Predicting Flows in Ungauged Catchments and Catchments Subject to Forest Cover Changes

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Abstract: This paper describes modelling tools developed for inclusion within a Biophysical Toolbox developed as part of a Decision Support System (DSS) for integrated catchment assessment and management of water resources in the highland regions of northern Thailand. The main modules within the toolbox are a hydrological model (IHACRES), a crop model (CATCHCROP), and an erosion model (USLE) modified to suit conditions in northern Thailand. The IHACRES module was developed to predict hydrological response to land use change in both gauged and ungauged catchments. The CATCHCROP model is a conceptual crop model developed for application within data sparse regions. With limited data availability being a common restraint to modelling, the aim was to strike a balance in the models between statistical rigour and model complexity. Initial sensitivity analysis and testing of the hydrological and crop modules are presented within the paper. The approach is generally applicable to catchments facing competing agricultural and forest land use.

Keywords: Water resources; CATCHCROP; IHACRES; Ungauged catchment; Northern Thailand

1. INTRODUCTION

Assessment of management issues relating to the distribution and use of water resources in agricultural areas requires an integrated approach. Two components of vital importance are considerations of the interactions between the hydrological regime of the catchment and the water requirements of farming activities. This paper presents a combined hydrological and crop modelling approach for exploring the effects of water resource options in northern Thailand. This work forms part of the Integrated Water Resource Assessment and Management (IWRAM) project which has developed a Decision Support System for the assessment and management of water resource issues in northern Thailand. However, the tools are considered to have applicability to other catchments with competing agricultural and forest land use activities.

Traditionally, agricultural activities in the highland regions of northern Thailand were dominated by swidden cultivation. These systems had minimal effects on the hydrological regime of a catchment, given their relatively small size within large areas of forest and the cycle between cropping and fallow [Turkelboom et al. 1997]. However, increasing agricultural intensification has seen the move from these relatively hydrologically stable systems towards permanent agricultural areas where the inherent problems in highland agriculture become more prominent.

The potential impacts of land use change on dry season flows is an issue of significant importance in upland regions of Northern Thailand where the climate exhibits strong seasonality. The availability of water during the dry season will greatly influence whether second or even third crop rotations can be grown. The hydrological and crop modules presented within this paper focus heavily upon improving the representation of the water quantity and use during the dry season in particular. Preliminary testing of the hydrological model and interactions with the crop model are presented in this paper.

2. THE BIOPHYSICAL TOOLBOX

2.1 The CATCHCROP Crop Model

The crop model applied within this toolbox is the CATCHCROP model developed by Perez et al.

[2001]. CATCHCROP is a conceptual crop generic model that has been applied within catchments in northern Thailand. The model was developed in response to the recognition that many existing crop models require large amounts of highly specific data such as detailed soil information (eg. conductivities of each soil layer, cation exchange capacity) to drive them. These are rarely collected outside of experimental stations. Whilst limiting data needs, CATCHCROP allows the dynamic simulation of crop yields A full description of CATCHCROP and initial model testing is provided in Perez et al. [2001]. Parameter values for the CATCHCROP model were taken from Perez et al. [2001].

2.2 The Hydrological Model

The hydrological module incorporated within the toolbox is based upon the IHACRES conceptual rainfall-runoff model [Jakeman and Hornberger, 1993]. The model consists of a non-linear loss module that converts rainfall to effective rainfall, and a linear routing model that generates modelled streamflow from the effective rainfall (Figure 1 and Table 1). IHACRES has been widely applied over a range of catchment scales and has been shown to successfully reproduce streamflow over a wide range of time-scales and climatologies.

