TROPICAL HYDROLOGY SIMULATION MODEL 1 FOR WATERSHED MANAGEMENT (Trophydsim-1)

by:

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Abstract

A hydrological simulation model, named the **Tropical Hydrology Simulation Model 1** (*Trophydsim-1*), was created in order to simulate the run-off processes in mountainous terrain in a tropical monsoon region. The hydrological cycles in five major land covers, i.e., forest, upland, plantations (normally tobacco areas), paddy fields, and settlements, were each analogized by a series of four storages representing interception, depression, upper-zone and lower-zone storages. A set mathematical equations expressing empirical formula as well as physical law were employed in the model. An automatic parameter optimization routine was presented.

The model was applied to the *Kali Progo* river basin, Central Java, Indonesia, which contains five subbasins. The simulated and recorded hydrographs were in close agreement both at every transfer point of the subbasins and in three different calendar years with different landuse patterns.

Some hydrologic characteristics were found from application of the model. The basin, which is mainly comprised of fresh volcanic formations, is capable of storing much water and releasing it gradually as groundwater flow. Therefore, the basin provides stable low flow for irrigating paddy land, which has expanded to 40 to 60 percent of the whole basin area, with multiple cropping patterns of rice-rice-upland crops or even rice-rice-rice.

The model was also applied to simulate the effect on water regime of different modes of watershed management of simply landuse patterns. Five scenarios representing extreme conditions of landuse and four more realistic scenarios of landuse management were considered. The results show that the model is sensitive enough as a hydrology simulator to predict the effect of rapid changes of landuse pattern on water regime. The hydrological implications of landuse management in the river basin due to changes in landuse patterns manifested by the irrigation water availability and river flow regime are presented.

I. Introduction

The present environmental conditions of watersheds in Indonesia, particularly in *Java*, are degrading. The Indonesian government has implemented many rehabilitation programs related to watershed management, such as reforestation, soil conservation measures ect., but the rate of degradation is still exceeds that of the programs, and an innovative hydrologic approach is still needed to ameliorate the situation, especially to conserve water resources.

In Indonesia, such hydrologic models as the *Stanford Watershed Model IV* (Crawford and Linsley, 1966), and the *Streamflow Synthesis and Reservoir Regulation* (SSARR) model developed by U.S. Army Engineer Division, North Pacific (1972), have been applied and modified, and others have been created by Indonesian hydrologists (Anonymous, 1977, 1983); but these can not be used to predict water regimes because of rapid changes in landuse pattern in the watersheds.

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The proposed Tropical Hydrology Simulation Model 1 (Trophydsim-1) has been created to evaluate the impact of landuse changes on run-off processes.

II. Model Building

2.1. The Concept of the Model

The design of the Trophydsim-1 model, which was inspired by Sugawara's tank model (Sugawara et al, 1984), has three basic components: a) run-off processes in different landuse types, b) run-off processes in subbasins, and c) channel flow routing (Fig. 1).

A given river basin is divided topographically into a number of smaller subbasins. The model assumes that there is no reservoir in any subbasin, and that every subbasin is subdivided into five different landuse types, namely, forest, upland, plantations (normally tobacco areas), paddy land and settlements.

As shown in Fig. 1, the different landuse types are actually all fragmented and mixed, but for simplicity it was assumed that each landuse type forms a single block in a subbasin, and that the five landuse types are connected in sequence. The hydrological cycles in each landuse type are analogized by a series of four imaginary storages representing interception, depression, upper-zone and lower-zone storages as illustrated in Fig. 2.

The model was created on the daily basis.

2.2. Run-off Processes in Each Landuse Type

A set of mathematical equations expressing empirical formulas as well as physical laws of hydrology were employed in the series of four storages to simulate stream flow. The total flow in each landuse type consists of direct rainfall into the river channel, surface, subsurface, and ground water flow. These components are calculated separately before they are synthesized to give the total flow as shown schematically in Fig. 3.

2.3. Run-off Processes in Subbasins

a) Irrigation water intake

In principle, the hydrograph of each subbasin should be the summation of flows from the five landuse types, i.e., forest, plantations, upland, paddy land and settlements; but it is not a simple summation because, as shown in Fig. 1, paddy lands are all irrigated by diverting water either from small streams which collect run-off from forest, plantations and upland landuse types, or from the main stream. Irrigation water is diverted by means of numerous weirs, but actual intakes are not always measured for the smaller ones that are not operated and maintained by Public Works Department's field offices. Therefore, the amount of irrigation intake was estimated by using "*two additional parameters of intake ratios from the small streams and the main stream*". Here, many actual intake points in many small streams were assumed to be represented by a single "*collector point*" for simplicity.

The two parameters of intake ratios were estimated on the basis of the fact that irrigation intake amount is determined largely by paddy land area at the time, which is variable from year to year.

b) Total run-off from subbasin

The total run-off from each subbasin was then calculated by the summation of flows from the five landuse types under consideration of the flow chart diagram as shown in Fig. 1 above.

2.4. Channel Flow Routing

The function of the channel flow routing component is to translate discharge from the upper subbasin outlet to the lower transfer point. Two methods were employed in the model: (1) the original *Muskingum* method, and (2) the kinematic wave routing of the *Muskingum-Cunge* method (Chow, V.T et al, 1988, Bedient, P. B and Huber, W.C, 1988).

2.5. Optimization of Parameters

Two steps of parameters optimization were taken. First, a set of parameters used in the equations of the four imaginary storages was optimized for a given subbasin using an automatic optimization routine.

There are 18 parameters, of which eight have to be postulated before the optimization process (see Table 1). The optimization was made using "*Powell's conjugate direction method*" (Kobayashi and Maruyama, 1976, Powell, 1964). Secondly, optimized parameter values were allocated to the five different landuse types with appropriate weighting factors, which were determinated through the computerized optimization processes. Thus, if a river basin has five landuse types, total parameter becomes 5 × 18 parameters.

2.6. Accuracy of Simulated Hydrograph

The accuracy of the simulated hydrographs was measured from graphical and numerical indicators. Two graphical indicators were drawn, a continuous time series and a scatter diagram for simulated and observed values. The numerical indicator was determined by five statistical measures of goodness of fit. These are standard error (SE), correlation coefficient (CC), coefficient of determination (CD), weighted moment (WM), and mass balance (MB).

