Proceedings of the 2005 International Conference on Simulation & Modeling
V. Kachitvichyanukul, U. Purintrapiban, P. Utayopas, eds
.

HYDROLOGICAL MODEL FOR INTEGRATED WATER RESOURCE ASSESSMENT AND MANAGEMENT

Pongsak Witthawatchutikul and Atthorn Boosaner

Watershed Group
National Park, Wildlife and
Plant Conservation Department
Chatuchak, Bangkok, 10900, THAILAND

Sompop Sucharit

Dam Safety
Royal Irrigation Department
Dusit, Bangkok, 10300, THAILAND

ABSTRACT

The Integrated Water Resource Assessment and Management (IWRAM) project was established to develop models for a decision support system (DSS) for managing soil and water resources. The DSS consists of 4 models (hydrology, crop, erosion and socio-economic), which are integrated to explore the impacts of land use and management options. The hydrological model was developed to estimate effective rainfall and daily runoff. The model divides the watershed area into zones of homogeneous physical factors, with the SCS curve number (CN) approach used to assign a CN value which was then modified by the antecedent precipitation index (API). The daily rainfall and API were used to determine the runoff of each zone. Finally, topographic index (TI) was introduced to calculate watershed daily runoff. Initial results show that the model can reproduce annual flow for normal and dry years, but underestimates it in wet years. Future model development is discussed.

1 INTRODUCTION

The potential impacts of deforestation on hydrological response are of significant importance in highland regions of northern Thailand and other parts of southern Asia. In these regions, where climate exhibits strong seasonality, the availability of water in the dry season determines the feasibility of multiple crop rotations. The aim of the Integrated Water Resource Assessment and Management project (IWRAM) is to develop a decision support system (DSS) for use in managing water resources and soil erosion (Cuddy et al, 2005). This includes consideration of the socio-economic constraints in the catchment, the effect of land use on soil erosion and the volume of temporal distribution of streamflow, and the amount of water available for irrigation as well as the amount of water available for downstream users. Subsequently, development on the DSS involved integration of crop; hydrological; erosion and socio-economic models.

The role of the hydrological model in the IWRAM DSS is to estimate the effective rainfall (rainfall that is available for transpiration) and the daily streamflow at any given points in the system given a particular land use scenario (Ngamsomsuke et al 2005). In order that the DSS model can be used effectively on any area of the country, the development of this hydrological model is established with the objective to get accuracy in physically based prediction of flow in quantity, changes with land use and timing.

2 CONCEPT OF THE MODEL

The hydrological model developed for the Mae Chaem catchment study site was based on the IHACRES rainfall-runoff model (Croke et al 2004). The development of hydrological model for the P37 catchment is based on the work by Schwab et al. (1971) which concluded that factors controlling the flow in stream are rainfall and watershed factors. The rainfall factors include rainfall amount, intensity, duration and its distribution over the watershed. The latter factors affecting the flow are topographical and geological characteristics and vegetative cover.

Viessman *et al.* (1989) explained that runoff (Q, mm) was the result of rainfall (R, mm) and the antecedent moisture content or antecedent precipitation index (API) and has a general model for flow estimation as follows:

$$Q = a + bR + cAPI \quad (1)$$

where a, b and c are coefficients.
Linsley *et al.* (1982) explained further that the value of API would deplete with number of days with no rain and can be expressed as:

$$API_{(t)} = k.\ API_{(t-1)} \quad (2)$$

where $API_{(t)}$ is API of day t, $API_{(t-1)}$ is API of the day before day t, and k is the recession coefficient which usually will has the value 0.85 and 0.98. However, if there is rainfall event on day t, ($R_{(t)}$), Equation (2) will change into the form of:

$$API_{(t)} = [k.\ API_{(t-1)}] + R_{(t)} \quad (3)$$

In Thailand, Witthawatchutikul (1985) has found that the value of streamflow recession is close to the value of k and can be applied as API value in estimation of flow. This is similar to the slow flow component used in the IHACRES rainfall-runoff model, though the decay coefficient k is allowed to vary with API here.

However, the US Natural Resources Conservation Service (formerly Soil Conservation Service, SCS) has developed "curve number" or CN to use in estimation of direct runoff from each rainfall event from small watersheds. This method can be developed to use on large watersheds with varied land uses. The curve number is the result of the interaction between soil cover complex and antecedent soil moisture content.

The IWRAM hydrological model used CN under actual moisture content at that period as an API to estimate streamflow by Equation (1). Then this API will be used to obtain API for the next day by Equation (2) or Equation (3). However, all the above mentioned equations were developed from small watersheds. Applying to larger watersheds will require modification in the model to account for the increased contribution from baseflow and reduced height of event peaks (Lee, 1980).

To account for this effect, the model was been modified by including a Topographic Index (TI) in flow estimation similar to the TOPMODEL index (Beven and Kirkby, 1979). The index can be defined as:

$$TI = \ln(a/\tan\beta) \quad (4)$$

where *a* is the ratio of watershed area (A) above a given point in stream to contour length distance (cld), and $\tan\beta$ is the average slope of watershed.

