Surface Runoff Modelling in Ungauged Subcatchments of the Mae Chaem Catchment, Northern Thailand: Part I, Methodology

S.Yu. Schreider[1] and A.J.Jakeman[2]
[1]Integrated Catchment Assessment and Management (ICAM) Centre and [2]Centre for Resource and Environmental Studies (CRES), The Australian National University, Canberra ACT 0200, Australia.

Abstract The present paper describes a methodology proposed for surface runoff modelling in gauged and ungauged subcatchments of Northern Thailand. Gauged catchments are modelled using calibration against measured flow data, whereas streamflow in the ungauged subcatchments is simulated by spatial disaggregation procedure utilising measured streamflow data from a larger gauged catchment in which the ungauged catchment may be nested. The disaggregation is based on the assumption that each subcatchment streamflow contribution to the total catchment yield is proportional to a terrain soil wetness index. The Mae Chaem catchment in the Upper Ping River basin was selected as a case study for applying the approach, the results of which are presented in the companion paper by Schreider *et al.* (1999b).

1. Introduction

Accurate water resource assessment in Northern Thailand is of crucial importance for sustainable agricultural development in this region as well as for resolving highland-downstream conflicts allegedly related to water overuse by highland rural communities. Fair water resource allocation is especially important during the dry season because in regions with a monsoon climate, such as Northern Thailand, the availability of water for irrigation during that season offers a prospect of growing a second crop in one year.

The major problem of accurate streamflow modelling in Thailand as well as in any developing country is that catchments under consideration are usually very poorly instrumented. For instance, the Mae Chaem catchment at Kong Kan (2157 km^2) has only three gauging stations: at Kong Kan (Station number 04061302), the 1268 km^2 catchment of the Mae Chaem River at Huai Phung (04061201) and the 70.6 km^2 Mae Mu River subcatchment at Ban Mae Mu (04061202). A map of the Mae Chaem catchment, subcatchments and station locations is presented in Figure 1.

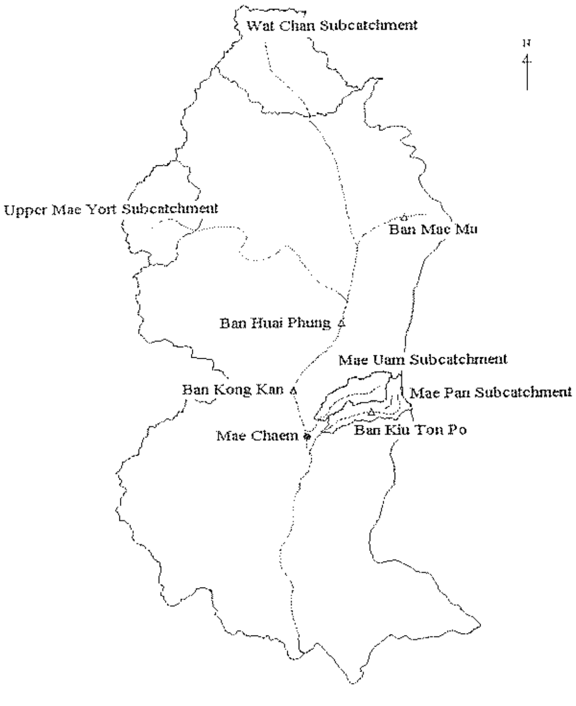

Figure 1 Map of the Mae Chaem catchment and locations of gauging stations

The major aim of this work is to develop a method of predicting streamflow in ungauged subcatchments. The algorithm proposed below is based on a spatial redistribution of streamflow yield within a catchment according to the terrain soil wetness index. The method will be tested for the gauged subcatchments of Huai Phung and Mae Mu by comparing the modelled and observed streamflow series. The suggested algorithm allows one to predict natural streamflow for each point in the Mae Chaem catchment if terrain characteristics above this point are available. The regulated flow for each village in the area could then be calculated as the difference between natural flow and irrigation diversion above this village.

An irrigation consumption module for predicting the water diversion in catchments under intensive agricultural development is introduced in Section 3. This module plays a significant role in the water balance in the Mae Chaem catchment. Apart from the modelling of historical streamflow, the model could be used for estimating water resource allocation under different climatic conditions (such as through scaling the historical input precipitation - temperature time series) and land use options (through their effect on the output of the irrigation diversion module) for each selected site in the Mae Chaem catchment.