2.7. Model Organization and Model Output

The model consists of the main program and a number of subroutines. The subroutine programs calculate evapotranspiration potential (four methods), analyze imaginary storages, optimize parameters, carry out channel flow routing (two methods), evaluate the goodness of fit, and plot various results. Two outputs, numerical and graphical outputs, are programmed in the model. Simplification diagram of the model organization is plotted in Fig. 4.

Numerical output tabulates daily discharge including direct rainfall into river channel, surface, subsurface and baseflow in every landuse type, at every subbasin as well as at every transfer point. Standard numerical output includes a summary table of average, maximum and minimum discharge as well as statistical measurement at every transfer point.

Graphical output includes daily hydrograph for each landuse type, at the collector point of subbasins, at every outlet of subbasins and at every transfer point. Comparison between recorded and simulated discharge at every transfer point is possible by graphical presentation of hydrographs and by scatter diagrams.

The program was written in Fortran 77 and requires 1269 KB.

III. Application of the Trophydsim-1

3.1. Site Description

The model was applied to *Kali Progo* river basin (2,027 km^2) located in Central Java, Indonesia. It drains itself into Indian

Ocean. The basin can be divided topographically into five sub basins (Fig. 5).

Thirty-six rain gauges are installed in the basin, together with five automatic water level recorders at the five transfer points. The hydrometeorological regimes are dominated by two monsoons which bring about two dramatically different seasons. The Southeast monsoons crosses this are between June and September bringing very little rainfall resulting in frequent drought. The moist Northeast monsoon brings rainy season from November to April with annual rainfall of about 2200—3200 mm. Class pan A gives annual evaporation of 1,200 — 1,600 mm.

Areas of the respective landuse types in every subbasin are tabulted in two different years, 1977 and 1981, during which major development and rehabilitation of irrigation facilities were implemented. The areas of respective landuse types were measured based on aerial photos.

The geological and lithological map of Indonesia shows that this area lies in the circum *Sunda* orogenic system of the central and southern belt of Java, and has two lithogical types: consolidated clastic sediments cover the northern half of the basin, and recent and unconsolidated *fluvial* and *lacustrine* sediments cover the southern part.

The *Kranggan* and *Borobudur* subbasins (W_1 and W_3) are composed of old deposits of *Mt. Sundoro* and *Mt. Sumbing*, respectively. Volcanic deposits of *Mt. Merbabu* cover the *Mendut* subbasin (W_2). The *Duwet* and *Bantar* subbasins (W_4 and W_5) in the eastern part are covered by *fluvio-volcanic* deposits of *Mt. Merapi* which meet the andesite rocks of the *Menoreh* hills in the western part of the basin. The *Kali Progo* river, the main river of the basin, runs along the boundary between the two different geological formations.

Mt. Merapi produces materials at a high rate, estimated at about 6.4 million m^3 per year averaged over the last 120 years (Nossin J J and Voute C, 1986; van Bemmelen, 1949). The area is underlain by two types of soil: *latosol (inceptisol/utisol)*, which covers 60 percent of total area and is found in the northern part; and *grumusol* (*vertisol*), which covers 40 percent of total area and is found in the southern part.

The basin contains many small weirs to divert stream flow for irrigation of paddy land. These have been built both by the government and farmers, and not all of them are monitored. The main river is diverted upstream of the *Duwet* transfer point to irrigate of 26,000 ha of paddy land on the left side through the *Mataram* and *Van der Weick* canals, which have average discharges of 9-13 m^3/sec and 4—5 m^3/sec, respectively. The river is also diverted to the right side to irrigate 6,000 ha through the *Kali Bawang canal*, which has an average discharge of 5—7 m^3/sec. The irrigation areas of the two systems all lie outside the study basin.

The general cropping pattern in this area is rice-rice-upland crops. In the upper part of the basin, tobacco is a very common crop in the dry season. Where there is enough irrigation water in the dry season, triple rice cropping is practiced.

3.2. Model Performance

The performance of the model was evaluated in two ways. One is in terms of the accuracy of the simulated river flow at each of the transfer points as compared with the recorded flow. The other is in terms of the validity of the various parameters which have been allocated to the respective landuse types. The latter is particularly important because the principal utility of this model is to evaluate the influence of landuse changes on the basin-wide water regime for better watershed management.

3.2.1. *River flow*

The Kranggan subbasin, the uppermost part of the *Kali Progo* basin, was chosen for calibration of the parameters. Modification of the *Penman* method proposed by *Wright-Jensen* for calculating evapotranspiration potential, and the instantaneous unit hydrograph of the Nash model for routing overland-flow were chosen. the data set of the calendar year 1977 was used to determine a set of optimal parameter values for each landuse type. The optimized parameter values were then allocated to the different landuse types with appropriate weighting factors, which were determined through the computerized optimization process. The simulated and recorded discharges for the *Kranggan* subbasin are plotted in Fig. 6a, and show good agreement.

The allocated parameter values were then amployed in the lower subbasins. The discharge from the upper subbasin outlet to the lower transfer point was routed by the *Muskingum-Cunge* method. Close agreement between the simulated and recorded discharges was obtained at all the transfer points. A typical result of final calibration of the hydrographs at the *Bantar* point, the end transfer point of the *Kali Progo* basin, is presented in Fig. 6b.

The model was then applied to the data set of 1981 to evaluate the effects of changes in landuse patterns since 1977. The model was also verified by using the data set of 1985. The results of the simulated and recorded hydrographs at every transfer point were still in close agreement. Fig. 6c and 6d show typical results for the *Duwet* transfer point (1981) and the *Kranggan* transfer point (1985), respectively. Some statistical measures for evaluating the performance of the model at each transfer point in three calendar years are listed in Table 2.

3.2.2. *Evaluation of the allocated parameters*

The validity of the parameters allocated to the respective landuse types were evaluated indirectly by looking at the components of discharge.

The discharge was separated into four components, i.e., direct discharge, or direct rainfall on river channels (Qd), surface run-off (Qo), subsurface run-off (Qs) and base flow (Qb). Two coefficients were defined: surface run-off coefficient (Co), which is an expression of Qo as a fraction of the net rainfall, and basin storage coefficient (Cb), which is defined Qb expressed as a fraction of net rainfall. These values are shown for each landuse type in Table 3.

Of the four the components of discharge, Qd and Qs are relatively insignificant, while Qo and Qb are more important. Qo derives largely from the settlements, then from the plantations, and insignificantly from the forest. The subbasin-wide coefficient of surface run-off (Co) is almost exactly the same, 38 percent, in the two subbasins; but Co in each of the five different landuse types is smaller in the *Mendut* subbasin than in the *Kranggan* subbasin. This may partly be explained by the difference in soil porosity, which was found to be about 60 percent in the Mendut subbasin and 50 percent in the *Kranggan* subbasin.

