Surface Runoff Modelling in Ungauged Subcatchments of the Mae Chaem Catchment, Northern Thailand: Part II, First Pass Approach

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Abstract This paper presents results of streamflow modelling in 'ungauged' subcatchments of the Mae Chaem catchment located in the headwaters of the Ping River, Northern Thailand. The methodology for ungauged catchments described in the companion paper (Schreider and Jakeman, 1999) is based on the principle of spatial disaggregation of streamflow according to a terrain soil wetness index calculated in each subcatchment considered. The core of this first pass approach is that each subcatchment is considered as one grid cell where the terrain soil wetness index is computed. The approach was implemented in the Huai Phung (1180 km^2) and Mae Mu (68.5 km^2) subcatchments of the Mae Chaem catchment (2157 km^2). The model testing performed in these two subcatchments, where the modelled streamflow was compared with the measured data, showed that the first pass approach provides an accuracy of 13-17% in terms of relative error for a monthly time step. An irrigation diversion module was developed for estimating water consumption in the catchments. Its application provided a considerable improvement in model performance for the area considered.

1. Disaggregation

The 'first pass approach' developed here is based on the major assumption that soil wetness index in the 'ungauged' subcatchment of interest can be computed using integral terrain characteristics of the subcatchment without calculating these characteristics for a set of grid cells constituting this subcatchment. The precision of this 'first pass approach' will be evaluated using the testing procedures described in Section 6 of the companion paper (Schreider and Jakeman, 1999). Note that the 'ungauged' catchments selected here (Huai Phung and Mae Mu) are actually gauged so that the approach can be tested.

An essential problem is how to estimate the soil transmissivity (T) used for calculating a wetness index (see Equation 5, Section 5 in Schreider and Jakeman, 1999). No particular data on soil transmissivity in the Mae Chaem catchment is available now. Thus, the assumption made for the first pass approach tested here is that transmissivity is constant over the whole catchment.

Another simplification of the methodology suggested in Schreider and Jakeman (1999) is that the volumetric coefficient of catchment storage in the non-linear loss module of the IHACRES model (Equation 4 in Schreider and Jakeman, 1999) is scaled using the ratio of area of the catchment and tangent of its mean slope:

$$C\frac{a}{tg(\phi)} = c\frac{A}{tg(\Phi)} \qquad (1)$$

Here c is a value of this volumetric coefficient for the non-linear module employed for simulating streamflow in the subcatchment, a is the area of this subcatchment and ϕ is its mean slope. A, C and Φ are the values of these parameters for the entire catchment (Kong Kan is used here). The logarithmic function has been excluded from this equation because the soil wetness distribution with depth is not considered in this algorithm (Quinn *et al.*, 1995).

An alternative disaggregation procedure is to scale the soil moisture index $s(k)$ from the non-linear model of IHACRES using the wetness index for each subcatchment. This method allows streamflow in the subcatchments of the Mae Chaem catchment to be simulated without using the parameters of the non-linear module, τ_w, f and c, optimised in the larger Kong Kan catchment. The soil moisture coefficient $s(k)$, obtained during the streamflow calibration in the whole Kong Kan catchment, can be scaled according to the terrain soil wetness index for each subcatchment and then used for streamflow simulation in this subcatchment. In this case the loss module of the IHACRES model is reduced for simulation of effective rainfall to one equation:

$$u(k) = r(k)\,(s(k) + s(k-1))/2. \qquad (2)$$

The linear model is applied as before to derive streamflow from effective rainfall $u(k)$.

2. Irrigation

Two significant simplifications applied in the present work are:

1. dry season irrigated crops are grown only on the paddy fields, and
2. the data provided by the Royal Irrigation Department (RID) on long term average values for irrigation demands, calculated for the central part of Thailand, are relevant for the Mae Chaem area located in Northern Thailand.

The irrigation consumption data for all type of crops, obtained from the RID, can be found in Schreider *et al.* (1999). Table 1 presents a simplified version of these data, where the consumption values were rounded to 50 mm. Onion, garlic, soybean, tobacco, barley, melon, groundnuts, cabbage and other vegetables, having similar irrigation demands, are united as one class of cash crops.