The proposed streamflow modelling algorithm will be applied for predicting surface runoff in several subcatchments of the Mae Chaem catchment within the framework of the Integrated Water Resource Assessment and Management (IWRAM) project. Objectives and general methodology of the IWRAM project are described in more detail in Jakeman *et al.* (1997). This project is developing a Decision Support System for management of water resources in rural catchments of Northern Thailand. Four highland subcatchments of the Mae Chaem catchment (Mae Pan, Mae Yort, Mae Uam and Wat Chan) and an area in the vicinity of Mae Chaem town were selected as case studies (see Figure 1). All these subcatchments are ungauged, except Mae Pan. However, the analysis of streamflow-precipitation relationships for this subcatchment provided a runoff (to rainfall) coefficient value higher then 150%, suggesting that the streamflow rating was not calibrated properly at this station or the location of the station site, and hence the catchment area, was incorrectly mapped. Therefore, streamflow records from the Mae Pan station were not considered here.

2. Methodology

The surface runoff modelling algorithm proposed has two major steps. Firstly, a rainfall-runoff model is calibrated at the catchment outlet against the streamflow recorded at the Kong Kan station. Secondly, the modelled streamflow is calculated at each point within this catchment by disaggregation of the streamflow discharge at the catchment outlet using a terrain soil wetness index weighting.

The first step (calibration of a gauged catchment) implies an application of some model allowing one to compute the streamflow using the climatic (precipitation and temperature) input. The criterion for the model parameter optimisation is a best fit of predicted discharge to the measured values. The IHACRES rainfall-runoff model (see Section 4) in conjunction with an irrigation consumption module can be used for this purpose. In a predominantly agricultural catchment, such as Mae Chaem at Kong Kan, the only major source of water consumption is irrigation supply, which can be calculated using information on areas under different crops and the irrigation consumption data for these crops per unit area. At the catchment outlet the natural flow can be calculated as a sum of measured discharge and irrigation diversion:

$$F(k) = Q(k) + D(k), \quad (1)$$

where $F(k)$ is natural (unregulated) streamflow, $Q(k)$ is a measured streamflow (regulated discharge) and $D(k)$ is irrigation diversion at the k-th time step. The IHACRES model will be calibrated against the natural flow values $F(k)$.

The second step is based on the approach proposed in Beven and Kirkby (1979), Beven *et al.* (1984) and Quinn *et al.* (1995) for the TOPMODEL hydrological model. This approach invokes the assumption that the contribution of each part of a catchment to the total water yield is proportional to the terrain soil wetness index. It allows one to predict the natural flow $f(k)$ for each part of a catchment using just a terrain characteristic of this area within the catchment considered. Therefore, if crop irrigation data of the selected subcatchment are available, the simulated regulated discharge $q(k)$ at its outlet can be expressed as a difference between natural flow $f(k)$ and irrigation diversion $d(k)$:

$$q(k) = f(k) - d(k). \quad (2)$$

Thus the irrigation diversion module will be used for model calibration at the outlet of the gauged catchments (1). It will also be employed for restoring natural flow using the recorded discharge and the total diverted amount of water, and for the simulation of discharge in the ungauged catchments, where the regulated streamflow will be calculated as a difference between modelled natural flow and diversions as in (2).

The major components of the methodology proposed can be outlined as follows:

1. Modelling of irrigation consumption and restoration of the natural (unregulated) streamflow in the gauged catchment (Section 3),
2. Modelling of the natural flow in the gauged catchment using the IHACRES rainfall-runoff model (Section 4),
3. Modelling of natural streamflow in ungauged subcatchments of this catchment using the streamflow disaggregation procedure (Section 5). The regulated streamflow values can be computed in these subcatchments using the irrigation consumption module, and
4. Testing the model performance in smaller gauged catchments.

3. Irrigation consumption module

A water consumption module is constructed for river discharge prediction in subcatchments with intensive agricultural activities and, therefore, a significant artificial component in streamflow regime. It is based on the assumption that water consumed is defined solely by irrigation use. Thus, water consumption is calculated as a sum of products of areas under each irrigated crop and the irrigation consumption of each crop per unit of area.

Let N be the number of crop types cultivated in the catchment. One plant species grown in wet and dry seasons is considered as two different types of crops. Let c_n^m be the irrigation consumption for crop n ($n=1,2,\ldots,N$) for time step m (monthly irrigation consumption data are available, hence $m=1,2,\ldots,12$) and s_n^i be area under the n-th crop in the i-th year. The yearly differences in s_n^i values reflect the changes in agricultural practice and can represent future crop/land use development in this area. Therefore, monthly water diversion for the m-th month in year number i can be calculated as

$$d_m^i = r\sum_{n=1}^{N} c_n^m s_n^i$$

where r is a unit correction constant.

