Development of long-term rainfall-runoff model and scenario analyses for water-saving effect in rice farming in the Ibague Watershed, Colombia

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Abstract

A distributed long-term rainfall-runoff model was developed and various scenarios analyzed to quantify water-saving effect at the watershed scale. This study focused two points: a water-saving irrigation method called early stopping to improve irrigation efficiency with respect to redundant paddy irrigation water, and the introduction of a new water-saving rice genotype in the Ibague Watershed, Colombia. The Sugawara's tank model, which is used for calculating runoff discharge from forests, upland and paddy fields, and urban areas, was incorporated into each mesh of a distributed rainfall-runoff model to overcome the scarcity of hydro-meteorological data. A hypothetical pond was placed in each mesh that included a paddy field to reproduce actual irrigation management practices in the watershed. Quantitative analyses of the various scenarios to evaluate the effect of water-saving paddy irrigation showed that using the early stopping irrigation method reduced the water consumption by 9.9 % compared to the conventional irrigation method. The scenarios, which prolonged one- and two-day irrigation intervals by assuming the use of a new water-saving rice genotype and the early stopping irrigation method, showed 33.3 % and 51.6 % reductions in water consumption, respectively, compared to the conventional irrigation method.

Keywords: *Grid-based distributed model, Watershed-scale water balance, Runoff characteristic, Sugawara's tank model, Water-saving irrigation*

Introduction

The paddy plots in the Ibague watershed, Colombia, have a wide area (2 ha–20 ha) and mean surface gradient (2 °–3 °). Therefore, many contour ridges are constructed within a plot and irrigation water is stored between ridges to maintain water depth and distributed throughout the plot with cutouts of ridges as shown in **Fig. 1**. Although farmers are aware of water-saving requirements, the use of water in a plot is more than crop requirement since each plot is wide and plot-level water management is still extensive. Thus, irrigating a plot usually results in the presence of redundant water. In this study, we developed a distributed long-term rainfall-runoff model to simulate the water balance at the watershed scale and analyzed various scenarios to evaluate the effects of water-saving at the same scale by introducing a water-saving irrigation method and a new water-saving rice genotype in the Ibague watershed.

Study area

Our study area is the Ibague watershed which is situated in mid-western Colombia. Maps of elevation, rain-gauge stations, and land use are shown in **Figs. 2–3**. The Ibague watershed has an area of 1439 km^2. Its highest and lowest altitudes are 4955 m and 243 m, respectively. The annual rainfall and maximum temperature are 1700 mm and 29–33 □, respectively. Runoff flows into the Magdalena River that flows along the eastern edge of the watershed. The western part of the watershed is a mountainous area. The primarily land use is agriculture, namely rice and coffee, which are cultivated in the plains situated between the central and the eastern parts of the watershed. There were no rain-gauge stations in the mountainous area; therefore, rainfall data measured at the Perales, Calicanto, El Chaco, and Camala rain-gauge stations, shown in **Fig. 2**, were used in this study.

Fig. 1 Paddy field with contour ridges in the Ibague watershed.

