum possible interception by the canopy (mm)	Real	Optional

4.6 GRM Static database

The GRM static database saves the default reference values for soil and land cover parameters used in the GRM model in xml format(GRMStaticDB.xml). Default values for soil and land cover parameters can be selected using the GRM Static database when a GRM project file (.gmp) is created. Table descriptions and specifications for each table of the GRM static database are shown below. Parameters values for each attributes can referred to GRMStaticDB.xml file.

Table 4.14 Table Definitions for a GRM Static xml file

Table name	Description
GreenAmptSoilParameter	Green–Ampt parameter values according to soil texture
SoilDepthParameter	Soil depth according to soil depth classification
LandCoverParameter	Roughness coefficient and impervious ratio according to land cover properties, land cover properties categorized into 7 are set as default values

Table 4.15 GreenAmptSoilParameter table

Field name	Description	Data type
SoilTextureE	Soil texture, English name	String
SoilTextureK	Soil texture, Korean name	String
GRMCode	Soil texture code	String
PorosityMin	Minimum porosity	Real
PorosityMax	Maximum porosity	Real
PorosityDefault	Default porosity	Real
EffectivePorosityMin	Minimum effective porosity	Real
EffectivePorosityMax	Maximum effective porosity	Real
EffectivePorosityDefault	Default effective porosity	Real
ResidualMoistureContent	Residual moisture content	Real
WFSoilSuctionHeadMin	Minimum wetting front soil suction head	Real
WFSoilSuctionHeadMax	Maximum wetting front soil suction head	Real
WFSoilSuctionHeadDefault	Default wetting front soil suction head	Real
HydraulicConductivity	Hydraulic conductivity	Real

Table 4.16 SoilDepthParameter table

Field name	Description	Data type
GRMCode	Soil depth code	String
SoilDepthClassE	Soil depth classification, English name	String
SoilDepthClassK	Soil depth classification, Korean name	String
SoilDepthMin	Minimum soil depth	Real
SoilDepthMax	Maximum soil depth	Real
SoilDepthDefault	Default soil depth	Real

Table 4.17 Soil texture code used in the GRM and soil texture name

GRMCode	SoilTextureE
C	Clay
CL	ClayLoam
L	Loam
LS	LoamySand
S	Sand
SC	SandyClay
SCL	SandyClayLoam
SiC	SiltyClay
SiCL	SiltyClayLoam
SiL	SiltLoam
SL	SandyLoam
USER	User defined attribute

Table 4.18 Soil depth code used in the GRM and soil depth name

GRMCode	SoilDepthClassE
D	Deep
M	ModeratelyDeepOrModeratelyShallow
S	Shallow
VD	VeryDeep
VS	VeryShallow
USER	User defined attribute

Table 4.19 LandCoverParameter table

Field name	Description	Data type
GRMCode	Land cover code	String
LandCoverE	Land cover, English name	String
LandCoverK	Land cover, Korean name	String
GRMCode	Land cover code	String
RoughnessCoefficient	Roughness coefficient	Real
ImperviousRatio	Impervious ratio	Real
CanopyRatio	Canopy area ratio by the control volume grid	Real
InterceptionMaxWaterCanopy_mm	Maximum possible interception by the canopy (mm)	Real

Table 4.20 Land cover code used in the GRM and land cover name

GRMCode	LandCoverE
AGRL	Agricultural Area
BARE	Bare
FRST	Forest
GRSS	Grass
URBN	Urban
WATR	Water
WTLD	Wetland
USER	User defined attribute

5. Output data

All hydrologic components of the GRM are calculated from every grid existing within a watershed and the user selects a grid cell for the calculation output, which becomes the ‘watch point’. Calculations from a grid cell set as the watch point are saved as a text file if GRMSSimulationType is set as SingleEvent in ProjectSettings of the project file (gmp). If GRMSimulationType is set as RealTime, they are saved as a text file and database (SQL, etc.). And simulation results for all grids within a watershed can be saved as ASCII raster file and image (bmp) file (by using MakeIMGFile and MakeASCFile options in gmp file).