On the other hand Qb derives largely from the forest, followed by insignificantly from the settlements. The coefficient of basin storage (Cb) is significantly higher in the *Mendut* subbasin than in the *Kranggan* subbasin, probably reflecting the more water-absorbing geological formation of the former subbasin. These characteristics all agree with our observation of the study basin.

The basin storage at the end of the calendar year was about 100 mm in both subbasins. There was positive storage in forest, paddy land and upland, and negative storage in the settlements and the plantations. However, these balances would have been closer to zero if the annual water budget had been computed according to a more appropriate water year, which should start and end in the late dry season when the basin storage should be minimum.

3.3. Some Basin Characteristics

3.3.1. Separation of surface flow and upper-zone storage components

The net rainfall, which is defined as the gross rainfall minus interception, was separated into two components, i.e., surface flow and upper-zone storage, by assuming linear correlations between surface run-off and the net rainfall, as shown in Fig. 7 for the *Kranggan* and the *Mendut* subbasins. The fraction of the net rainfall that goes to the surface flow component is 37 — 38 percent under saturated soil conditions in the rainy season, and 15 — 20 percen under dry-soil conditions. The difference between the two subbasins was not noticeable. Fro the maximum net rainfall, however, 27 percent of the net rainfall goes to the surface run-off in the *Kranggan* subbasin, whereas the figure is 44 percent in the *Mendut* subbasin. This partly reflects the difference in forest cover, which is 20 percent in the former, and only 7 percent in the latter subbasin.

3.3.2. Minimum flow

It is amazing that more than half of the area of the *Kali Progo* basin has been opened as paddy land. It is also an amazing to see water gushing down the mountainous streams in the midst of the long lasting dry season. This water has been diverted to feed the paddy land. The river basin must be releasing the water very gradually, and the minimum flows from forested areas in this basin must be analyzed. The minimum flow is interpreted, in a physical sense, as ground water run-off of the basin. Considering this, it must significantly reflect the hydrogeological structure of the area, which can be detected indirectly from the geological formation of the basin. The fact that the forest area is the main supplier of groundwater during dry season as already discussed above, the landuse type was used for analyzing the minimum flow. Japanese river basins were used for comparison.

The minimum flows from the forest areas in the Mendut and Kranggan subbasins are presented in Table 4. For comparison, the same table shows the minimum flow of the *Kizu* river basin, a tributary of the *Yodo*, as computed by use of this model. The table also lists the minimum flows of ten river basins in the *Kanto* region of Japan from an interesting study by Mushiaki et al. (1975) in which hydrological regimes were correlated with geological characteristics of the basins.

It is interesting to note that the relatively sparse Javanese forest yields as much as 10 to 15 times more stable low flows than the much more densely foreste *Kizu river* basin. The *Mendut* river basin, which has relatively fresh volcanic deposits from Mt. *Merbabu*, yields the highest and most stable low flow regime. The *Kanto* region's 10 river basins are divided into three groups: (a) three river basins that have quarternary volcanic rock formations yield as much low flow as the *Kranggan* basin, (b) three rivers that have *mesozoic* to *palaeozoic* geologic formations consisting mainly of *sandstone, slate* and *chert* have as little low flow as the *Kizu* river, and (c) four river basins consisting of *granitic rocks* and/or *tertiary volcanic rocks* have medium low flows between the former two categories.

It may be concluded that the determining factor of low flow regime is the geologic structure of river basin and not, as is generally believed for Indonesia, the vegetative cover. The young volcanic formations and deposits have a large capacity to store water in their bodies by virtue of the quick infiltration rate and the numerous cracks and large voids that have developed in the formations.

3.3.2. Irrigation water intake and water availability in paddy land

The *Borobudur* subbasin was selected as a typical hydrograph of water intake for irrigation (Fig. 8). The total amount of diverted water from the two sources is about 10 — 50 m^3/sec in the rainy season (November — June), and about 4 — 8 m^3/sec in the dry season (July — October). This water was predominantly derived from small streams: 7 — 40 m^3/sec, or 70 — 80 percent, in the rainy season; and 4 — 7 m^3/sec, or 88 —100 percent, in the dry season.

Figure 8 also reveals that the amount of water diverted during the dry season both from small streams through the collector point and from the main stream is all provided by base flow from forest, upland and plantations. On the assumption that three rice crops a year are grown in the paddy fields that occupy 45 percent of the *Borobudur* subbasin, Fig. 9 indicates the availability of water during the year. For rice planted in early December (first rice crop), water is short during land preparation in November but thereafter sufficient to sustain crop growth. For the second rice crop planted in early March, water is sufficient for land preparation in March but occasionally slight drought occurs during the growing period. For the third rice crop water is in severely short supply all through the growing period including land preparation in July. In this case, only 30 — 40 percent of the paddy lands can be watered properly.

IV. Using the Trophydsim-1 for Landuse Management

4.1. Methods

The model was also applied to evaluate the hydrological consequences of different modes of watershed management, or simply different landuse patterns, in the same river basin, on the basis of five extreme and four more realistic scenarios of possible landuse patterns. The hydrological data set for calendar year 1981 was used for the simulation. Percentage of the landuse patterns in each subbasin in that year are tabulated in Table 5.

The model scenarios of landuse the basin are presented in Table 6. The first five scenarios are quite unrealistic, envisaging 80 percent of the total basin are occupied by a single landuse, namely, forest (I), paddy (II), upland (III), plantation (IV), and settlement (V). These scenarios were selected to test sensitivity of this model.

In the more realistic scenarios, the areas of settlement and plantation were fixed at 20 and 2.5 percent, respectively, as no drastic change in these are envisaged. Scenario VI represents the most extreme landuse alternative, being heavily oriented to paddy land at the expense of forest, but this is very close to the actual landuse pattern in the basin. Actually, in some subbasins like the *Mendut, Borobudur* and *Duwet* subbasins, this extreme landuse could be realized by converting a small part of the present upland into paddy land. Scenario VII represents the conversion of most of the present paddy land into upland, which may not be an attracting alternative. Scenario VIII is designed to observe what will happen if part of upland is returned to forest and the present forested area is doubled, one of the most realistic alternatives. Scenario IX represents the maximum possible restoration of forest under the prevailing conditions (30%). All of the subbasins used the same scenarios.