Table 1 Average monthly irrigation water demand (in mm) used in the irrigation consumption module

Month	Wet season rice (wr)	Dry season rice (dr)	Cash crops (cc)	Fruit trees (ft)
Jan	0	250	150	100
Feb	0	200	150	100
Mar	0	200	100	150
Apr	0	0	0	150
May	250	0	0	50
Jun	300	0	0	50
Jul	350	0	0	50
Aug	150	0	0	0
Sep	50	0	0	0
Oct	50	0	0	0
Nov	0	300	300	50
Dec	0	500	100	50

The GIS data required for this 'first pass approach' to streamflow modelling are summarised in Table 2. Despite the total irrigated area in the Mae Chaem catchment reaching only one percent of total catchment size, the irrigation consumption in the catchment can be very significant. The water requirement for irrigation for two possible land use scenarios in 1995 are illustrated in Figure 1. The 'maximum consumption' scenario corresponds to rice growing on 100% of paddy area during both the wet and dry seasons ($\lambda = 1$, $\mu_1 = 1$ *and* $\mu_2 = 0$). The 'medium consumption' scenario represents the rice grown on 50% of paddy areas during the wet season and cash crops grown in 50% of paddy areas during the dry season ($\lambda = 0.5$, $\mu_1 = 0$ *and* $\mu_2 = 0.5$).

In the 'first pass approach' modelling the irrigation consumption for orchards is neglected for two reasons. Firstly, no data on the area under these kinds of crops are available. Secondly, analysis of topographic maps for this catchment indicates that area allocated to orchards is not significant in the Mae Chaem catchment. Therefore, the irrigation diversion, in month i, for the 'first pass approach' modelling in the selected year can be calculated in the wet season as (see Section 3 of Schreider and Jakeman, 1999):

$$d_i = \lambda\, wr_i\, Sp \quad (i = Jun, July, \ldots, Oct),$$

where λ $(0 \le \lambda \le 1)$ is a proportion of total paddy area (Sp) covered by wet rice with irrigation demand (wr_i) as shown in Table 1. During the dry season monthly irrigation diversion is calculated as:

$$d_i = (\mu_1\, dr_i + \mu_2\, cc_i)\, Sp \quad (i = Nov, Dec, \ldots, Mar),$$

where, μ_1 *and* μ_2 $(0 \le \mu_1 + \mu_2 \le 1)$, are the proportion of the total paddy area (Sp) covered by dry season rice, with monthly irrigation demand dr_i, and cash crops, with monthly irrigation demand cc_i, respectively. The daily streamflow diversion is calculated according to the algorithm described in Section 3 of Schreider and Jakeman (1999) and the natural flow is restored using Equation 3 from the same Section.

3. Calibration and testing

The calibration is performed for a one year period starting 1st January 1994[1]. Then, the model was tested using the Type 1 test (see Section 6 in

[1] No temperature data were available for the period of 1995. The previous year was calibrated under assumption that in 1994 the land use patterns were the same as in 1995.

Schreider and Jakeman, 1999) for other periods in the Kong Kan catchment.

Table 2 The characteristics of subcatchments used in the streamflow modelling

Sub-catchment	Area (km^2)	Mean slope (°)	Total area under irrigation by year (km^2)		
			1985	1990	1995
Mae Chaem at Kong Kan	2157	19.0	11.8	18.6	20.1
Mae Chaem at Huai Phung	1180	18.5	8.3	12.5	13.5
Mae Mu at Mae Mu	68.5	14.3	0	0	0

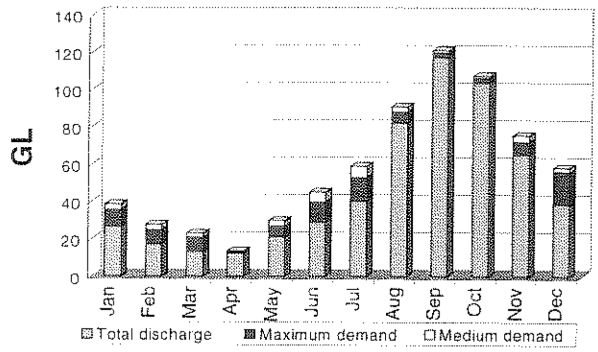

Figure 1 Mean monthly discharge in the Mae Chaem catchment at the Kong Kan station and plausible irrigation diversions for two land use scenarios in 1995

Model tests of Type 2 (see Section 6 in Schreider and Jakeman, 1999) were performed for two gauged sites in the Mae Chaem catchment: Mae Mu and Huai Phung. The results of model simulation performed with and without the irrigation consumption module were compared. The simulations of natural streamflow (simulation of Type 1) were performed for four nodes of the Mae Uam subcatchment. The calibration was implemented on a daily basis, whereas model simulation results were aggregated to the monthly time step.

3.1 Calibration of whole catchment

The results of model calibration for the Kong Kan catchment are presented in Table 3. Table 2 shows that the areas under paddy fields remain similar in the 1990-95 period. The calibration was implemented for five one year periods in 1990-94; period 1995 was not considered because the temperature data were not available in this year. Table 3 illustrates the calibration results for these four calibration periods. The quality of the model calibration was estimated using the Nash – Sutcliffe (1970) efficiency R^2 and bias (mean daily error). Figure 2 illustrates graphically the model calibration for 1994.