The calculation results mainly include discharge data. The water depth should not be calculated from a hydrologic model, such as the GRM, but from a hydraulic stream model or the ‘water level–discharge’ relationship equation. The calculation result files and the main contents of them are shown in the table below.

Table 5.1 GRM simulation output file

Sim. Type	Output File	Content
Normal	*[Project name]*-_Discharge.out	Flow calculation results, mean rainfall, etc. for the watershed, and used calculation time for every watch point
	[Project name]-_Discharge_Ave.out	The average value of the discharge during the average value print out time interval at all the watch points, and the average rainfall in the entire domain
	[Project name]-_FCStorage.out	Reservoir storage for every flow control grid (1,000m^3) (only printed if the flow control is simulated)
	[Project name]-_FCinflow.out	Reservoir inflow for every flow control grid (only printed if the flow control is simulated)
	[Project name]-_FCinflow_Ave.out	The average value of the reservoir inflow during the average value print out time interval at all the flow control grids (only printed if the flow control is simulated)
	[Project name]-_PRCPGrid.out	Precipitation data at all the watch point grids
	[Project name]-_PRCPUpMean.out	The average values of precipitation for the upstream of all the watch point grids
	*[Project name]*_WP-_[*watch point name*].out	All calculation results for corresponding watch points (the files are created for every watch points)
RealTme	*[Project name]*-_[*watch point name*].out	Discharge, average precipitation of upstream watershed, etc. from corresponding watch points
	Saved in DB	Discharge, average precipitation of upstream watershed, etc. from corresponding watch points
ASCII file		Distributions of discharge, soil saturation ratio, incremental precipitation, and cumulative precipitation are saved in ASCII files
Image file		Distributions of discharge, soil saturation ratio, incremental precipitation, and cumulative precipitation are saved in bmp files

The calculation result file created for each watch point (*[Project name]*_WP_*[watch point name]*.out) contains various results such as flow and soil saturation calculated from the target watch point grid. The details of the file are shown in the table below.

Table 5.2 Contents of output file for a Watchpoint

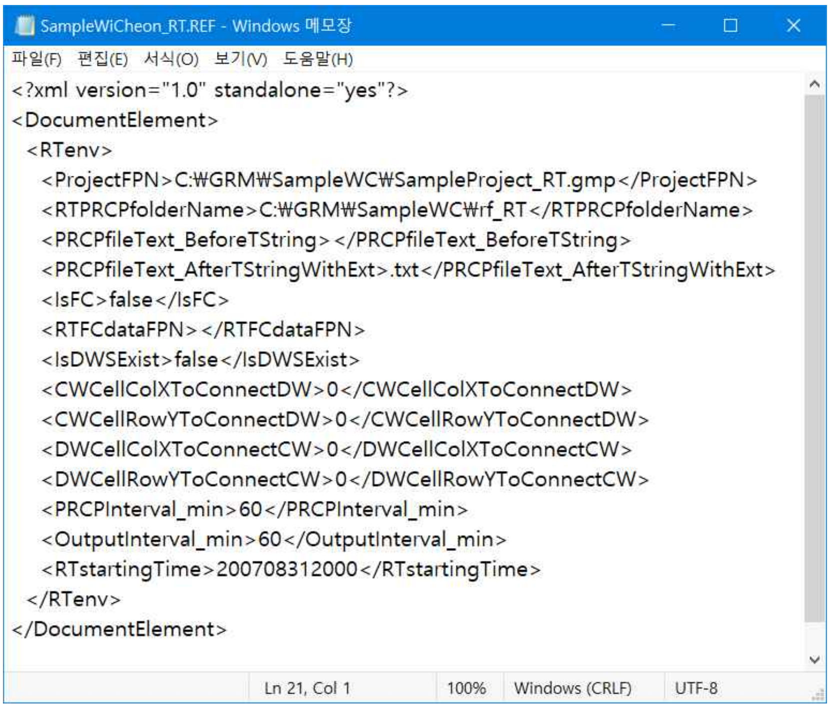
Item	Content
Discharge[CMS]	Flow rate
BaseFlowDepth[m]	Base flow
SoilWaterContent[m]	Soil water content
SoilSatR	Soil saturation ratio
PRCP_Grid[mm]	Precipitation of the watch point grid
PRCP_UpMean[mm]	The average values of the precipitation for the upstream of all the watch point grids
PETGrid[mm]	Potential evapotranspiration
ETGrid[mm]	Actual evapotranspiration
INTCPAccGrid[mm]	Cumulative interception
SnowPackAccGrid[cm]	Cumulative snowpack depth
SnowMeltGrid[mm]	Snow melt
FCResStor[1,000m^3]	Reservoir storage (only printed if the flow control is simulated)