4.2. Results of the Simulation

4.2.1. Five extreme scenarios

Kranggan subbasin (415 km ^{2}), the uppermost subbasin of the *Kali Progo* basin, was chosen for the simulation in the five extreme scenarios. The results are discussed in term of: (a) river flow regime, (b) surface run-off and upper zone storage components, and (c) availability of water for paddy irrigation.

a) River flow

The predicted discharge from the verification model in the water year 1981 was used as standard discharge for comparing the simulated discharge under these scenarios.

In scenario I (80% forest), the maximum flow (Qmax) decreases sharply (— 28%) and the minimum flow increases sharply (+ 43%), while the annual flow (Qanl) remains almost unchanged (— 1%) (Fig. 10 a and Table 7). When the basin is predominated either by upland (scenario III), plantation (scenario IV), or settlement (scenario V), a drastic change in the flow regime occurs. Scenario V gives the most extreme picture, showing almost double the maximum discharge (+ 97%), almost half of the minimum flow (— 40%), and a substansial increase in the annual discharge (+ 29%) (Fig. 10d and Table 7). When the basin is converted into the upland (scenario III), Qmax is increased by 57%, Qmin is decreased by 14%, while the annual discharge increases substantially by 35% (Fig. 10c and Table 7). As the plantation area is occupied mainly by tobacco, the hydrographs in scenario IV are similar to those in scenario III, but Qmax, Qmin and Qanl are slightly different (table 7).

The paddy-oriented scenario II, however, displays a different picture. Qmax naturally decreases because of paddy land's water storage capacity, but Qmin as well as Qanl also decrease, reflecting the insufficiency of water for the unrealistically expanded area of paddy land (Fig. 10b and Table 7). Further investigation into the availability of irrigation water for paddy lands is required.

b) Separation of surface flow and upper-zone storage components

The net rainfall was separated into a surface flow component and an upper-zone storage component. The separation was effected by making use of the relationship between surface run-off and the net rainfall in these five scenarios.

Fig. 11a through 11e show the curves separating the two components, and these fall into two groups. In the "*forest*" scenario the upper-zone storage component is predominant, which means that the fraction of water infiltrating into the ground is much bigger than the fraction flowing as surface run-off (Fig. 11a). The same is true of the "*paddy*" scenario, reflecting the temporary storage of water on the surface (Fig. 11b). In contrast, in scenario V, in which the basin is dominated by settlement landuse, the surface flow component increases sharply (Fig. 11e). The "*upland*" and "*plantation*" scenarios show a similar trend to the "*settlement*" scenario, though the upper-zone storage component is slightly larger (Fig. 11c and 11d).

These results accord with the results of river flow simulation as described above.

c) Availability of water for paddy irrigation

Typical hydrographs of water intake at the collector point for the forest, paddy land and upland scenarios are shown in Fig. 12a to 12c. Under the abundant but contrasting flow regimes in the "*forest*" and "*upland*" scenarios, water intake for paddy irrigation remains very small as the area of paddy land to be irrigated is very small. In "*paddy*" scenario, all available water is taken in at the collector point, but it is definitely insufficient for cropping of the expanded paddy land.

2.2. Four realistic scenarios

Under these scenarios, river flow regime and water availability for paddy land irrigation were investigated.

a) River flow regime

The river flow regime of the Duwet transfer point as shown in Fig. 13a to 13d for each of the four scenarios.

In the paddy-oriented scenario VI, in which the paddy lands occupy 50 percent of each subbasin, there was no noticeable increase in the high flow, but in the dry season the base flow descreased significantly. Almost all the water in the main river, about 13—20 m^3/sec, is diverted before reaching the *Duwet* transfer point into the Mataram canal on the left and the *Kali Bawang* canal on the right of the main river for irrigating paddy land located outside the basin (Fig. 13a).

In scenario VII, in which upland culture is more pronounced than at present at the expense of some forest and a large part of the present paddy land, the high flow in the wet season increased sharply by 39 percent while the minimum flow remained unavailable (Fig. 13b).

Scenario VIII, which has a similar landuse pattern to the present landuse, especially in the *Kranggan* subbasin (Table 5), showed a similar hydrograph for 1981. Scenario IX, which has almost the maximum possible forest cover under foreseeable conditions, yielded 5 percent larger annual flow, 2 percent higher maximum flow and increased minimum flow from zero to 3.3 m^3/sec.

b) Water availability for paddy land

Results in each scenario indicate that the sum of rainfall and irrigation water available at the collector point is more or less enough to sustain two rice crops, although with slight to moderate shortage of water for land preparation in November and March, but that a third rice crop in the dry season, which normally starts with land preparation in July, is definitely unfeasible (see Fig. 14c).

With the increase in paddy land percentage, the deficit of water available at the collector point increases, even with increased forest areas as in scenario IX. If paddy land is expanded up to 40% (scenario VIII), the deficit occurs more frequently, and only 30—35% of required water can be supplied at the collector point in the dry season. In scenario VI, which is oriented to the maximum paddy land development, the deficit becomes extreme, and only 25 — 30% of the required water would be available in the dry season.

A regression analysis was carried out with taking a dependent variable indicating water seufficiency (W), represented by the ratio of the sum of annual effective rainfall plus available irrigation water to crop water requirement, and three independent variables, i.e., the ratios of the areas of forest, upland and plantation to paddy land area (AF/AP, AU/AP, AO/AP). The results show good correlation in every subbasin, as indicated in Table 8.

From the standpoint of efficient water use for paddy irrigation, a landuse patern that makes the W unity is optimal. The most efficient scenarios in this regard are presented in Table 9 and Fig. 14a to 14d. From the figures it can be observed that water deficit still occurs in the second and third rice seasons. This means that even under the best conditions of landuse, insufficient water is available for paddy land in the dry season.

The results in Table 9 suggest that (a) in order to sustain the present triple paddy growing in the *Borobudur* subbasin, which occupies almost 45 percent of the subbasin, a part of the present upland should be converted into forest to restore the forest cover to the appropriate level of 20 percent; (b) in the *Duwet* subbasin, a similar conversion should be made; (c) in the *Kranggan* and *Mendut* subbasins, a large part of the tobacco areas and upland, respectively, should be afforested to restore the forest covers to 30 percent; (d) and in *Bantar* subbasin, 20 percent of the basin should be forested.

c) Matrix of alternative modes of landuse

Table 10 presents the irrigation water availability (W) and river flow regimes corresponding to each of the scenarios. So far as the availability of water for paddy irrigation is concerned, especially in the first and second rice growing seasons, the maximum allowable percentage of paddy land is 30% (scenario IX) in the *Kranggan* and *Mendut* subbasins, 40% (scenario VIII) in the *Bantar* subbasin. On the other hand, paddy land can be expanded up to 50 percent of the basin in the *Borobudur* and the *Duwet* subbasins (scenario VI). However, as discussed in the previous section, for the third rice crop, grown in the dry season, the water available can sustain cropping of only 25 — 30 percent of the paddy land, beyond which water deficiency becomes serious.