Then the regulated flow $q(k)$ can be calculated for each monthly time step as

$$q(k) = f(k) - e^{-1}\,[d_m^i(k) + P + W], \qquad (3)$$

where $f(k)$ is natural streamflow (flow value without diversion) and e is an irrigation efficiency coefficient. This coefficient is defined as a ratio of the amount of water used for irrigation to the amount of water diverted. The Royal irrigation Department of Thailand (RID) has estimated this efficiency coefficient as 0.60 for the wet season and 0.85 for the dry season. Values P and W characterise the amount of water lost due to deep percolation (P) and for land preparation in irrigated paddies (W). According to the RID information, deep percolation can be roughly estimated as 1 mm/day for wet and 1.5 mm/day for dry seasons. Land preparation in paddy fields needs 250 mm for the wet and 300 mm for the dry season.

If a monthly time step is selected for modelling then natural flow can be calculated using monthly consumption data provided by some agricultural institutions. When a daily time step is selected some additional assumptions are needed, for instance an assumption that irrigation diversion is uniform during each day of the month (that is, the daily diversion is the same for each day of the month).

4. Modelling of unregulated (natural) flow in gauged catchments

Several modelling approaches are utilised in hydrology for predicting surface runoff in instrumented catchments. Following the model classification suggested by Wheater *et al.* (1993), three major model classes can be identified: empirical, physically based and conceptual. The class of conceptual models is most appropriate for this work, because of their relative simplicity and relatively low data requirements. The conceptual rainfall-runoff model IHACRES, based on the Instantaneous Unit Hydrograph technique, can be used for streamflow modelling within the methodological framework outlined in Section 2. This model was described in Jakeman *et al.* (1990) and Jakeman and Hornberger (1993). It is based on the conception that effective rainfall passes through two parallel reservoirs: quick and slow. In catchments with monsoonal climates quick recession predominantly happens during the wet season whereas the slow flow component dominates during the dry season. Schreider *et al.* (1999a) justify the selection of IHACRES for this work as well as present the preliminarily results of streamflow modelling for gauged subcatchments of the Mae Chaem catchment.

The IHACRES model has two modules. A non-linear loss module which at each time step k (daily and monthly time steps are proposed in this work) transforms measured rainfall $r(k)$ into effective rainfall

$u(k)$ using temperature or pan evaporation data $t(k)$. The non-linear loss module is used to account for the effect of antecedent weather conditions on the current status $s(k)$ of soil moisture and vegetation conditions, and for evapotranspiration effects. Here the effective rainfall $u(k)$ is calculated from the measured rainfall $r(k)$ and temperature $t(k)$ in the catchment area by the formulae:

$$\begin{gathered} u(k) = r(k)\,(s(k) + s(k-1))/2 \\ s(k) = c\,r(k) + (1 - 1/\tau_w(t(k)))\,s(k-1) \qquad (4) \\ \tau_w(t(k)) = \tau_w\,exp(20f - t(k)f) \end{gathered}$$

The constant c is calculated so that the volume of effective rainfall is equal to the total streamflow for the calibration period. Importantly, it reflects the amount of potential storage in the catchment. τ_w and f are parameters to be optimised: τ_w is a time constant reflecting the rate of drying of the catchment at 20°C and f is a factor which modulates this rate as temperature varies.

A linear module then describes the travel of effective rainfall to streamflow $y(k)$ on the basis of a total unit hydrograph approximation. The latter module invokes a recursive relation at time step k for modelled streamflow $y(k)$, computed as a linear combination of its past values and current and past effective rainfall. The model's conceptual structure implies that the effective rainfall is considered to travel through two parallel stores. This means that the recession of streamflow is a superposition of two exponential decay functions, one of them being responsible for quick recession (recession of high flow events) and the other for recession of the slow flow component. In other words, the modelled streamflow $y(k)$ can be represented as a superposition of quick and slow components $x_q(k)$ and $x_s(k)$:

$$y(k) = x_q(k) + x_s(k),$$

where x_q and x_s decay in an exponential fashion according to:

$$\begin{gathered} x_q(k) = -\alpha_q\,x_q(k-1) + \beta_q\,u(k) \\ x_s(k) = -\alpha_s\,x_s(k-1) + \beta_s\,u(k) \end{gathered}$$

As stated previously, in regions with a monsoon climate, such as Northern Thailand, the constants α_q and α_s could be interpreted roughly as rates of wet and dry season flow recessions, respectively.