6. GRM Real Time

Real-time simulation using GRM can be performed using the "/r" option. However, it is recommended to modify and optimize at the source code level of the GRM model in order to build an optimized real-time system that reflects whether DBMS is used, the file and folder structure of the inputs, and the characteristics of the catchment system. (Under GRM v2020.1 developed by C#, the "/r" option is not provided, and the real time system has to be developed using the real-time analysis module in GRMCore.dll or source code)

Real-time flow analysis uses distributed precipitation data created from real-time radar or watershed mean precipitation data collected in real time. Using distributed precipitation data requires clipping and resampling areas that correspond to topographical data of the targeted watershed with the same grid size and region.

Environmental parameters for real-time flow analysis are saved in xml text file (.REF). The REF file includes data on watershed system components and initial environmental conditions for flow simulations such as data on flow analysis project file (gmp), subwatersheds connected to the downstream (when multi-site calibration of connecting subwatersheds is used), real time flow control data, etc.




```
<?xml version="1.0" standalone="yes"?>
<DocumentElement>
  <RTenv>
    <ProjectFPN>C:₩GRM₩SampleWC₩SampleProject_RT.gmp</ProjectFPN>
    <RTPRCPfolderName>C:₩GRM₩SampleWC₩rf_RT</RTPRCPfolderName>
    <PRCPfileText_BeforeTString></PRCPfileText_BeforeTString>
    <PRCPfileText_AfterTStringWithExt>.txt</PRCPfileText_AfterTStringWithExt>
    <IsFC>false</IsFC>
    <RTFCdataFPN></RTFCdataFPN>
    <IsDWSExist>false</IsDWSExist>
    <CWCellColXToConnectDW>0</CWCellColXToConnectDW>
    <CWCellRowYToConnectDW>0</CWCellRowYToConnectDW>
    <DWCellColXToConnectCW>0</DWCellColXToConnectCW>
    <DWCellRowYToConnectCW>0</DWCellRowYToConnectCW>
    <PRCPInterval_min>60</PRCPInterval_min>
    <OutputInterval_min>60</OutputInterval_min>
    <RTstartingTime>200708312000</RTstartingTime>
  </RTenv>
</DocumentElement>
```


Fig. 6.1 An example of a REF file

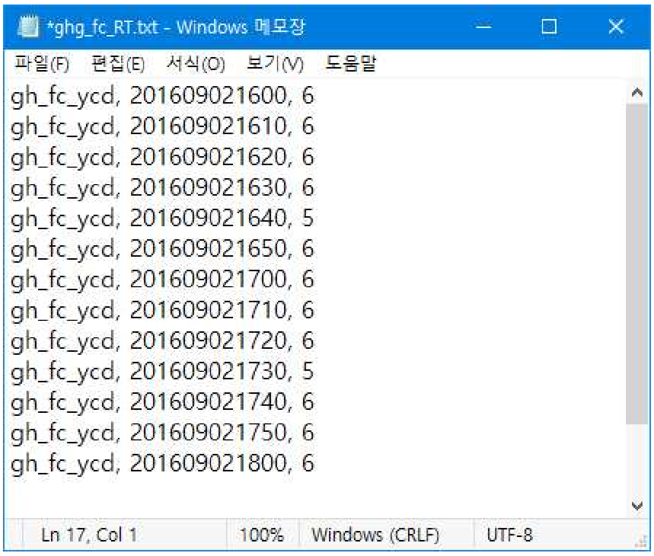
Table 6.1 File (.REF) structure for real-time flow analysis settings