Expansion of the paddy land to the maximum allowable extent as indicated in Table 10 will affect the river flow regime in term of the maximum flow in the high water season, the minimum flow in the dry period, and the annual discharge. This in turn will affect the downstream water users, the majority of whom are also farmers.

V. Conclusion

The proposed hydrological simulation model, the *Trophydsim-1*, which was created based on a series of four storages for simulating run-off processes in different landuse types, has been applied to predict the run-off of the five subbasins of the *Kali Progo* basin in Central Java, Indonesia. Of the 18 parameters in the model, 10 were optimized automatically to achieve the best fitness in five different tests of fitness. These were then allocated optimally to the five landuse types, namely, forest, upland, plantations, paddy land, and settlements. The model was then tested and proved useful as an operational tool for predicting water regimes under different and changed landuses.

The hydrological regime simulated by the above processes revealed certain characteristics peculiar to this area. The *Kali Progo* basin, which is mainly comprised of fresh volcanic formations, is capable of storing much water and releasing it gradually as base flow. The flow, ranging from a low of 0.05 ton to a high of 0.1 $m^3/sec/km^2$, was 10—15 times more than that of river basins with non-volcanic geological formations, for example, the *Kizu* river subbasin of the *Yodo* river and others in Western Japan, and almost equivalent to those of basins in Japan that consist of fresh volcanic substances. This peculiar basin characteristic provides stable low flows for irrigating multiple cropping patterns of rice-rice-upland crops or even rice-rice-rice. Paddy lands have expanded amazingly to occupy as much as 40 to 60 percent of the whole river basin. Even in the long dry season almost 30 — 40 percent of the paddy lands are kept irrigated by either diverting local small streams or the main river, despite the fact that forest cover is extremely poor, being as low as 7 — 20 percent.

Application of the model for evaluating the hydrological consequences of different modes of watershed management, or simply different landuse pattern, in the same river basin, performed that the model is sensitive enough as a hydrology simulator to predict the effect of rapid changes of landuse pattern on water regime. The hydrological implications of landuse management in the river basin due to changes in landuse patterns manifested by the irrigation water availability and river flow regime are presented. This hidrological simulation model therefore affords decision makers a useful tool with which to plan proper landuse and appropriate watershed management.

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Table 1. **Postulated and optimized parameters**

Hydrologic processes	Postulated	Optimized
Interception	SI	—
Throughfall	CTRF	—
Soil moisture	WP, FC, SAT	—
Direct runoff into river channel	—	CDR
Depression storage	SDC	—
Infiltration	CK	CIFf, CIFe
Instantaneous Unit Hydrograph: *)		
a. IUH_g (I)		
b. IUH_m (I)	m	k
c. IUH_n (I)	n	K
Overland flow routing**)	—	C_0, C_1, C_2
Subsurface flow	—	CS
Groundwater addition	—	CGA
Base flow	—	CB

*) one of three methods (a, b, and c)
**) using Muskingum method

Table 2. **Accuracy of simulated and observed hydrograph in every subbasin**

Statistical measures	Kranggan			Mendut			Borobudur			Duwet			Bantar		
	1977	1981	1985	1977	1981	1985	1977	1981	1985	1977	1981	1985	1977	1981	1985
SE	0.84	1.66	1.13	1.23	1.38	1.07	0.86	*)	0.91	*)	0.76	0.95	1.12	0.98	*)
CC	0.98	0.83	0.92	0.93	0.83	0.93	0.94	*)	0.91	*)	0.95	0.93	0.91	0.91	*)
CD	0.95	0.67	0.84	0.85	0.60	0.84	0.85	*)	0.75	*)	0.89	0.82	0.81	0.79	*)
r	0.95	0.79	0.88	0.89	0.77	0.88	0.92	*)	0.89	*)	0.93	0.92	0.91	0.90	*)
WM	0.83	0.74	0.78	0.87	0.67	0.85	0.84	*)	0.76	*)	0.90	0.91	0.86	0.80	*)
MB	−1.68	−0.52	−0.28	4.92	−0.67	3.69	−8.09	*)	−0.62	*)	3.73	3.73	−5.58	0.57	*)

Notes: SE is standard error, CC is coefficient of correlation, CD is coefficient of determination, r is Pearson moment, WM is weighted moment and MB is mass balance. *) no observed data.

Table 3. **Annual discharge components, surface runoff and basin storage coefficient**

Landuse Type	R (mm)	Qd (mm)	Qo (mm)	Qs (mm)	Qb (mm)	Co	Cb	Eta (mm)	Storage (mm)
Kranggan									
Forest	2724	85	210	91	1211	0.077	0.445	804	+ 323
Upland	2724	136	1200	36	440	0.441	0.162	638	+ 174
Plantation	2724	119	1538	0	406	0.565	0.149	731	— 67
Paddy land	3280	153	1158	42	672	0.425	0.247	1076	+ 180
Settlement	2724	238	2123	0	265	0.779	0.097	366	— 267
Subbasin	2724	124	1041	33	585	0.382	0.215	845	+ 96
Mendut									
Forest	2502	69	114	38	1351	0.046	0.613	804	+ 127
Upland	2502	110	911	12	500	0.364	0.227	638	+ 332
Plantation	2502	96	1192	0	714	0.476	0.324	731	— 230
Paddy land	3589	124	1009	14	958	0.403	0.435	1076	+ 109
Settlement	2502	192	1690	0	525	0.675	0.238	366	— 270
Subbasin	2502	107	867	11	640	0.377	0.291	770	+ 107
Borobudur									
Forest	2415	69	134	51	1285	0.055	0.532	804	+ 72
Upland	2415	110	933	0	459	0.386	0.190	638	+ 275
Plantation	2415	97	1212	0	647	0.502	0.268	731	— 272
Paddy land	4001	124	1494	68	1004	0.373	0.251	1076	+ 235
Settlement	2415	193	1709	0	471	0.708	0.195	366	— 324
Subbasin	2415	87	910	27	532	0.377	0.220	845	+ 14
Borobudur basin	2547	104	935	24	581	0.367	0.228	799	+ 104
Duwet									
Forest	2174	69	110	49	1129	0.051	0.519	804	+ 13
Upland	2174	110	762	0	391	0.350	0.180	638	+ 273
Plantation	2174	97	1004	0	607	0.462	0.279	731	— 265
Paddy land	3307	124	1045	42	926	0.316	0.280	1076	+ 94
Settlement	2174	193	1436	0	464	0.660	0.213	366	— 285
Subbasin	2174	98	755	17	516	0.347	0.237	767	+ 21
Duwet basin	2361	103	703	22	569	0.298	0.241	793	+ 171
Bantar									
Forest	0	0	0	0	0	0	0	0	0
Upland	2229	110	574	0	697	0.258	0.313	638	+ 210
Plantation	0	0	0	0	0	0	0	0	0
Paddy land	2991	124	675	10	1276	0.226	0.427	1076	— 170
Settlement	2229	193	1153	0	845	0.517	0.379	366	— 328
Subbasin	2229	119	677	4	826	0.304	0.371	725	— 122
River basin	2295	105	699	20	607	0.305	0.264	784	+ 80