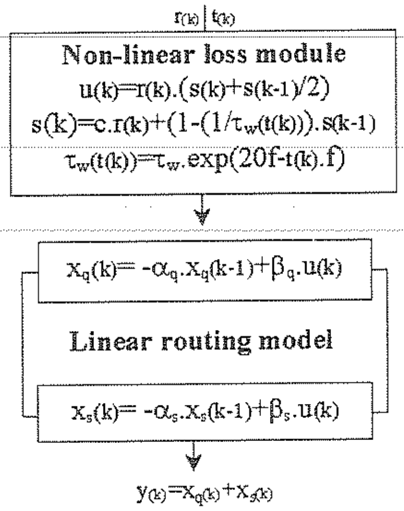


Figure 1. The IHACRES model.

The hydrological module was developed to serve two purposes:

- to explore impacts of land use change on hydrological response, and
- to provide a means of estimating hydrologic response in ungauged catchments.

Table 1. Symbols used in Figure 1.

Model inputs and outputs at timestep k	
$r(k)$	Rainfall
$t(k)$	Temperature
$s(k)$	soil moisture index
$u(k)$	Effective rainfall
$y(k)$	Streamflow
Model parameters	
c	Volumetric storage coefficient of catchment
τ_w	Drying rate of catchment
f	Temperature modulation of drying rate
α_q, α_s	Quick and slow flow recession rates
β_q, β_s	Fractions of u(k) for peak response
$v_s = \dfrac{\beta}{1+\alpha_s}$	Relative volume of quick flow response
$v_q = \dfrac{\beta}{1+\alpha_q}$	Relative volume of slow flow response

The latter point is a major hurdle in water resource analyses in regions like northern Thailand where there is a dearth of stream gauge instrumentation or where assessment of water availability is required as input to agricultural production models at locations between gauging sites.

The hydrological module presented in this paper continues the rationale of modelling an ungauged catchment developed in previous approaches applied within the Mae Chaem catchment in northern Thailand [Schreider et al. 2001; Merritt and Schreider, 2000] – that is: scaling the volumetric storage coefficient, c, of the IHACRES model for a calibrated reference catchment according to forest cover and catchment area; and redistribution of the quick and slow flow component volumes according to forest cover. The current model employs the CATCHCROP model to estimate percolation (P) and surface runoff (RO) for two representative crops (corresponding to forested and cleared areas) on all land units in both the reference and model catchments.

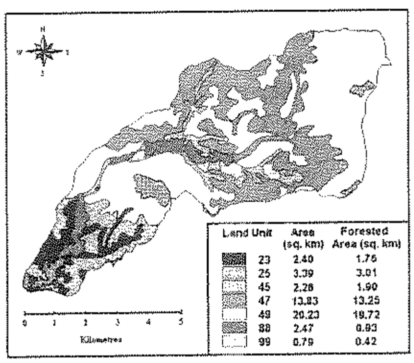


Figure 2. Land unit distribution and areas within the Mae Uam subcatchment.

The Department of Land Development (DLD) in Thailand classify catchments into land units that represent the soil types and topography within the catchment (Figure 2). These land units are the modelling unit upon which the CATCHCROP model is based.

Once estimates of RO and P have been generated for each land unit type within the reference (gauged) and modelled (ungauged) catchments the lumped catchment estimates based on forested area for each land unit (in mm) are calculated according to:

$$X^m = \left(\sum_{lu=1}^{n} a_{lu}^{f,m} X_{lu}^{f,m} + (a_{lu}^{m} - a_{lu}^{f,m}) X_{lu}^{c,m} \right) / \sum_{lu=1}^{n} a_{lu}^{m} \quad (1)$$

where X is RO or P, $a_{lu}^{f,m}$ is the forested area of land unit lu in catchment m, and a_{lu}^{m} is the area of land unit lu in catchment m.

The volumetric storage coefficient, c, for the reference catchment (c_g) is scaled according to the ratio of the areas of the ungauged catchment (a_u) to reference catchment (a_g) and the surface runoff and percolation ($RO+P$) for the gauged and ungauged catchments. Thus

$$c_u = c_g(a_u / a_g)\frac{RO_u + P_u}{RO_g + P_g} \quad (2)$$

Here it is assumed that total discharge is equal to the surface runoff plus percolation, that is, subsurface flow out of the catchment is negligible.

