Sensitivity Testing of a Biophysical Toolbox for Exploring Water Resources Utilisation and Management Options

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Abstract: This paper investigates the sensitivities of model outputs to model parameter values within a Biophysical Toolbox developed as part of a Decision Support System (DSS) for integrated catchment assessment and management of land and water resources in the highland regions of northern Thailand. The toolbox contains a hydrological module based upon the IHACRES rainfall-runoff model, a crop model (CATCHCROP), and an erosion model (USLE) modified to suit conditions in northern Thailand. Emphasis in the development of the individual models within the Biophysical Toolbox was placed upon limiting model complexity. Limited data availability commonly restricts the complexity of the model structure that can justifiably be used to model natural systems. The challenge under conditions with limited data is then to strike a balance in the model(s) between statistical rigour and model complexity. Once encompassed within the Biophysical Toolbox, linkages between the models increase the complexity of the system, despite the relative simplicity of the individual models. Consequently, the impacts of outputs from individual models on the outputs of other models deserve considerable attention. Understanding model sensitivity is of particular importance where there is a lack of data with which to support or adequately verify model behaviour. Sensitivity analysis potentially allows the identification of model components that require attention in terms of improved parameter estimation or improvement in model structure. Preliminary testing of the individual models within the Biophysical Toolbox has been reported previously within the literature and the Biophysical Toolbox as a whole has been described. This paper explores sensitivities within the Biophysical Toolbox, targeting in particular the identification of components of the toolbox in which sensitivities are propagated throughout the model.

Keywords: Water resources; CATCHCROP; IHACRES; Northern Thailand; Sensitivity analysis

1. INTRODUCTION

Assessment of management issues relating to the distribution and use of water resources in agricultural areas requires an integrated approach. In many catchments in northern Thailand rapid agricultural intensification, and government conservation policies have created points of tension in relation to land and water resource management. Land use options for resource management within such catchments have both on-site and off-site effects, and involve multiple choices over uses of scarce resources, particularly water. The Integrated Water Resources Assessment and Management (IWRAM) project (http://incres.anu.edu.au/icam) was instigated to develop modelling tools within an integrated framework to assist in exploring the environmental and social outcomes of land management options.

A Decision Support System (DSS) was developed, comprising a 'Biophysical Toolbox' that can be used to explore environmental impacts from biophysical land management scenarios [Merritt et al. 2002], and an 'Integrated Toolbox' that can be used to consider trade-offs of a variety of land and water development options through comparison of biophysical and economic indicators [Letcher et al. 2002].

The Biophysical Toolbox contains three main models; a hydrological model (IHACRES), a crop model (CATCHCROP), and an erosion model (USLE). This paper considers the sensitivity of model outputs from the toolbox in response to changes in parameter values for the models. Emphasis is placed on the link between the crop and hydrologic models – the major component of the toolbox where errors and uncertainties are likely to be propagated through the toolbox.

2. THE BIOPHYSICAL TOOLBOX

2.1 The CATCHCROP Crop Model

The crop model applied within the Biophysical toolbox is the conceptual CATCHCROP model (Perez et al. 2002). The model predicts crop yield, actual evapotranspiration (ETA), surface runoff (RO), deep drainage (DD) and crop water demand (DEM). A full description of CATCHCROP and initial model testing is provided in Perez et al. [2002].

Table 1. CATCHCROP model parameters and parameter for paddy rice on land unit 88 in the Mae Uam subcatchment.

	Definition	Value
KCini	Initial crop coefficient	1.05
KCmid	Crop coefficient in the middle of the cropping period	1.20
KCend	Final crop coefficient	0.9
RDini	Initial root depth	200
RDend	Final root depth	500
P	The fraction of soil water that a crop can extract without suffering moisture stress	0.2
CC	Infiltration correction factor for crop management	2.0
KY	potential crop yield	1.2
YM	water stress coefficient that reduces the potential yield	5.0
TAW	Total amount of water available in the soil reservoir available for crop evaporation	150
TEW	Total amount of water available in the surface reservoir available for soil evaporation	30
REW	Total amount of water available in the surface reservoir, readily available for soil evaporation	10
IS	Daily infiltration ate for a given soil	5
SD	Maximum soil depth above a limiting layer	1500
CS	Infiltration correction factor for slope	1.0

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 2).