Field name	Description
ProjectFPN	Name and path of the GRM project file (gmp) of the current watershed
RTPRCPfolderName	Real-time precipitation data receiving folder path
PRCPfileText_BeforeTString	Characters before the time identification text in the precipitation data file (For example, if the rainfall file name is RDR_201609021600_RKDP.asc, "RDR_")
PRCPfileText_AfterTStringWithExt	Characters after the time identification text in the precipitation data file (For example, if the rainfall file name is RDR_201609021600_RKDP.asc, “_RKDP.asc”)
IsFC	Whether FlowControlGrid is included or not
RTFCdataFPN	The full path and name of the file where the real-time flow control data will be stored. **This term is not needed if real-time data from the DBMS will be used.
IsDWSExist	Whether subwatershed connected to the downstream exists or not
CWCellColXToConnectDW	Column number of the current watershed grid that is to be connected with a downstream watershed
CWCellRowYToConnectDW	Row number of the current watershed grid that is to be connected with a downstream watershed
DWCellColXToConnectCW	Column number of a downstream watershed grid that is to be connected with the current watershed
DWCellRowYToConnectCW	Row number of a downstream watershed grid that is to be connected with the current watershed
PRCPInterval_min	Precipitation data time interval (min)
OutputInterval_min	Output time interval (min)
RTstartingTime	Real-time modeling start time (yyyymmddhhmm)

For real-time simulation using the "/r" option, a real-time simulation environment file (.REF) have to be specified to run the model (see Appendix ‘How to Run’).

In case of real-time simulation using the "/r" option, the real-time precipitation data shall be in a folder separated by month. That is, the precipitation files for September 2016 (for example, the "201609021600.asc" file) should all be in the "*RTRFfolderName*₩201609" folder. If you wish to change this rule, you must modify the source code of the GRM model.

If real-time flow control information stored in a text file (*RTFCdataFPN* field value saved in .REF file) is used, "flow control point name", "date and time" and "flow" shall be stored separated by commas (,) as shown below. If there are multiple flow control points in one basin, store the real-time data of all points in the same file. However, if there are multiple real-time simulation processes (i.e., when multiple grm.exe are running), access to the data in one text file causes an error in relation to the file lock issue. Therefore, it is recommended to use DBMS when multiple real-time simulation processes are implemented in connection with each other.


*ghg_fc_RT.txt - Windows 메모장
파일(F) 편집(E) 서식(O) 보기(V) 도움말

```
gh_fc_ycd, 201609021600, 6
gh_fc_ycd, 201609021610, 6
gh_fc_ycd, 201609021620, 6
gh_fc_ycd, 201609021630, 6
gh_fc_ycd, 201609021640, 5
gh_fc_ycd, 201609021650, 6
gh_fc_ycd, 201609021700, 6
gh_fc_ycd, 201609021710, 6
gh_fc_ycd, 201609021720, 6
gh_fc_ycd, 201609021730, 5
gh_fc_ycd, 201609021740, 6
gh_fc_ycd, 201609021750, 6
gh_fc_ycd, 201609021800, 6
```

Ln 17, Col 1 100% Windows (CRLF) UTF-8

Fig. 6.2 An example of real-time flow control data file

7. Prediction

In order to predict future floods, all input time series data used in the flood simulation must be forecasts. If all the input time series data used in the GRM could be constructed using predictive data, this case can be simulated in the same way as in simulating common flood events (i.e., flood simulation of past events). In general, however, forecasted rainfall data are available (e.g., numerical forecasting data), but dam discharge data are difficult to predict.