The quick and slow flow volume components for the ungauged catchment, $v_{s.u}$ and $v_{q.u}$ (or under a forest cover change) are obtained by scaling the volumes calibrated for the gauged catchment ($v_{s.g}$ and $v_{q.g}$) according to catchment estimates of percolation and surface runoff. The slow flow component, $v_{s.u}$, is assumed to be dominated by percolation,

$$v_{s.u} = v_{s.g}(P_u / P_g) \quad (3)$$

whilst $v_{q.u}$ is assumed to be the controlled by surface runoff

$$v_{q.u} = v_{q.g}(RO_u / RO_g) \quad (4)$$

The flow components are then normalised to ensure that $v_{s.u}$ plus $v_{q.u}$ is equal to 1. Streamflow is then simulated using the re-calculated c parameter and quick and slow flow volume components. All other parameters calibrated for the reference catchment are assumed to the same for the ungauged catchment. In this method, therefore, no attempt was made to adjust for changes in the recession rates (α_q, α_s) of the quick and slow flow stores.

Studies on the impact of deforestation on streamflow yield have often shown conflicting responses particularly with respect to the effect of deforestation on dry season flow rates. However, Bruijnzeel [1990] in his state of knowledge review on the hydrology of tropical forests and effects of conversion noted that forests may increase the proportion of streamflow in the dry season relative to the wet season, whilst decreasing total streamflow, due to higher percolation than other vegetation cover types. It is this behavior that the simple regionalisation procedure presented within this paper attempts to capture.

3. MODEL TESTING

3.1 Site Details

Testing of the hydrological module was performed within a number of subcatchments within the Mae Chaem catchment located in the Chiang Mai Province in northern Thailand.

The Mae Chaem catchment is characterised by steep topography and is predominantly forested with the main land use being agricultural activities. The catchment has a monsoonal climate for up to seven months of the year and exhibits strong seasonality. The wet season starts from mid to late April and extends through to November with approximately 95% of rainfall occurring during this period.

The regionalisation procedure is tested upon the gauged 2157 km^2 Kong Kan catchment and the 68.5 km^2 Mae Mu catchment. The influence of changes in forest cover upon the quick and slow flow volume components of the IHACRES model and CATCHCROP output and hence streamflow are investigated for the 45.3 km^2 Mae Uam subcatchment.

Model calibrations and a description of the procedure used to generate the climate series used within this paper can be found in Merritt and Schreider [2000]. Superior calibrations were achieved in 1988 water year for Mae Mu and water year 1994 for the Kong Kan catchment.

3.2 Initial Results

3.2.1 Flow prediction in ungauged catchments

IHACRES parameters calibrated for the Kong Kan subcatchment for 1994 and the Mae Mu subcatchment for 1988 were used to predict streamflow in Kong Kan over the period 1985-

1993. As can be seen in Figure 3 predicting streamflow for Kong Kan regionalised from the Mae Mu parameters (▲) grossly over-estimates annual discharge. In Figure 4, predictions of streamflow (from 1988 to 1993) for the Mae Mu catchment using Kong Kan parameters (▲) overestimate discharge although generally perform better than predictions based upon the Mae Mu 1988 calibrated parameters with the exception of two year - 1988 and 1992. Tables 1 and 2 show annual rainfall (mm), the Nash-Sutcliffe efficiency (R^2) and the bias (in mm) based upon monthly discharge excluding data from the 1987 hydrological year. The quality of both the hydrological series over this period were considered dubious. Thus this year was excluded.