A procedure can be used with IHACRES to predict streamflow for a land cover scenario based on the proportion of forested and non-forested areas in the new scenario. The IHACRES model is used to calibrate streamflow for a gauged catchment under the current land cover. Then, CATCHCROP is used to partition discharge between surface runoff (RO) and deep drainage (DD) based upon the catchment area of forest and fallow under the current land use and for the scenario. The volumetric storage coefficient, c (See Figure 1), obtained from the calibration of the non-linear loss module is scaled according to the relative change in (RO+DD). That is, an increase of 10% in (RO+DD) under a new land cover scenario results in an increase in the c parameter value of 10%. The quick and slow flow components in the linear module are recalculated. The slow flow component v_s, (See Table 2), is assumed proportional to DD whilst the quick flow component is assumed proportional to RO. The hydrologic module has been described in Merritt *et al.* (2001).

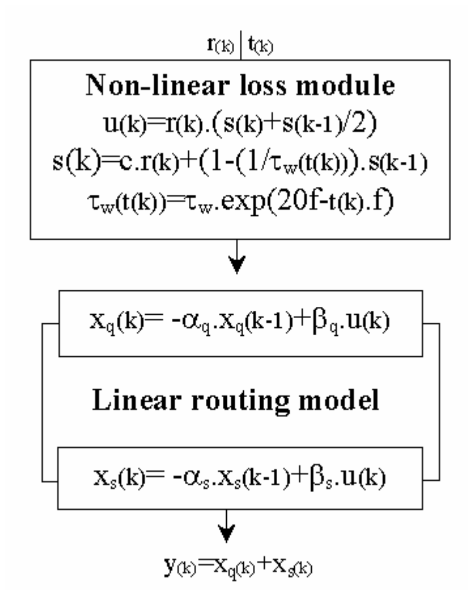

Figure 1. The IHACRES model.

2.3 The Erosion Model

Estimates of erosion rates for each land unit type within a catchment are calculated using a Universal Soil Loss Equation (USLE – Wischmeier and Smith, 1979) modified to suit conditions in northern Thailand. Currently, the erosion model is not linked with either the crop or hydrology modules within the Biophysical Toolbox.

Table 1. Inputs, outputs and model parameters of IHACRES. Derived values of parameters for Mae Uam that are scaled for forest cover scenarios (v_q, v_s, and c) are shown in brackets.

	Description
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 (0.001998)
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
$v_s = \dfrac{\beta_s}{1+\alpha_s}$	Relative volume of quick flow response (0.325)
$v_q = \dfrac{\beta_q}{1+\alpha_q}$	Relative volume of slow flow response (0.675)

2.4 The Biophysical Toolbox

The models within the Biophysical Toolbox operate at a number of spatial and temporal scales. The common spatial scale of the indicators is the (residual) subcatchment upstream of a selected node in the river network. If a selected node i has an upstream subcatchment j nested within it, then the area of the smaller nested catchment down to point j in the river network is subtracted from the larger catchment at point i to provide the residual subcatchment area. The crop and erosion models operate on a land unit basis, where the models are applied to each land unit type within the catchment (Figure 2). The crop model operates on a 10 day time step whilst the erosion model is applied on a seasonal basis. The hydrologic model, on the other hand, outputs lumped catchment estimates of daily discharge at nodes i and j.

Outputs from the Biophysical Toolbox can be used to calculate environmental indicators at selected spatial and temporal scales. These indicators can be summarised as: crop yield (tonnes/ha), crop water demand (mm), irrigation (mm), residual streamflow [streamflow after abstractions for crop irrigation] (in ML), gross erosion loads (tonnes), and erosion rates for land units and crops (tonnes/hectare). Indicators are provided for the total growing season or annually.