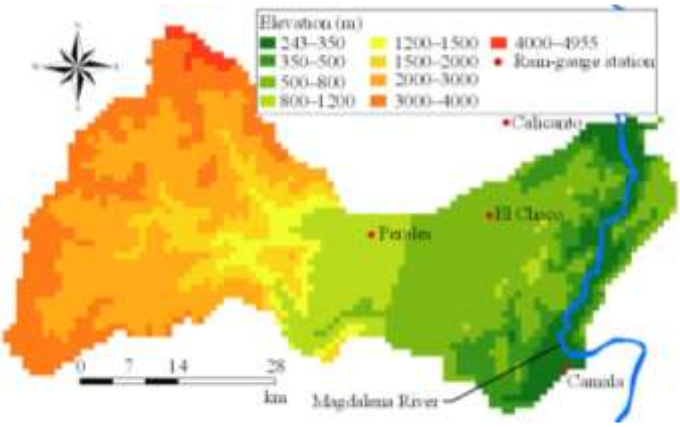
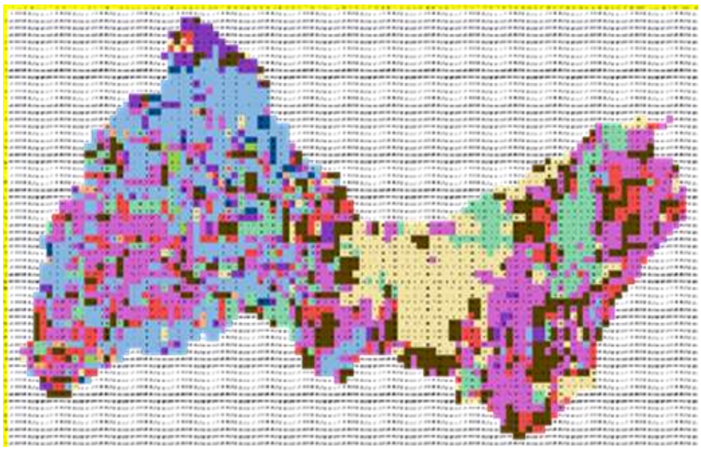


Fig. 2 Digital elevation model and rain-gauge stations of the Ibague watershed.

(http://www.diva-gis.org/gdata)



Color	Land use
🟦	Tree cover, broadleaved, evergreen.
🟩	Tree cover, broadleaved, deciduous, closed.
🟥	Shrub cover, closed-open.
🟪	Herbaceous cover, closed-open.
🟫	Sparse herbaceous or sparse shrub cover.
🟦	Regularly flooded shrub and/or herbaceous cover.
🟩	Cultivated and managed areas.
🟪	Cropland/tree cover/other natural vegetation.
🟨	Cropland/shrub or grass cover.
🟧	Bare areas.

Fig. 3 Land use map of the Ibague watershed.

(http://forobs.jrc.ec.europa.eu/products/glc2000/data_access.php)

Methods

To develop a long-term rainfall-runoff model, it is essential to express the rainfall-runoff processes for several land uses in the study area. A mesh-based distributed rainfall-runoff model was proposed to meet these requirements. The model with a mesh size of 4500 m was developed to evaluate water balance at the watershed scale. Although the original resolution of the digital elevation model was 900 m, a mesh size of 4500 m was selected to reduce computation time.

A conceptual diagram of the model structure is shown in **Fig. 4**. As it was not possible to obtain observed river discharge data to verify the model, the Sugawara's tank models (Sugawara, 1979) which have long history of practical applications in analyzing rainfall-runoff processes and can generally predict rainfall-runoff discharge for typical land uses were introduced as a core part of the water balance modeling in each mesh. Therefore, all meshes contained forest, paddy, upland field, and urban tank models. The various types of land uses, as shown in **Fig. 3**, were categorized into four land use classes. The runoff discharges from each land use class were calculated depending on the proportional area of each land use class inside the mesh. These discharges flowed into a river arranged in each mesh, as shown in **Fig. 4**. There were several land uses in each 4500 m mesh. However, the runoff discharges from the above-mentioned for land use classes were calculated individually using these tank models. An irrigation canal was set up in each mesh with reference to satellite images and a channel network map. Several agricultural ponds in the Ibague watershed store water which is used for paddy irrigation. However, the data on these agricultural ponds was not available. Therefore, hypothetical ponds were placed on the meshes with a paddy field.