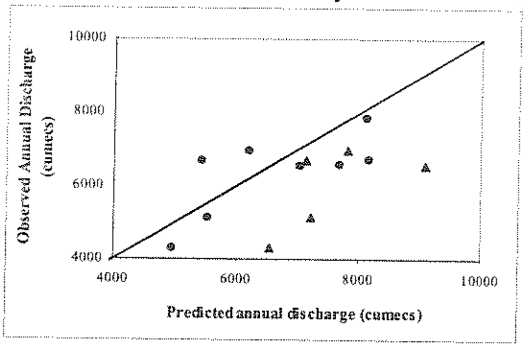


Figure 3. Observed versus predicted annual discharge for Kong Kan using Kong Kan 1994 calibrated parameters (●) and regionalised parameters from the Mae Mu catchment (▲).

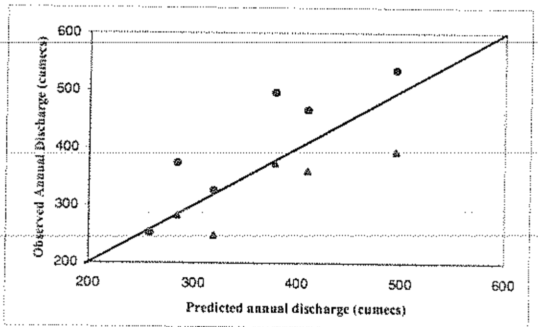


Figure 4. Observed versus predicted annual discharge for Mae Mu using Mae Mu 1988 calibrated parameters (●) and regionalised parameters from the Kong Kan catchment (▲).

Table 1. R^2 and bias (mm) for simulating Mae Mu from Mae Mu 1988 calibration (mm1) and Kong Kan 1994 calibration and regionalisation (mm2).

Year	mm1		mm2		Annual
	R^2	Bias	R^2	Bias	Rainfall (mm)
1988	0.65	51	0.62	-127	1521
1989	0.44	71	0.68	-62	1329
1990	-1.48	149	-0.08	-6	1387
1991	0.82	8	0.69	-90	1192
1992	0.39	113	0.89	-2	1121
1993	0.39	-7	0.52	-78	882

Table 2. R^2 and bias (mm/year) for simulating Kong Kan discharge from Kong Kan 1994 calibration (kk1) and Mae Mu 1988 calibration and regionalisation (kk2).

Year	kk1		kk2		Annual
	R^2	Bias	R^2	Bias	Rainfall (mm)
1985	0.76	10	0.52	98	1268
1986	0.82	16	0.36	84	1009
1988	0.79	43	0.03	146	1210
1989	0.46	-51	0.50	18	955
1990	0.81	19	0.53	102	1149
1991	0.80	57	0.13	147	1194
1992	0.65	-31	0.73	34	1048
1993	0.69	26	0.02	89	972

3.2.2 Forest cover impacts on streamflow

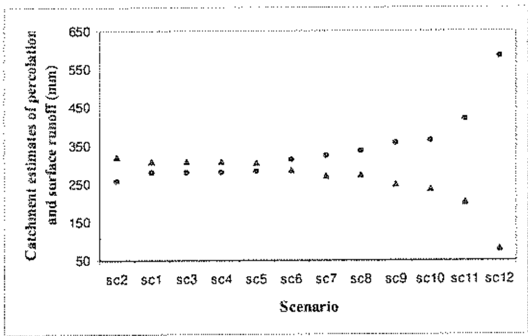
The distribution of land units within the Mae Uam subcatchment is shown in Figure 2. The catchment is largely dominated by steeply sloping loamy soils in the upper catchment (land units 47 and 49) with gently sloping paddy land and mid-sloping gravel soils in the lower catchment.

Table 3 Land cover scenarios and net forest cover change (+ afforestation, - deforestation).