Table 3 Calibration results for the Mae Chaem catchment at Kong Kan for 'no irrigation' and 'medium irrigation diversion' scenarios

Year of calibration	No irrigation diversion		'Medium' irrigation diversion	
	R^2	Bias (cumecs)	R^2	Bias (cumecs)
1990	0.655	-2.32	0.680	-2.05
1991	0.763	-0.14	0.759	0.03
1992	0.609	-1.43	0.614	-0.71
1993	0.619	-1.73	0.675	-1.46
1994	0.877	-1.31	0.882	-1.13

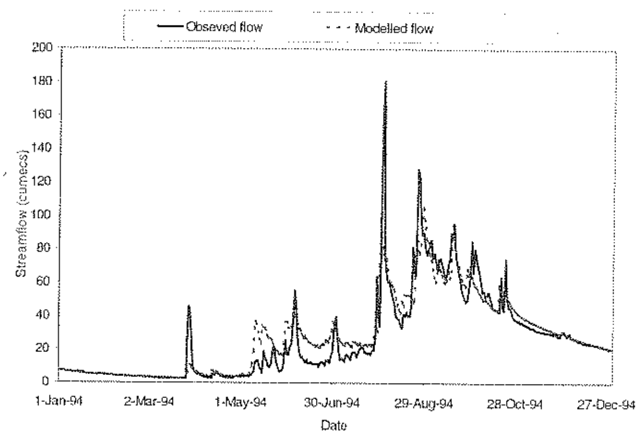

Figure 2 Calibration results for the Mae Chaem catchment at Kong Kan ('medium' irrigation diversion scenario)

Results of the monthly modelling were estimated using the mean monthly absolute error E and mean relative error R. These errors are computed for each month $(i=1,2,\ldots,12)$,

$$E_i = \frac{1}{n}\sum_{j=1}^{n} abs(q_i^j - y_i^j),$$

with mean value E calculated as:

$$E = \frac{1}{12}\sum_{i=1}^{12} E_i$$

Here n is the number of years when the modelled streamflow (y) is compared with the measured values (q).

Similarly,

$$R_i = \frac{1}{n}\sum_{j=1}^{n} \frac{abs(q_i^j - y_i^j)}{q_i^j},$$

$$R = \frac{1}{12}\sum_{i=1}^{12} R_i$$

Monthly streamflow values for the model calibration in 1994 for the 'no irrigation' and 'medium irrigation' scenarios are shown in Figure 3. The mean monthly absolute errors E for these scenarios are 9500 ML/month and 8600 ML/month, respectively, whereas the values for mean relative errors are 24% and 23%.

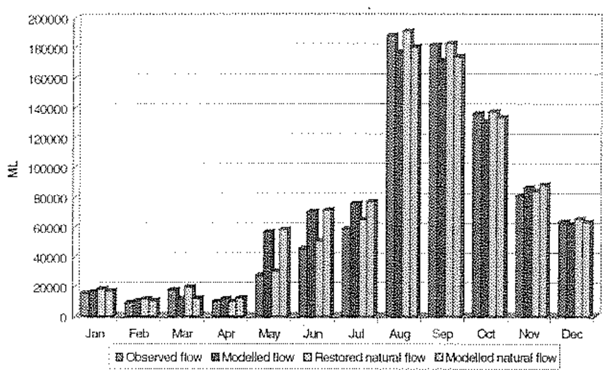

Figure 3 Monthly streamflow for model calibration run of the Kong Kan site in 1994. The 'no irrigation' (observed and modelled flow) and 'medium' irrigation diversion (restored natural and modelled flow) scenarios were considered

3.2 Testing of whole-catchment calibration

The model parameters calibrated in 1994 were used for modelling streamflow for the six-year period of 1989-94 when the areas under irrigated crops, hence the water consumption for irrigation, can be assumed to remain reasonably constant (see Table 2). Percent of explained variance (Nash-Sutcliffe statistics) is 0.73 calculated on a monthly basis for the 'no irrigation' diversion scenario and 0.74 for the 'medium irrigation' diversion case. Mean relative error reaches values of 30% and 22%, respectively. Mean monthly absolute error, calculated for these model tests, is 10300 ML/month ('no irrigation' diversion) and 8800 ML/month ('medium irrigation' diversion). The mean annual relative error are low, at 8% and 5% for these scenarios, respectively. This model test for medium irrigation diversion is illustrated in Figure 4.