The GRM model (v.2020.05 or later version), if predicted dam discharge data are not available, the "/a" option can be used. Using the "/a" option, the GRM model uses all the data entered by the user (e.g., the dam discharge) in the flow control simulation, and if there is no more flow control data, the AutoROM is applied using the reservoirs specification. Therefore, when applying the "/a" option, specifications of all the reservoirs included in the runoff simulation must be entered.

If *ControlType* of *FlowControlGrid* is 'Inlet', the upper region of the reservoir is not be simulated. Therefore, if *ControlType* is 'Inlet', "/a" option can not be applied.

References

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Appendix

A. Download

1. Download executable files (GRM v2020.5 or later)

(1) The GRM does not require a software installation process but it simply copies the dll and exe files to be used.

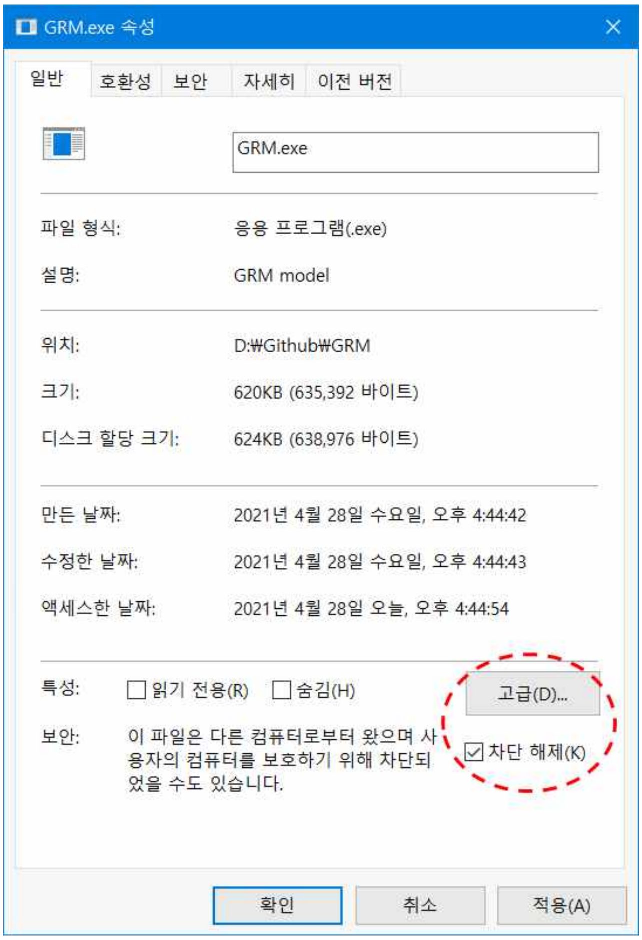
- Download the GRM executible file (GRM.exe) from

https://github.com/floodmodel/GRM/tree/master/DownloadStableVersion

- If you want to develop an GRM application using Python, you can use GRM.dll, and you can refer to the code below for how to use the APIs.

https://github.com/floodmodel/GRM/tree/master/GRM_cpp/pyGRM/pyGRMdll.py

(2) Users have to check on ‘Unblock’ in file property window the downloaded executable files (exe, dll, zip, etc) from web.



2. Download sample data

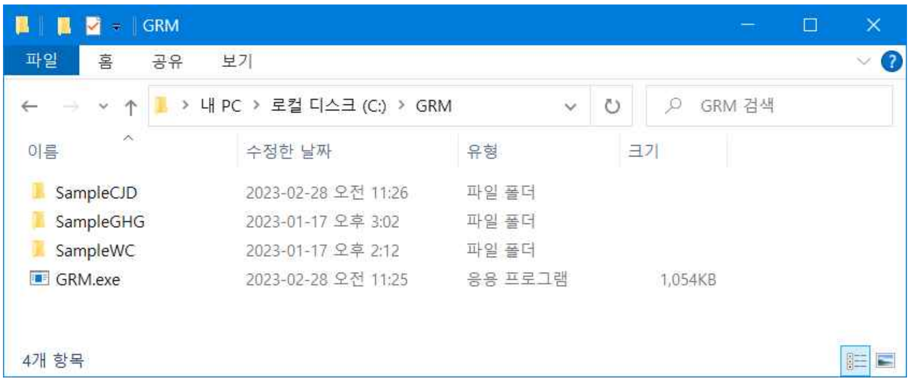
(1) The characteristics of each sample data are shown as follows