A groundwater tank model covering the entire watershed area was also incorporated to represent the stable groundwater component. The water that percolates from the lowest tank of the tank models for each land use class flows into the groundwater tank model and subsequently to the Magdalena River from the basin end, depending on the depth of the reserve water in the groundwater tank model. The structure and parameters of the tank models for each land use class were defined based on Nakagiri *et al.* (1998), as shown in **Fig. 5**. In addition, data from interviews conducted with

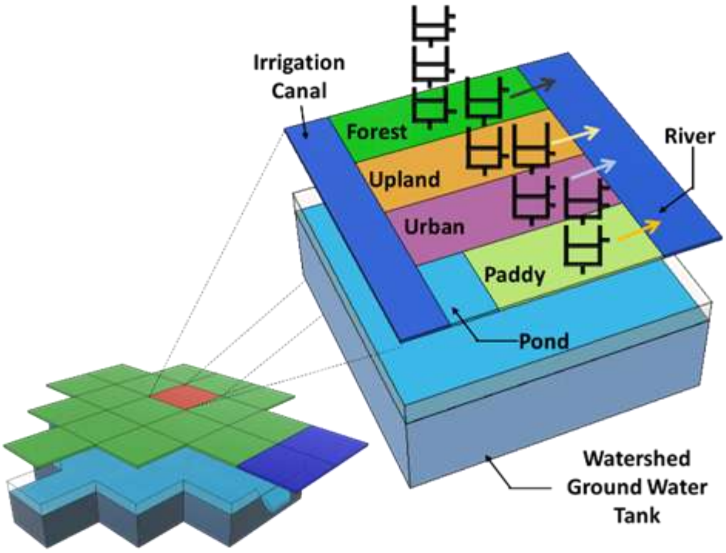


Fig. 4 A distributed long-term rainfall-runoff model.

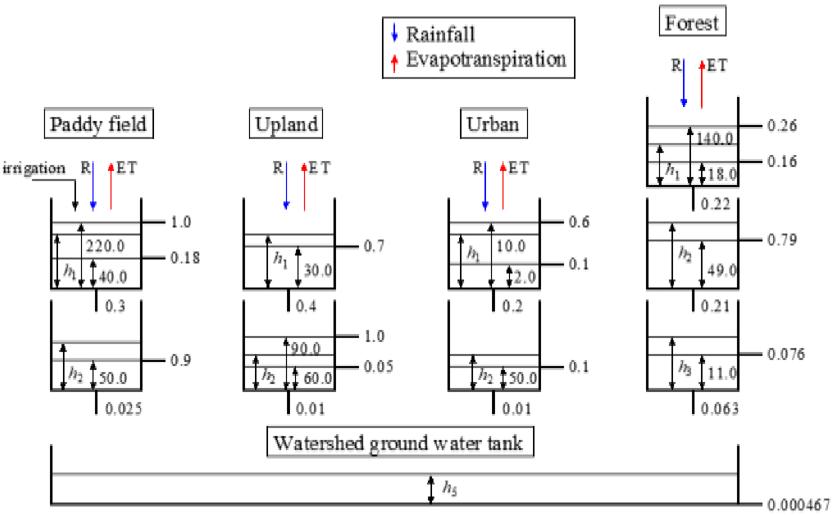


Fig. 5 Structure and parameters of tank models for the four land use classes.

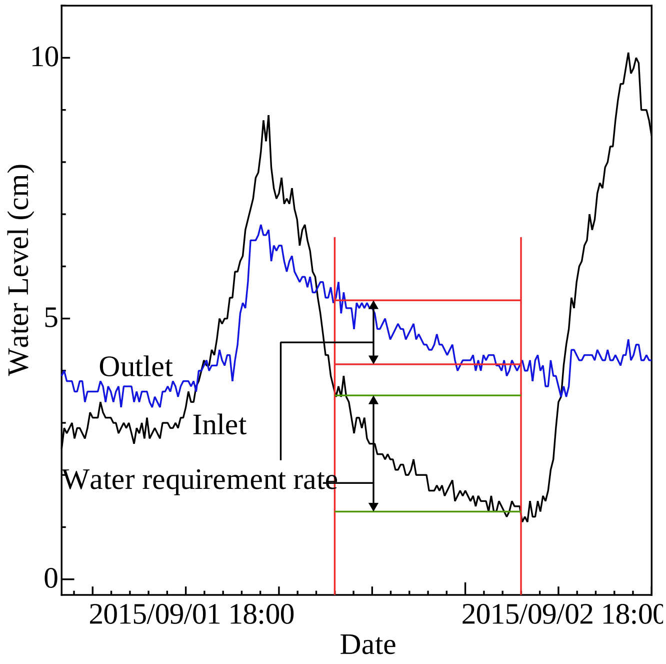


Fig. 6 The variations in water levels measured in a paddy plot experiment after taking irrigation water.