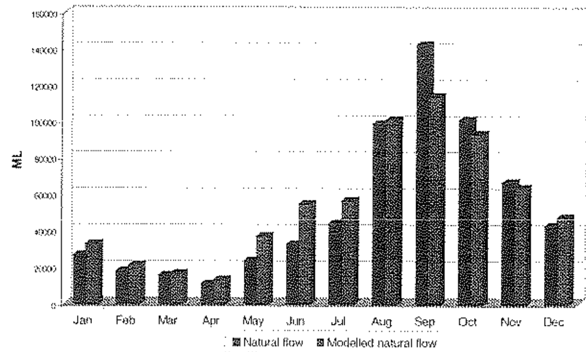

Figure 4 Model testing results for the Mae Chaem in Kong Kan. The model is applied for the period 1989-94 for the 'medium' irrigation diversion

4. Disaggregation results

4.1 Disaggregation using volumetric coefficient c

The streamflow disaggregation procedure was employed for streamflow modelling in two instrumented subcatchments: Mae Mu and Huai Phung using the method in equation (1). This test was also implemented for the 'no irrigation' and 'medium irrigation' cases. The mean relative errors and monthly residuals for this model test are summarised in Table 4. Figures 5 and 6 show the mean monthly observed and modelled discharge for the Huai Phung and Mae Mu subcatchments simulated using the model parameters estimated in the Kong Kan catchment for the 'medium irrigation' scenario.

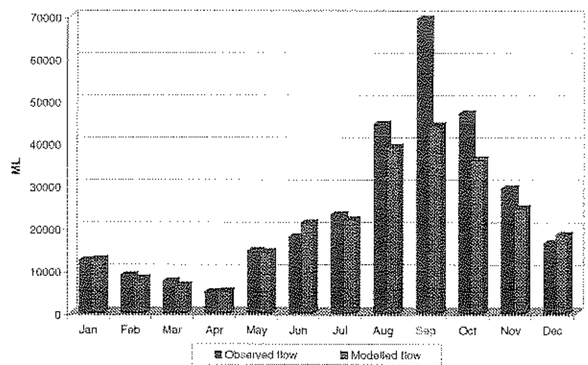

Figure 5 Results of streamflow modelling based on the disaggregation procedure for the Huai Phung subcatchment and observed average monthly discharge for the period of 1989-94

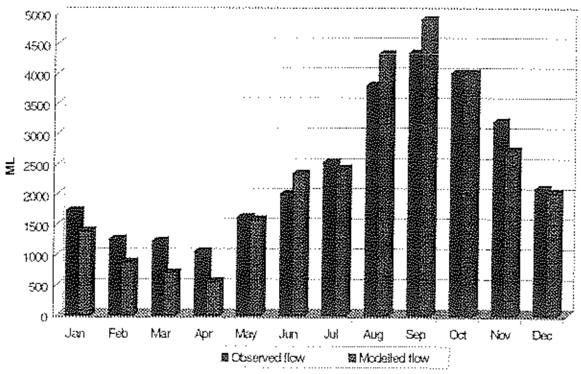

Figure 6 Results of streamflow modelling based on the disaggregation procedure for the Mae Mu subcatchment and observed average monthly discharge for the period of 1989-94

Table 4 Errors of the flow disaggregation procedure for two subcatchments in the Mae Chaem catchment (model test 2)

Sub-catchment	Irrigation diversion scenario	Mean monthly relative error (%)	Mean annual relative error (%)	Mean monthly absolute error (ML)
Mae Chaem at Huai Phung	no irrigation	16	10	4800
	medium irrigation	13	15	4600
Mae Mu at Ban Mae Mu	no irrigation	18	5	330
	medium irrigation	17	3	320

4.2 Disaggregation using soil moisture index s_k

This test was performed for the Mae Mu subcatchment, utilising the approach of equation (2). Comparison of the simulated streamflow with the streamflow records for the period 1989-94 provided values for the mean monthly and annual relative errors of 18% and 6.5%, respectively. The average monthly absolute error was 330 ML/month. Figure 7 graphically illustrates the performance of streamflow modelling based on this algorithm and demonstrates that qualitatively the model's predictive patterns are much the same as for the model obtained using the volumetric constant c (cf. Figure 6).

5. Discussion and conclusions

The methodology of surface runoff modelling in ungauged catchments suggested in the companion paper (Schreider and Jakeman, 1999) has been applied and tested in the present paper. The algorithm of catchment discharge disaggregation to subcatchment level is based on the assumption that the streamflow yield in each subcatchment is proportional to a terrain soil wetness index calculated in this subcatchment. The data requirements and limitations of the proposed algorithm are discussed. The relationship between the scaling issues and model precision is considered. The proposed methodology contributes to the development of the general concept of regionalisation in hydrology.