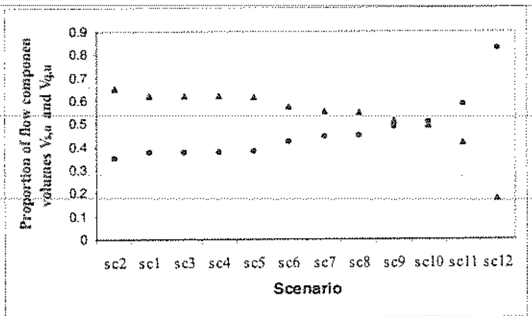
Scenario	Description	Net change in forest cover from 1990 (%)
sc1	1990 forest cover	--
sc2	100% forest cover on all land units	+9.6
sc3	0% forest cover on paddy fields (land units 88 and 99)	-3.0
sc4	70% forest cover on land units with slopes less than 16° (land units 23, 88, and 99)	+1.9
sc5	50% forest cover on land units with slopes less than 16° (land units 23, 88, and 99)	-0.6
sc6	70% on land unit 49 (slopes greater 35°)	-13
sc7	70% forest cover on land units with slopes less than 35° (land units 23, 25, 45, 47, 88, and 99)	-8.1
sc8	50% on land unit 49 (slopes greater 35°)	-21.2
sc9	70% on all land units	-20.4
sc10	50% forest cover on land units with slopes less than 35° (land units 23, 25, 45, 47, 88, and 99)	-8.1
sc11	50 % on all land units	-40.4
sc12	0% on all land units	-90.4

Twelve scenarios of forest conversion were run to illustrate the effect of forest cover on the catchment estimates of percolation and runoff and hence the impact on the quick and slow flow volume components of the IHACRES model and predicted streamflow (Table 3). The change in forest cover in Table 1 is relative to the forest cover in 1990 (sc1) where forest cover is 90.4% of the catchment (See Figure 2).

Decreasing forest cover increases the catchment estimates of surface runoff whilst decreasing percolation for an average rainfall year of 1990 (Figure 5a). Given our assumption that the slow flow volume component of the IHACRES model, v_s, is dominant during the dry season – where the majority of streamflow derives from water that has percolated through the soil subsurface – deforestation increases the quick flow component, $v_{q,s}$, relative to the slow flow component, $v_{s,u}$ (Figure 5b).



(a)



(b)

Figure 5. Effect of forest cover change scenarios on (a) percolation (▲) and surface runoff (●) estimates for Mae Uam, and (b) the IHACRES quick (●) and slow (▲) flow volume components.

With decreasing forest cover we see increases in the total annual discharge predicted by the procedure. The increase in annual discharge from 1990 land cover conditions (sc1) to complete deforestation (sc12) corresponds to 1214 ML in the driest hydrological year (April 1989 to March 1990) and 3592 ML in the wetter hydrological year of April 1985 to March 1986. Table 4 illustrates the impact of forest cover on mean annual, wet season and dry season discharge under the same climatic series over the period 1985 to 1993.

Table 4 Percentage change from the 1990 land cover scenario (sc1) for annual, wet season and dry season yields (- indicated as the decrease from sc1). Yields (in ML) are provided for sc1.

Scenario	Annual	Wet Season	Dry season
sc1	18271	13433	4838
sc2	-1.2	-2.5	2.2
sc3	0.3	0.3	0.4
sc4	-0.2	-0.2	-0.3
sc5	0.1	0.3	-0.5
sc6	2.4	4.5	-3.5
sc7	2.3	4.0	-2.5
sc8	3.9	7.4	-5.7
sc9	3.2	8.4	-11.1
sc10	2.3	8.3	-14.4
sc11	6.2	16.0	-21.1
sc12	13.6	36.6	-50.2

The increase in the quick flow volume v_q with decreasing forest cover results in a peakier hydrograph with more rapid streamflow response to rainfall. Similarly, the decreases in the slow flow volume result in reduced flows in the dry season. This is illustrated in Figure 7 for a six month period (1/06/92 to 31/11/92) for four of the scenarios presented in Table 3 (sc1, sc9, sc11 and sc12). For an event on the 18th September the difference in the peak flow between the two extreme scenarios is 1.96 cumecs (sc1 – 2.2 m^3/s, sc9 – 2.65 m^3/s, sc11 – 3.05 m^3/s and sc12 – 4.16 m^3/s). In a falling stage period (25th November) streamflow under sc12 forest cover has reached considerably lower streamflow than the other scenarios (sc1 – 0.14 m^3/s, sc9 – 0.31 m^3/s, sc11 – 0.37 m^3/s and sc12 – 0.43 m^3/s).