Notes: R is rainfall; for paddy land R is rainfall + irrigation; Qd, Qo, Qs, Qb is direct rainfall on the river channel, surface run-off sub surface run-off, and base flow, respectively

Table 4. **Low flows in Javanese and Japanese river basins**

No.	Basin	Basin area (km2)	Forest area (%)	Minimum flow mm/day	Minimum flow m3/sec	Minimum flow m3/sec/km2	Geological formation
1.	Mendut	438	5	8.6	2	0.1	Fresh volcanic deposit
2.	Kranggan	415	20	4.1—6.2	4—6	0.048—0.071	Old volcanic deposit
3.	Kizu*)	1469	88	0.5	8	0.006	Mixed formations**)
4.	Ayusawa***)	186	—	5—6	11—13	0.058—0.069	Quarternary volcanic rocks
5.	Daiya	200	—	3—6	7—13	0.035—0.069	Quarternary volcanic rocks
6.	Manza	59	—	2.5—4	2—3	0.029—0.046	Quarternary volcanic rocks
7.	Yamada	84	—	1.7	1.7	0.02	Tertiary volcanic rocks
8.	Kinu	70	—	1.6	1.2	0.019	Tertiary volcanic rocks
9.	Huehuki	66	—	1.9	1.5	0.022	Granitic rocks
10.	Hori	48	—	1.4	0.8	0.016	Granitic rocks
11.	Katsuno	48	—	0.7	0.4	0.008	Mesozonic/paleozoic
12.	Kanna	305	—	0.7	2.5	0.008	Mesozoic/paleozoic
13.	Ana	927	—	0.6	6.4	0.007	Mesozoic/paleozoic

Notes:

*) The Kizulow flow was computed by the Trophydsim-1 model for 1964.

**) The geologic formation of consolidated clastic sediments (*sandstone siltstone, shale, conglomerat*)

***) The following ten river basins are after Musiake, K. et al. (1975). The basins are mainly covered by forest. 1. Kali Progo river system at Mendut: 2. Kali Progo river system at Kranggan; 3. Kizu river in Yodo river system at Kamo; 4. Ayusawa river in Sakawa river system at Ikudo; 5. Daiya river in Tone river system at Shinkyoshita; 6. Manza river in Tone river system at Manza; 7. Yamada river in Tone river system at Sima; 8. Kinu river in Tone river system at Kawasata; 9. Huehuki river in Huzi river system at Hirose; 10. Hori river in Gokase river system at Horigawa; 11. Katsuno river in Sagami river system at Katsunogawa; 12. Kanna river in Tone river system at Sakahara; 13. Ara river in Yorii river system at Yorii.

Table 5. **Percentage of landuse patterns in each subbasin in 1981**

Subbasin	Forest (%)	Paddy (%)	Upland (%)	Plantation (%)	Settlement (%)	Total (%)	Total km2
Kranggan	20	40	5	24	11	100	415
Mendut	4	44	38	2	12	100	438
Borobudur	7	45	33	1	14	100	566
Duwet	4	49	26	1	20	100	310
Bantar	0	59	19	0	22	100	298
Kali Progo	8	46	25	6	15	100	2027

Table 6. **Model scenarios**

Unit: %

Scenario	Forest	Paddy	Upland	Plantation	Settlement	Total
			Extreme scenarios			
I	80	7.5	5	2.5	5	100
II	2.5	80	7.5	5	5	100
III	5	2.5	80	5	7.5	100
IV	7.5	5	5	80	2.5	100
V	5	5	2.5	7.5	80	100
			Realistic scenarios			
VI	10	50	17.5	20	2.5	100
VII	10	10	57.5	20	2.5	100
VIII	20	40	17.5	20	2.5	100
IX	30	30	17.5	20	2.5	100

Table 7. **Typical changes in annual, maximum and minimum discharge in the *Kranggan* subbasin in the extreme scenarios**

Extreme Scenario	Changes in Discharge, %		
	Annual	Maximum	Minimum
I	— 1	— 28	+ 43
II	— 19	— 20	— 35
III	+ 35	+ 57	— 14
IV	+ 29	+ 97	— 40
V	+ 28	+ 37	+ 4

Table 8. **Correlation between W and AF/AP, AU/AP and AO/AP**

Subbasin	Equation	r^2
Kranggan	$W = 0.06005^{*}(AF/AP) + 0.00561^{*}(AU/AP) + 0.06101^{*}(AO/AP)$	0.92
Mendut	$W = 0.00070^{*}(AF/AP) + 0.07847^{*}(AU/AP) - 0.06101^{*}(AO/AP)$	0.86
Borobudur	$W = -0.00153^{*}(AF/AP) + 0.05971^{*}(AU/AP) + 0.00267^{*}(AO/AP)$	0.74
Duwet	$W = 0.01723^{*}(AF/AP) + 0.11815^{*}(AU/AP) - 0.01669^{*}(AO/AP)$	0.85
Bantar	$W = -0.03417^{*}(AF/AP) + 0.10811^{*}(AU/AP) + 0.02615^{*}(AO/AP)$	0.89