the farmers and the paddy plot experiment for plot-level water requirement in the Ibague Watershed, as shown in **Fig. 6**, were used to set the percolation coefficient, irrigation interval, and irrigation water intake for the first tank of the paddy tank model. The paddy plot experiment shown in **Fig. 6** was conducted in a no rainfall period. Irrigation water was taken from the hypothetical ponds that were placed in each mesh and the pond water was supplied from the river and irrigation canal in the mesh. In the watershed, we assumed the rice cultivation to follow single cropping and that the time of cultivation varies in each paddy plot. Therefore, the initiation of rice cultivation was set at each mesh by using the uniform random number.

The flow in the rivers or the irrigation canals between meshes was simulated based on kinematic wave method considering the momentum equation (1) and the continuity equation (2) that were calculated using the Runge-Kutta-Gill method.

$$Q_{i,j} = \frac{1}{N} B_{i,j} h_i R_i^{2/3} I_{i,j}^{1/2} \tag{1}$$

$$\frac{dh_k}{dt} = \frac{1}{A_k} \left\{ Q_{\text{in}(k)} - Q_{\text{out}(k)} + Q_{\text{tank}(k)} \right\} + R - ET \tag{2}$$

where i, j, and k are the mesh numbers; $Q_{i,j}$ is the flow discharge from mesh i to j (m^3/s); N is the Manning's roughness coefficient, which was set to 0.15 $m^{-1/3}s$ based on the standard value of the coefficient in natural water channels as shown by Chow (1973); $B_{i,j}$ is the mean river width between mesh i and j (m); h_i and h_k are the water depths in mesh i and k (m); $I_{i,j}$ is the topographic gradient between mesh i and j; t is the time step (= 300 s); $Q_{\text{in}(k)}$ is the inflow discharge into mesh k (m^3/s); $Q_{\text{out}(k)}$ is the outflow discharge from mesh k (m^3/s); $Q_{\text{tank}(k)}$ is the flow discharge from the tank model for each land use class to the rivers in mesh k (m^3/s); R is the amount of rainfall (m/s); ET is the amount of evapotranspiration (m/s), calculated using the Thornthwaite method (Thornthwaite, 1948); and A_k is the area of the river in mesh k (= $B_k \times 4{,}500$ m^2). The value of B was defined using equation (3), as proposed by Sayama and Takara (2003):

$$B_k = B_0 \left(\frac{C_k}{C_{\max}} \right)^l \tag{3}$$

where B_0 is the width of the river at the end of the basin (m), C_k is the catchment area at mesh k (m^2), $C_{\max}$ is the catchment area at the end of the basin (m^2), and l is a constant value (= 0.3).

Scenario analyses

The scenario analyses were conducted for the year 2016 as the rainfall data were available for all rain-gauge stations during this year. To quantify the effect of water-saving paddy irrigation, the four scenarios SC_{Base}, SC_{ES}, SC_{01}, and SC_{02} were analyzed using the developed model. The scenario SC_{Base} was based on rice farming with the current irrigation management (five- or six-day interval). According to the paddy plot experiment data shown in **Fig. 6**, the water requirement rate of the paddy field was calculated as 15.9 mm/d, based on the mean value of the decrease in water depth near the inlet and outlet during the period when irrigation water was not taken and there was no rainfall. In addition, the interviews conducted with the farmers revealed that irrigation water was taken only when the paddy surface dried. The irrigation interval was approximately 5–7 days. Therefore, the water depth of an irrigation intake into the first tank of the paddy tank model was set to 44.4 mm in order to set the intake interval of irrigation water as 5 days when there was no rainfall, and the irrigation water was taken when the water depth of the first tank reached zero.