File name	Target watershed	Num. of sub-domains	Rainfall	Meteorol-igical data	Num. of watch points	Flow control	Target sim.
SampleWC.zip	Wicheon(Riv.)	1	Mean areal rainfall	×	1	×	Rainfall-runoff event
SampleGHG.zip	Gumho-river	7	ASCII raster	×	2	Inlet	Rainfall-runoff event
SampleCJD.zip	Chungju-dam	49	Mean areal rainfall for each sub-domain	○	2	Reservoir-Outflow	Continuous runoff

(2) Download sample data (SampleGHG.zip, SampleWC.zip, SampleCJD.zip) from
https://github.com/floodmodel/GRM/tree/master/DownloadStableVersion

(3) Unzip the downloaded files to "C:₩GRM". When the sample files are in another folder, the file paths in the gmp files (ampleWicheon.gmp, SampleGHG.gmp, SampleCJD.gmp) and the file (..₩SampleGHG₩ghg_rf_201609021600.txt) contains the ASCII raster rainfall list have to be changed.

(4) The following is a picture of all sample data and the GRM executable file placed in the "C:₩GRM" folder.



<Files and folders - the GRM v2022.11 or later>

B. How to run the GRM (console window)

To run the GRM, either the menu in a modeling softwares (QGIS-GRM, GRMAnalyzer, etc.) can be used or the user can manually run it in a console window. The methods to run the model in console window are described below.

1. Input of spatial data, VAT file, and hydrological time-series data is required.
2. Make a gmp file by using a text editor or the QGIS-GRM.

   (GRM v2020.1 and v2020.5 and later, gmp files are compatible with each other. The gmp file is not compatible with the versions prior to GRM v2020.1)
3. In the console window, the gmp file is entered as the argument to run GRM.exe.

For example,

The execute statement when the GRM.exe file is in the 'C:₩GRM' folder and the SampleProject.gmp file is in the 'C:₩GRM₩Sample' folder is as follows:

C:₩GRM>GRM.exe C:₩GRM₩Sample₩SampleProject.gmp

If there are spaces in the project file name or path, quotation marks "" are used to enclose it for input.

C:₩GRM>GRM.exe "C:₩GRM₩Sample₩Sample Project.gmp"

When the GRM.exe and gmp files are in the same folder, the project file path does not have to be entered. Thus, the following example shows how to run it when the GRM.exe and gmp files are in the 'C:₩GRM' folder.

C:₩GRM>GRM.exe SampleProject.gmp

When running it by entering "/f folder path," the GRM can run at once for all gmp files in the corresponding folder.

C:₩GRM>GRM.exe /f C:₩GRM₩Sample

When "/fd folder path" is entered, the GRM can run at once for all gmp files in the corresponding folder and all files, except for the discharge file (*discharge.out), are deleted. (So, you have to bakup the gmp files before using this option.)

C:₩GRM>GRM.exe /fd C:₩GRM₩Sample

"/?" can be entered for help.

C:₩GRM>GRM.exe /?

Real-time simulation can be executed using the "/r" option. When applying the "/r" option, you should specify a real-time simulation environment file (.REF).

C:₩GRM>GRM.exe /r C:₩GRM₩SampleWC₩SampleProject_RT.REF

If "/a" option is applied, the cells set as "ReservoirOutflow", "SinkFlow", or "SourceFlow" ("Inlet" is exclusive) are converted to "ReservoirOperation" and "AutoROM" when there is no (more) flow data to apply.

C:₩GRM>GRM.exe /a C:₩GRM₩SampleGHG₩GHG500.gmp

C:₩GRM>GRM.exe /r /a C:₩GRM₩SampleWC₩SampleProject_RT.REF