Table 9. **The best scenario regarding water availability for paddy land**

Subbasin	W	AF/AP	AU/AP	AO/AP	RP	Scenario	GCP
Kranggan	0.96	1	0.58	0.08	0.3	IX	rru
Mendut	1.02	1	0.58	0.08	0.3	IX	rru
Borobudur	1.49	0.2	0.35	0.05	0.5	VI	rrr
Duwet	1.04	0.2	0.35	0 05	0.5	VI	rru
Bantar	0.99	0.5	0.60	0.06	0.4	VIII	rru
Kali Progo	1.08	0.48	0.46	0.06	0.4		

Notes: W = ratio of the sum of annual effective rainfall + irrigation water to water requirement for crops

GCP = general cropping pattern, rru = rice-rice-up land crops, rrr = rice-rice-rice

RP = ratio of paddy land area to total subbasin area

Table 10. **The consequences of the alternative scenarios on irrigation water availability and river flow regime**

Transfer Point At	Scenario	W in Subbasin	Discharge change in %		
			Max	Min	Annual
Kranggan	VI	0.80	+ 11	+ 11	+ 15
	VII	1.05	+ 48	— 13	+ 36
	VIII	0.87	+ 8	+ 11	+ 13
	IX	0.96	+ 5	+ 10	+ 11
Mendut	VI	0.87	— 2	— 2	— 3
	VII	2.16	+ 34	— 6	+ 11
	VIII	0.93	— 3	— 3	— 3
	IX	1.02	— 4	— 4	— 3
Borobudur	VI	1.49	+ 9	— 11	+ 5
	VII	2.60	+ 49	— 11	+ 32
	VIII	1.61	+ 8	— 8	+ 5
	IX	1.66	+ 8	— 5	+ 6
Duwet	VI	1.04	+ 9	— 29	+ 4
	VII	3.05	+ 45	— 27	+ 30
	VIII	1.17	+ 7	— 18	+ 5
	IX	1.32	+ 6	— 3	+ 7
Bantar	VI	0.89	+ 6	— 15	— 1
	VII	2.54	+ 36	— 11	+ 21
	VIII	0.99	+ 3	— 20	— 1
	IX	0.89	+ 1	— 24	— 2

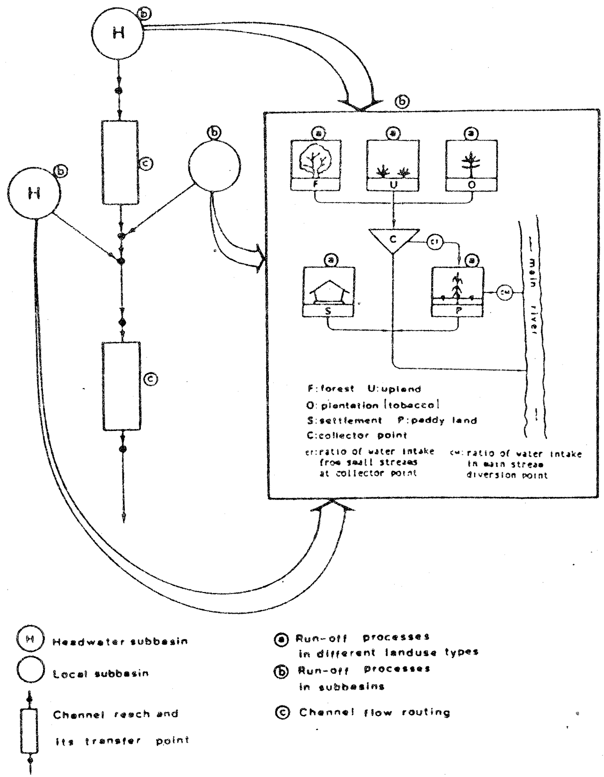


Figure 1: Schematic representation of three basic components of a river basin

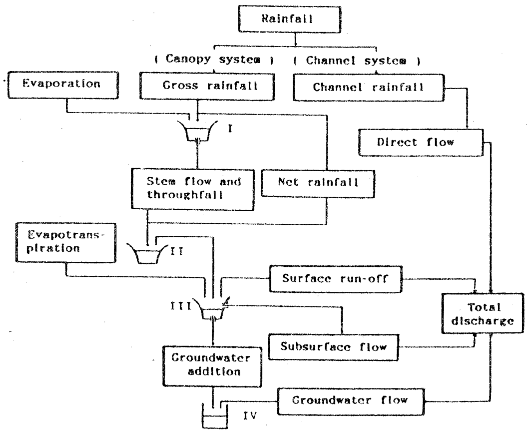


Figure 2: Concept of hydrological phenomena in each landuse type

I: interception storage II: depression storage
III: upper-zone storage IV: lower-zone storage

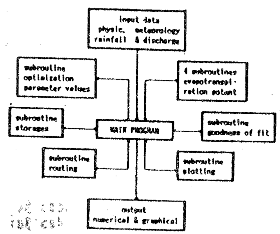
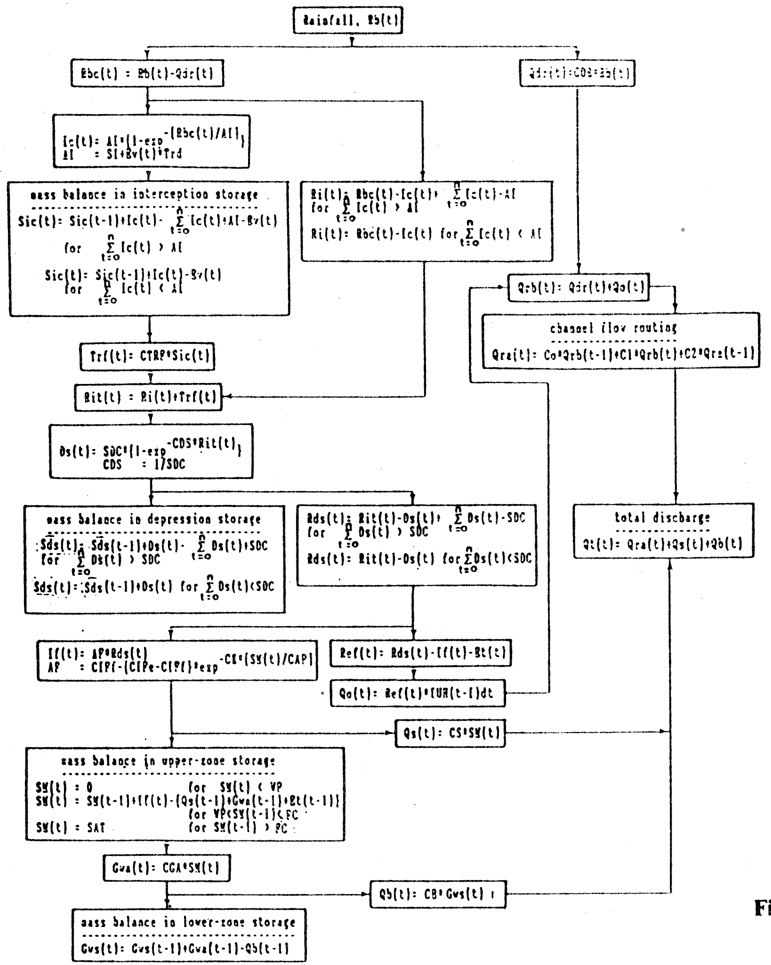