The scenario SC_{ES} was set by assuming that the early stopping irrigation method, in which the redundant water in the current irrigation management was cut away by stopping an irrigation intake early, would be widely used in the whole basin. The redundant irrigation water amount in the current irrigation management was estimated to be 4.4 mm from the paddy plot experiment, which indicated the time ratio of the irrigation duration time and the period when the redundant water occurred. Therefore, the irrigation water intake for the early stopping irrigation method was set to 40.0 mm by subtracting the amount of redundant water from the amount of the current irrigation water intake. The

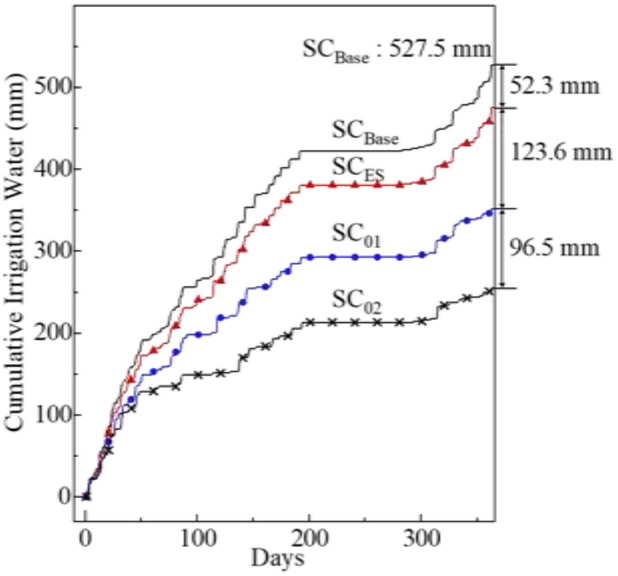


Fig. 7 Cumulative yearly amount of irrigation water for the four scenarios.

timing for supplying the irrigation water was the same as that in the scenario SC_{Base}.

The scenarios SC_{01} and SC_{02} were considered to simulate the effect of introduction of a new water-saving genotype of rice, in which the irrigation interval was extended by one- and two-day, respectively, together with the early stopping irrigation method. The irrigation water was taken one- and two-day after the water depth of the first tank for the paddy field tank model reached to be zero in the scenarios SC_{01} and SC_{02}, respectively. The amount of the irrigation water intake was the same as that in the scenario SC_{ES}.

The cumulative amount of the irrigation water of the scenarios SC_{ES}, SC_{01}, and SC_{02} in the target year 2016 were compared with that of the scenario SC_{Base} to evaluate water-saving effect at the watershed scale.

Results and Discussion

The results of the scenario analyses are shown in **Fig. 7**. The scenarios SC_{ES}, SC_{01}, and SC_{02} showed a reduction of irrigation water by 52.3 mm, 175.9 mm, and 272.4 mm from the baseline scenario SC_{Base}, respectively. The spread of the early stopping irrigation method (SC_{ES}) resulted in a 9.9 % reduction of irrigation water, as compared to the conventional irrigation management scenario (SC_{Base}). In the scenarios SC_{01} and SC_{02}, the negative impact of water-saving on rice growth was not considered. However, the scenarios SC_{01} and SC_{02} showed 33.3 % and 51.6 % reductions of irrigation water, respectively, from the baseline scenario SC_{Base}.

Conclusions

In this study, a distributed long-term rainfall-runoff model was developed to assess the watershed scale water balance in the Ibague watershed, Colombia and to evaluate the effect of water-saving rice farming quantitatively. Despite the scarcity of hydro-meteorological data, especially river discharge data for model verification and rainfall data in the western side of the watershed, the effect of water-saving rice farming could be quantified at the watershed scale. In our future studies, we will detect the ponds from satellite images to better demonstrate conventional paddy irrigation.

Acknowledgement

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