3. SITE DETAILS

The sensitivity analysis of the models within the Biophysical Toolbox was performed for the Mae Uam subcatchment of the Mae Chaem catchment in northern Thailand. The subcatchment is a 45.3 km^2 predominantly forested catchment (Figure 2). Significant areas of paddy agriculture exist in the lowland areas of the catchment, whilst agriculture in the upland areas is confined to relatively few pockets of cleared area.

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.

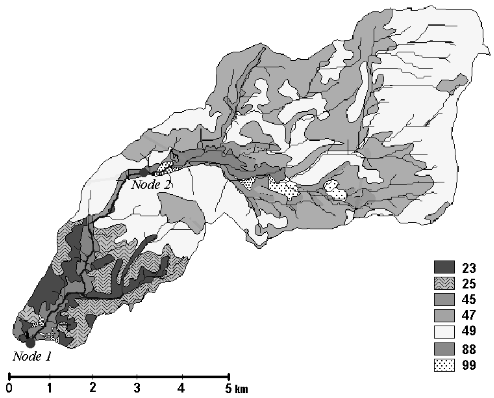

Figure 2. Land unit distribution and location of nodes in the Mae Uam subcatchment at which outputs from the Biophysical Toolbox are provided.

4. RESULTS

Sensitivity analysis of the crop and hydrology modules, and the Biophysical Toolbox as a whole, were performed. All components were assessed using 1990 climate and 1990 land cover. For the assessment of model outputs from the crop model and the Biophysical Toolbox as a whole, the cropping patterns assumed were; 100% of the paddy fields (land units 88 and 99) cropped with irrigated crops, and 25% of upland fields (land units 23, 25, 45, 47, and 49) cropped with non-irrigated crops. Parameter values were perturbed between. 10% and 190% of the nominal parameter value.

4.1 Sensitivity of CATCHCROP outputs to perturbations of model parameters

To investigate sensitivities of the crop model outputs to changes in model parameters, CATCHCROP was run, perturbing one model parameter at a time. Parameters were varied between 10% and 190% of the original value of the parameter in 10% increments. Results are presented (Figures 3 and 4, and Table 3) for paddy rice grown on land unit 88 in the wet season. The outputs considered were crop yields (Figure 3), deep drainage (DD – Figure 4), and surface runoff (RO – Table 3).

Figure 3 shows a contour plot of crop yields (t/ha) for changes in all parameters. The P, KCend, IS, CS, SD parameters have little influence upon yield estimates. KY and YM, the parameters that define the final yield of the crop, have a linear influence upon crop yield. Yield shows a non-linear response to changes in RDend with yield increasing between 10% and 70% of the original value after which final root depth has little impact upon crop yields. Yield decreases with increasing KCini and decreasing RDini and CC. A slight decrease in yields is seen between 0.1 and 0.5 times the original value of KCmid after which little change occurs.

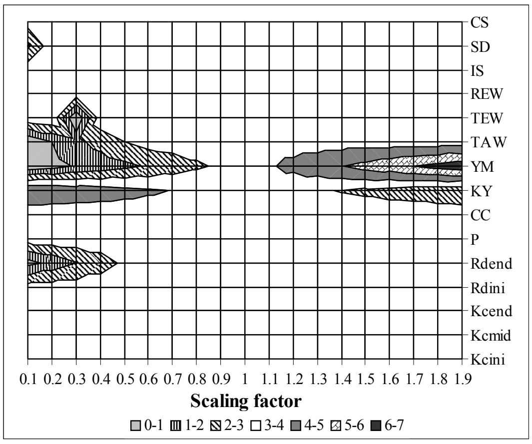

Figure 3. Response in crop yields to changes in CATCHCROP model parameters for paddy rice on land unit 88.

A contour plot of deep drainage estimates (in mm) with changes in the CATCHCROP model parameters is shown in Figure 4. Deep drainage is not sensitive to KCend, RDini, REW or TEW. RDend and P influence DD similarly, linearly decreasing from approximately 1000 mm to under 700 mm between 0.1 and 1.9 × the original parameter. Deep drainage shows strongly non-linear responses to perturbations in CC and CS compared with a near linear decrease with increasing TAW.