5. Streamflow disaggregation procedure

Beven and Kirkby (1979) and Beven *et al.* (1984) argue that each particular subcatchment of a catchment contributes to the total catchment yield in proportion to the terrain soil wetness index. The soil wetness index v_i is defined for each grid cell in the catchment considered as

$$v_j = ln\,[(A_j/l_j)/(tan(\phi_j)\,T_j)], \qquad (5)$$

where A_j is the drainage area above the grid cell with width l_j of the contour of the grid cell. The ϕ_j value is an average slope of the grid cell and T_j is a soil transmissivity coefficient. The soil wetness index coefficient over each subcatchment ω is computed as a mean arithmetic value of these indices calculated for each of n grid cells of the subcatchment considered:

$$\omega = \frac{1}{n}\sum_{i=1}^{n} v_i.$$

Hence, if the modelled streamflow F is known at the catchment outlet, the natural (unregulated) streamflow f for each subcatchment can be computed using an assumption that

$$f \sim F,$$

with proportionality coefficient ω/Ω, where ω is a soil wetness index in this subcatchment and Ω is a soil wetness index calculated for the entire catchment. In the methodology accepted in the present work, which employs the IHACRES model, the terrain soil wetness index is used for scaling the volumetric constant c of the non-linear loss module of the IHACRES model (See Equation 4 of Section 4).

6. Tests of model calibration and simulation

A. Calibration at the gauged catchment outlet:

The calibration procedure is implemented in two steps:

- The natural (unregulated) streamflow discharge F_i is restored for the gauged catchment (Mae Chaem at Kong Kan here) using relationship (1) from Section 2. The irrigation diversion component of the water balance is computed as stated in Section 3.
- The hydrological model (IHACRES) is calibrated against the restored values of natural flow.

B. Simulation for ungauged subcatchments:

Two possible simulation procedures can be outlined for simulating natural and regulated flow in subcatchments:

1. For each selected site in the catchment the natural streamflow is calculated by disaggregating natural flow of the entire catchment using the soil wetness index weighting.
2. The actual amount of water (regulated discharge) in this site is calculated according to Equation 2 from Section 2, using the data on areas under different irrigated crops and irrigation consumption for each crop taken into account in the irrigation consumption module from Section 3.

C. Model testing:

There are three different ways to test the model:

1. The streamflow data for the catchment outlet (Mae Chaem at Kong Kan) are simulated for a period other than one when the model was calibrated. It means the model is run with the same values of parameters, which were established during the calibration, in order to predict streamflow outside the calibration period.
2. The second test is a comparison of the simulated flow series obtained through the disaggregation procedure with the measured flow values available in some subcatchments (these are Mae Mu and Huai Phung in the case of the Mae Chaem catchment).
3. A third test can be implemented by comparing the terrain soil wetness indices calculated for gauged subcatchment and the modelled value of soil index calculated using Equation 3 from the non-linear module of IHACRES. However, some additional work is needed to develop some time-independent characteristic of the IHACRES modelled soil wetness.

7. Discussion of data requirements and the accuracy of algorithm

The data required for streamflow prediction within the methodology developed in the present work are:

- **Climate** data for the catchment considered (precipitation and temperature).
- **Streamflow** records for the larger catchment, used for the model calibration, and for some subcatchments within this catchment, are used for model testing (see Section 6).
- **Agricultural landuse** (areas under different crops) and **irrigation** consumption data. This information is used for model calibration at the catchment outlet (Kong Kan) and for streamflow simulation in the gauged subcatchments in order to implement the second test (C2) described in Section 6. Landuse data are employed for calculating areas under each crop in the subcatchments considered. More precise modelling should be based on results of a detailed survey implemented in each subcatchment under study.
- **Terrain** data required for calculation of the soil wetness indices for each selected sub-areas within the catchment.

The major problem related to climate data availability is that all these data are recorded at the meteorological stations located in the central (Mae Chaem and Kong Kan) or eastern (Mae Mu) parts of the Mae Chaem catchment. For catchments with monsoonal climates this is a significant disadvantage because during the wet season south-westerly winds prevail in this region that might cause a significant heterogeneity in the spatial distribution of rainfall within the catchment. Continuous temperature data are available at the Kong Kan meteorological station.