Figure 4: Model organization



AF = fraction of gross rainfall minus depression storage Rds(t) infiltrating into the ground
AI = interception storage capacity
CAP = maximum possible infiltrating storage; CAP is equal to SAT
CB = soil parameter which controls Qb(t)
CGA = soil parameter which controls Gwa(t)
CDR = river parameter which controls Qdr(t)
CIFe = infiltrating capacity when the existing infiltration storage is empty
CIFf = infiltrating capacity when the existing infiltration storage is full
CK = non-negative constant
CS = soil parameter which controls Qs(t)
CTRF = plant parameter which controls Trf(t)
C_0, C_1, C_2 = overland-flow routing constants of the Muskingum method

CDS = soil parameter which controls the rate of decrease in depression storage
Ds(t) = contribution to depression storage during time period t
Et(t) = evapotranspiration for specific crops during time period t
Eto(t) = potential Et(t) during time period t
Ev(t) = evaporation during time period t
FC = soil moisture at field capacity
Gwa(t) = groundwater addition during time period t
Gws(t) = groundwater or lower-zone storage at the end of time period t
Ic(t) = interception during time period t
If(t) = infiltration during time period t
IUH = instantaneous unit hydrograph
Qb(t) = base flow or groundwater during time period t
Qdr(t) = direct rainfall into river channel during time period t
Qo(t) = surface run-off during time period t
Qra(t) = discharge in the stream after routing during period t
Qrb(t) = discharge in the stream before routing during period t
Qs(t) = subsurface run-off during time period t
Qt(t) = total flow during period t
Rb(t) = basin rainfall during period t
Rbc(t) = basin rainfall minus direct rainfall into river channel during time period t
Rds(t) = gross rainfall minus interception and depression storage at the end of time period t
Ri(t) = gross rainfall minus interception rate at the end of time period t
Ref(t) = effective rainfall; gross rainfall minus infiltration and evapotranspiration at the end of time period t
Rit(t) = Ri(t) plus throughfall at the end of period t
SAT = soil moisture in saturated condition
SDC = depression storage capacity
Sds(t) = depression storage at the end of time period t
SI = projection of interception capacity per unit area
Sic(t) = interception storage at the end of time period t
SM(t) = soil moisture at the end of time period t
Sds(t) = upper-zone storage at the end of time period t
Trd = duration of rainfall, day
Trf(t) = throughfall during time period t
WP = soil moisture at wilting point

Figure 3: Schematic flow chart for obtaining hydrographs in each kind of landuse type

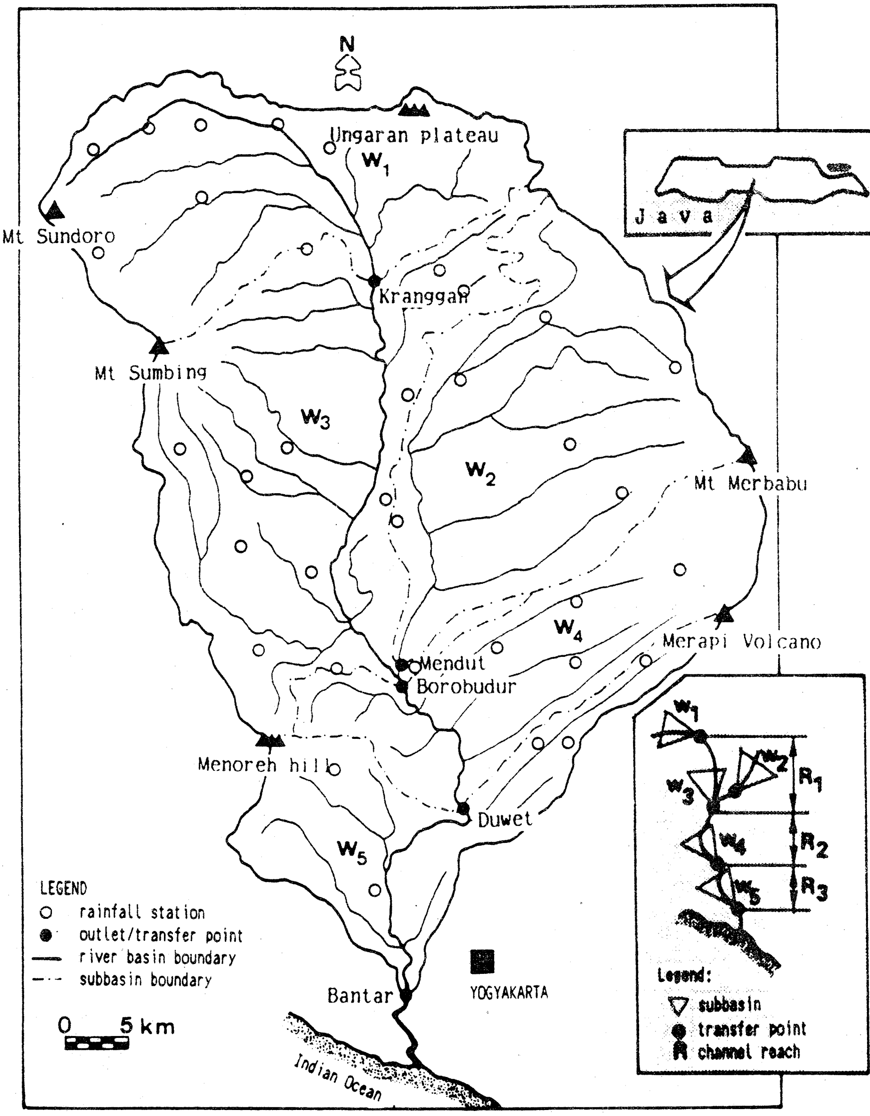


Figure 5: Kali Progo river basin and its subbasin