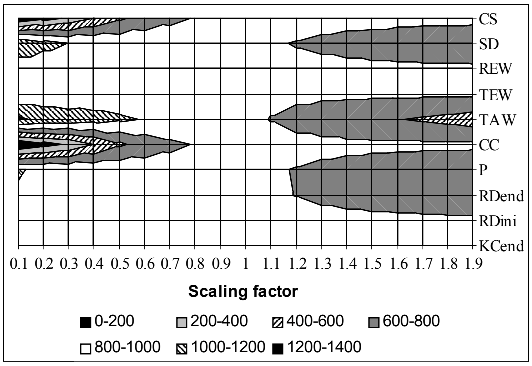

Figure 4. Contour plot of deep drainage (in mm) with changes in CATCHCROP model parameter values.

Only two parameters were shown to highly influence surface runoff calculated within CATCHCROP using the SCS (1973) methodology (Table 3). Both decrease RO estimates as the parameters increase between 0.1 and 1.1 × the nominal parameter value, after which RO estimates remain constant.

Table 3. Decrease in CATCHCROP estimates of surface runoff (RO) with increasing CC and CS parameter values for paddy rice on land unit 88.

	Scaling Factor										
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	1.1
CC	979	798	661	486	317	191	109	49	25	25	25
CS	1012	826	683	504	331	201	117	54	27	25	0

4.2 Sensitivity of the hydrologic module to changes in crop model parameters

The parameters identified as affecting CATCHCROP estimates of deep drainage and surface runoff under crops were varied to test the sensitivity of the hydrologic module to crop model parameters. The CATCHCROP parameters were systematically varied by increments of 0.1 between 0.1 and 1.9 × the nominal parameter value. The CATCHCROP model was run for all land units under forest and fallow land cover to produce estimates of DD and RO for each land unit. These estimates were then weighted by the area of forest within a land unit and the land unit area, and used to scale the IHACRES volumetric storage coefficient, c, and the relative proportions of quick v_q and slow flow, v_s.

Table 4 details those parameters found to impact upon DD and RO in Section 4.2.1, the values of these parameters under forest and fallow covers and the land units within Mae Uam. In addition, Table 5 shows the directional changes in catchment estimates of RO, DD and the relative volume of slow flow v_s. Varying KCend, RDini, P, TEW, and REW had no significant impact on the catchment estimates of RO and DD. Hence, when simulating a new forest cover change scenario, no change in the distribution of flow between the quick and slow flow components was observed.

The infiltration parameters CC, IS and CS have similar effects upon estimates of catchment DD and RO. This is shown in Figure 5 for the nominal CC parameter. Multiplying CC by 0.3 to 1.9 results in estimates of surface runoff decreasing from 1000 mm (at 0.3 × CC) to approximately 200 mm (at 1.9 × CC). Conversely, deep drainage increases from 0 mm (at 0.3 × CC) to approximately 200 mm (at 1.9 × CC). However, increasing CC increases the distribution of streamflow into the quick flow component. That deep drainage increases yet v_s decreases is, at first sight, counter-intuitive given our assumption that v_s is proportional to deep drainage. However, the CATCHCROP model is run for both fallow and forest and then weighted by area for both the reference and scenario forest covers to obtain catchment estimates of surface runoff and percolation. Both the reference and scenario cases have the scaling factor applied to them. The slow flow volume component, v_s, is scaled according to the ratio of the scenario to reference percolation estimates. How v_s varies with changes to CC then depends on the way in which both the scenario and reference estimates of percolation vary.

The three remaining parameters (TAW, SD, and RDend) that affect RO and DD act in similar ways – by increasing the crops ability to extract water hence reducing the DD estimates from CATCHCROP. Within the hydrology module, the scaling of v_s for a new forest cover scenarios is assumed proportional to DD. With decreasing DD, more water is partitioned into quick flow.

Table 4. CATCHCROP model parameters identified to impact on estimates of DD and RO under crops; the values of the crop parameters under forest and fallow covers; the values of soil parameters for land units in Mae Uam, and directional changes in catchment estimates of RO, DD and the relative volume of slow flow v_s.