Land use data in the Mae Chaem catchment are available in GIS format for three time slices: in 1985, 1990 and 1995 (NRC, 1997). These data allow one to calculate areas under rice paddies and upland fields. In the sense of irrigation water use, the only functional information obtained from this GIS data is the area under paddy fields because no particular crops growing on these paddies are specified. The irrigation water use for on-slope cultivation is assumed to be negligibly small because only sprinkler irrigation in some Kmong villages is employed for irrigating such fields in the Mae Chaem catchment (results of the 1998-99 preliminary IWRAM project household survey). Sprinkler irrigation consumption is neglected in the present stage of the project (see companion paper Schreider *et al.*, 1999b) but should be taken into account in future work. More information on the cropping practice, especially about crops growing on paddy fields, will be obtained after completion of the survey in the Mae Chaem catchment.

A very important issue is resolution of grid cell size for calculation of the terrain soil wetness indices defined (Quinn *et al.*, 1995). Ideally, grid cells can have a minimal resolution allowed by the Digital Elevation Model (DEM) available for the region under consideration. In the Mae Chaem catchment it could be a resolution of 30 m x 30 m. However, the use of the finest possible resolution is very computationally demanding. The companion paper, Schreider *et al.* (1999b), presents the streamflow modelling results obtained by applying the first pass approach methodology when the subcatchments modelled are considered as one cell.

8. References

Beven, K.J. and Kirkby, M.J. A Physically Based Variable Contributing Area Model of Basin Hydrology, 1979, *Hydrological Sciences Bulletin*, 24(1), pp. 43-69.

Beven, K.J., Kirkby, M.J., Schofield, N. and Tagg, A.F. Testing a Physically-Based Flood Forecasting Model (TOPMODEL) for Three U.K. Catchments, 1984, *Journal of Hydrology*, 69, pp. 119-143.

Jakeman, A.J., Littlewood, I.G and Whitehead, P.G. Computation of the Instantaneous Unit Hydrograph and Identifiable Component Flows with Application to Two Small Upland Catchments, 1990, *Journal of Hydrology*, 117, 275-300.

Jakeman, A.J. and Hornberger, G.M. How Much Complexity is Warranted in a Rainfall-Runoff Model?, 1993, *Water Resources Research*, 29(8), 2637-2649.

Jakeman, A.J., Chaithawat Saowapon, Attachi Jintrawet, Karn Trisophon, Evans, J.P. and Wong, F. Biophysical Component of an Integrated Water Resources Assessment Project, in the Upper Chao Phraya Headwaters, Northern Thailand, *International Congress on Modelling and Simulation (MODSIM97)*, Hobart, 8-11 December 1997, 2, 687-691.

NCR, Thailand Landuse and Land Cover Change case Study, Bangkok, National Research Council of Thailand, 1997.

Quinn, P.F., Beven, K.J. and Lamb, R. The ln(a/tanβ) Index: How to Calculate it and How to Use It Within the TOPOMODEL Framework, 1995, Hydrological Processes, 9, 161-182.

Schreider, S.Yu., Jakeman, A.J. and Pittock A.B. . Modelling Rainfall-Runoff From Large Catchment to Basin Scale: the Goulburn Valley, Victoria, 1996, *Hydrological Processes*, 10, 863-876.

Schreider, S.Yu., Scoccimarro, M., Jakeman, A.J., Dietrich, C.R., Chaithawat Saowapon and Merritt, W.S. Hydrologic Component of a DSS for Sustainable Development of Northern Thailand Highland Catchments, MODSS 1-6 August 1999a, Brisbane, Australia.

Schreider, S.Yu., Gallant, J., Jakeman, A.J. and Merritt, W.S. Surface Runoff Modelling in Ungauged Subcatchments of the Mae Chaem Catchment, Northern Thailand: Part II, First Pass Approach, *International Congress on Modelling and Simulation (MODSIM99)*, Hamilton, 6-9 December 1999b, this volume.

Wheater, H.S., Jakeman, A.J. and Beven, K.J. Progress and Directions in Rainfall-Runoff Modelling, Chapter 5 in: *Modelling Change in Environmental Systems*, Jakeman, A.J., Beck, M.B. and McAleer, M.J. (eds.), 1993, John Wiley and Sons, Southampton, U.K., 101-132.