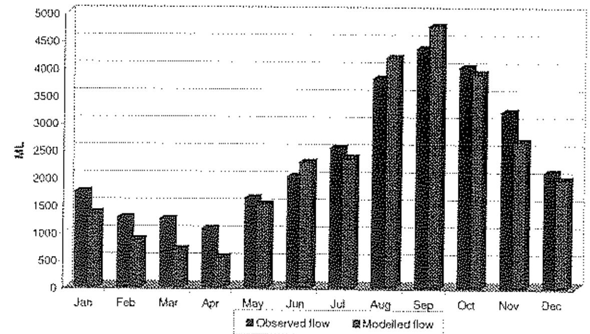

Figure 7 Observed and simulated streamflow modelling based on the scaling of the IHACRES soil wetness coefficient for the Mae Mu subcatchment and observed average monthly discharge for the period of 1989-94.

The major limitation of the algorithm developed in the present work is that the scaling is restricted to the non-linear module of the IHACRES model. The rates of recession of quick and slow flow components α_q and α_s (see Section 4 of Schreider and Jakeman, 1999) are quite different for different subcatchments, but are assumed the same in the linear component of the IHACRES model in this work. Subcatchments in the higher part of the catchment have flatter recession rates for the dry season than subcatchments with lower mean elevation. The dry season streamflow in the Mae Mu subcatchment (Figure 6) is consistently underestimated because the recession of dry season streamflow in the Kong Kan catchment, which was scaled for modelling of the Mae Mu subcatchment, is steeper than that in the Mae Mu subcatchment. A possible explanation of this difference in the recession rates of dry season flow is that the catchments located in the higher areas are mist-fed during the dry season of the year. This means that during the dry season direct moisture exchange is possible between the high mountainous areas and clouds concentrating on the mountain slopes. The location of perennial swampy rainforests[2] on the ridges around Mount Doi Inthanon (2500 m ASL) is additional justification that such mist-fed humidity can play a significant role in the water balance in highly elevated subcatchments.

The results of the first pass approach to streamflow modelling described here are encouraging. The relative errors for monthly streamflow modelled in the 'ungauged' subcatchments, estimated in the Mae Mu and Huai Phung subcatchments, fall in the interval of 13% - 17%. The algorithm allows one to predict the naturally regulated flow and the real discharge after irrigation diversion. The input information required for this modelling is restricted by the subcatchment area and slope for natural flow modelling and areas under different crops grown in the subcatchment for estimating the irrigation diversion.

The natural question arising here is what is the difference between the algorithm described in the present paper and the simplistic idea that streamflow discharge is contributed uniformly over the catchment area. Streamflow, when modelled using the scaling of discharge according solely to subcatchment areas, fits observed flow considerably worse than the streamflow estimated by the algorithm proposed in the present paper. The ratio of areas of the Huai Phung subcatchment and the Kong Kan catchment is very close to the ratio of their terrain soil wetness indices because these catchments have very similar slopes (Table 2). However, the difference in average slopes of the Mae Mu and Kong Kan catchments (19^{o} and 14.3^{o}, respectively) makes the values of ratios of wetness indices (0.043) and catchment areas (0.032) quite different.

The streamflow was simulated for the Mae Mu subcatchment using the c value scaled according to the catchment area for the 'medium' irrigation diversion scenario. Comparison of simulated streamflow with the observed values (model test of Type 2) provided a mean monthly relative error of 33% and a mean annual relative error of 28%. These results are significantly worse than those obtained using the c value scaled according to the terrain soil wetness index (17% for the monthly relative error and 3% for annual relative error).

[2] Results of field studies implemented in this area showed that these swamps do not dry out even during the driest months of the year.

An important component of the algorithm is an irrigation consumption module developed in the present work. The results of the first pass approach demonstrate that the application of this module provides significant improvements in the modelling results for both model calibration and tests.

The approach taken here is one possible method for linking terrain attributes with the parameters of a conceptual hydrological model such as IHACRES. There is considerable scope for further research exploring and developing these relationships. If one is interested in the daily dynamics of streamflow response, then it would be worthwhile developing relationships between the non-linear response parameters of IHACRES and terrain attributes (e.g. Post and Jakeman, 1996). If interest is solely on monthly volume predictions, then the simple first pass approach proposed here can be assessed for its effectiveness by calibrating IHACRES at a larger scale and utilising information on slope and area for the smaller ungauged catchment and the larger catchment in which it is nested.

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