4. DISCUSSION AND CONCLUSIONS

This paper presents a combined hydrological and crop modelling approach for exploring water resources issues in northern Thailand. Preliminary testing presented within this paper focussed upon the performance of the hydrological model in predicting discharge in ungauged catchments and model sensitivity to a series of forest cover change scenarios.

The regionalisation results to date indicate the difficulty in developing relatively simple techniques with low data requirements for predicting flow in ungauged catchments. The regionalisation model predicts daily streamflow poorly. Given data constraints within the region such outcomes are not surprising. The approach

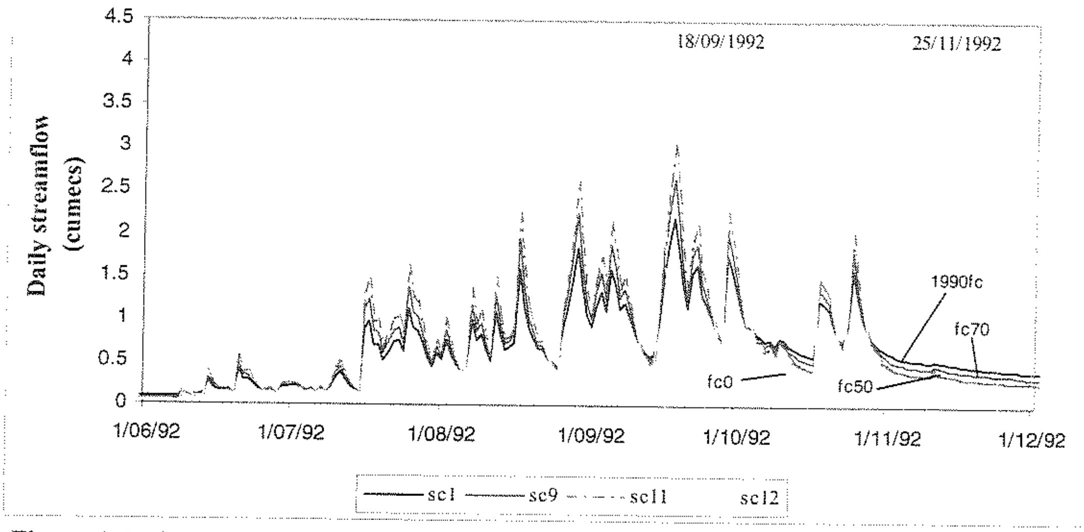


Figure 6. Daily streamflow for 1992 forest cover (sc2), 70% forest cover across all land units (sc10), 50% forest cover on all land units (sc11) and complete deforestation (sc12).

is currently limited to monthly time-scales where results are likely to be better than for a daily timetep (eg. R^2 from daily streamflow for Kong Kan [kk1 in Table 2] in 1988 was 0.65 compared with 0.79 based upon monthly discharge).

As forest cover within the gauged catchments of the Mae Chaem did not change significantly over the duration of the hydrological record, it was not possible to test the performance of the procedure in predicting hydrological response to changes in forest cover. The scenarios performed for the Mae Uam catchment suggest that considerable land cover conversion is required to affect annual discharge whereas wet and dry season yields show large changes in response to modest changes in forest cover.

Further quantification of the sensitivity of the procedure to forest cover change is required. Namely, this paper has not examined the effects of changing parameters within the CATCHCROP crop model on the hydrological model, particularly those that impact upon infiltration into the soil. This paper has focussed purely on the performance of the hydrological model. Future work will investigate more closely the interactions between the crop and hydrological models and impacts on model outputs of the crop model in response to cropping scenarios and hydrology inputs.

5. ACKNOWLEDGMENTS

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