Parameter	Land Unit	Fallow	Forest	DD	RO	v_s
KCend	--	1.0	0.95	—	—	—
RDini	--	200	200	—	—	—
RDend	--	1800	2000	↓	↑	↓
P	--	0.7	0.5	—	—	—
CC	--	1.5	3	↑	↓	↓
TAW	23, 25, 88, 99 45, 47,49	150 170		↓	↑	↓
TEW	23, 25, 88, 99 45, 47,49	30 35		—	—	—
REW	23, 25, 88, 99 45, 47,49	10 11		—	—	—
IS	23, 25 45, 47,49 88,99	13 10 5		↑	↓	↑
SD	23, 45, 88, 99 25, 47, 49,	1500 1000		↓	↑	↓
CS	23, 45, 88, 99 25, 47 49	1 0.7 0.5		↑	↓	↑

Despite the impacts on the RO and DD estimates, the procedure does not appear to greatly affect estimates of discharge over the wet season or annually. For the wet season of 1990, varying parameter values between 50% and 150% of the nominal value gave variations in the total streamflow (ML) and residual streamflow (ML) of the order of 500 ML in total – no more than 3% of the indicator values obtained using the nominal parameter values.

5. DISCUSSION AND CONCLUSIONS

Although considerable effort has been made to keep the models within the Biophysical Toolbox relatively simple in terms of the model structure and number of model parameters, the toolbox as a whole is reasonably complex and some interactions between the models – particularly the crop and hydrology model – show non-linearity.

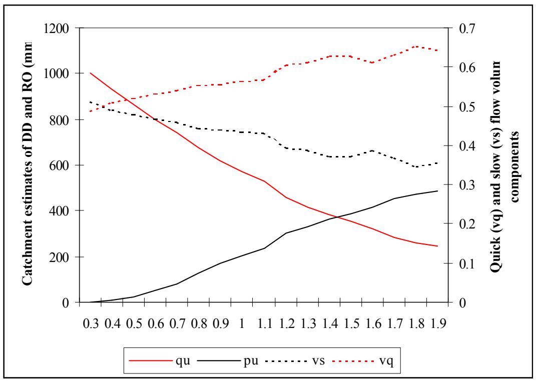

Figure 5. Effect of perturbing CC on catchment estimates of DD and RO, and scaled estimates of v_s and v_q.

Despite the relative simplicity of CATCHCROP, compared with many existing crop models, there are 19 model parameters required to drive the model. Given difficulties in capturing the spatial heterogeneities of these parameters, there is potential for considerable uncertainties in the model outputs. Basic sensitivity analyses performed for the Mae Uam catchment suggested that model outputs are strongly sensitive to a number of parameters. Yield was heavily dependent on YM, KY, KCini, and RDini, whilst deep drainage was largely influenced by CS, CC, TAW, SD, RDend and P. Surface runoff is sensitive to the CC and CS infiltration parameters. The sensitivities of the DD and RO outputs to parameter values in turn make the hydrology module sensitive to CC, CS, IS, RDend, Sd, and TAW model parameters.

This work indicated that care is required in measuring or determining appropriate parameter values for many of the parameters within the CATCHCROP model. In particular, the model outputs are highly sensitive to the infiltration parameters CC, CS, and IS of CATCHROP. Without accurate measurements of these parameters the performance of the CATCHCROP model (and hence the hydrologic module of the Biophysical Toolbox) may potentially be compromised. Model outputs were shown to be insensitive to a number of parameters, suggesting that simplification of the model may be possible without adversely affecting model performance.

No consideration was made for interactions between model parameters although it is acknowledged that a more detailed sensitivity analysis whereby multiple parameters are varied may provide further information as to model behaviour. Additionally, sensitivities of the individual models and the toolbox as a whole to inputs have not yet been addressed.

6. ACKNOWLEDGMENTS

The land unit data used in this work were provided by the of Land Development Department in Thailand. Nominal CATCHCROP parameters were taken from Perez et al. [2002].

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