In general, TI is used to indicate hydrological characteristics of the watershed response. Watershed areas with the same TI have the same response. Dendritic shaped watersheds will have TI distributed similar to a hydrograph i.e., from low to high and then back to low again.

The TI corresponding to each zone (defined in section 3) will be used to weight the estimated flow from each zone using:

$$Q_W = d\,[\Sigma(TI_{ij}\,Q_{ij})/\Sigma TI_{ij}]^e \quad (5)$$

where the i subscript refers to the day, the j subscript to the zone, and d and e are coefficients

3 CASE STUDY

The P.37 watershed, a small mountainous with moderate slope, 5 km^2 in area sub-watershed of Mae Kuang watershed (a tributary of Ping river), was selected for the development of the DSS. The dominant land use for the watershed is mixed deciduous and dry dipterocarp forests. Minor land use within the catchment include cash crops, orchards and reservoirs. Data needed for using the model included daily rainfall and streamflow, and topographic, soil, geological and land use maps.

The model will be verified by running it with the data used in development of the model to check for sensitivity. Next, the calibration in different parts of the model is carried out to get the estimate as close as possible to the actual values before the model validation with other watersheds is carried out.

4 APPLICATION OF THE HYDROLOGICAL MODEL

Based on topographic, soil, and geological characteristics and vegetative cover, P37 Watershed area was divided into 3 homogenous zones. In each zone, area (A), length of contour line (cld) and average slope (tan β) were obtained and then Equation (4) was used to find topographic index (TI) (see Table 1).

Table 1: Topographic index value (TI) for each zone area of the P.37 Watershed

Zone no.	TI value
I	10.98
II	9.98
III	9.66

In each zone, CN values for topography (CN_t), infiltration (CN_s), vegetative cover (CN_v) and surface storage (CN_{ss}) are assigned for each cell based on Schwab *et al.* (1971) (see Table 2) and then added up to be the CN for the corresponding zone. The zonal CN value is then adjusted to give the initial value for API ($API_{initial}$) of each zone by using the method of Witthawatchutikul (1997) as shown in Table 3. The details of the results are shown in Table 4.

The streamflow recession constant, k in equation 2 is the ratio of flow of a given day, $Q_{(t)}$ to flow of the previous day $Q_{(t-1)}$. The result from an analysis of flow data of P. 37 Watershed by trial and error method showed that the k value (recession coefficient) and API are closely correlated with a high coefficient of determination (r^2) of 0.9959 and the relationship is as follows:

$$k = 0.9136\, e^{-0.0079\, API} \quad (6)$$

From this relationship, the recession coefficient for ranges of API is obtained as shown in Table 5.

Table 2: Runoff producing characteristics of watershed with corresponding weighted CN.

Characteristics	Extreme CN (100)	High CN (75)	Normal CN (50)	Low CN (25)
Relief(CN_t) (A)	Mountainous area Slope > 30 % (30-40)	Hilly with slope slope10-30 % (25-32)	Rolling terrain Slope5-10 % (17-24)	Relatively flat slope 0-5 % (5-16)
Soil Infiltration (CN_s) (B)	Rocky, thin soil mantle (17-20)	Clay, slow infiltration (12-16)	Prairie soil, loam, deep soil mantle (7-11)	Sand, deep soil mantle, rapid infiltration (2-6)
Vegetative cover (CN_v) (C)	No effective cover, plant cover bare (17-20)	Less than 10 % of area under good cove (12-16)	50 % of area in good grassland, woodland(17 -11)	90 % of area in good grassland, woodland (2-6)
Surface storage (CN_{ss}) (D)	No surface detention, no pond, no marshes (17-20)	Small drainage way (12-16)	Lakes, ponds and marshes less than 2% (7-11)	Large number of lakes, ponds and marshes (2-6)

CN = A+B+C+D
Source: Schwab *et al.* (1971)

Table 3: Coefficient for adjusting the CN value to give the initial value of API.

Conditions of rainfall pattern	Correction coefficient by the ratio of annual rainfall(R_a) and evaporation(E_a)	
	$R_a/E_a > 0.64$	$R_a/E_a < 0.64$
Heavy rain throughout of that period	+20	+10
Moderate with heavy rain 3-4 days before	+10	0
Moderate rain and scattered	0	-20
Low rain but scattered	-25	-40
Low rain and low rainy day	-50	-60

Source: Witthawatchutikul (1997)

Table 4: CN and API Values assigned for Areas in Zone I, II and III of Watershed P.37

4.1 CN for Topography or CN_t:

Zone	DEM	(m)Elevation	CNt	Remarks
I	800 <	1,000 <	40	Fog belt zone
II	800 – 601	1,000 – 580	24	DLD
III	600 >	580 >	17	DLD

4.2 CN for Infiltration or CN_s:

Zone	Texture	CNs	Remarks
I	Sandy clay loam	6	Shallow soil
II	andy clay loamS	11	Moderate depth soil
III	(clay)Mixed soil	13	Clay

4.3 CN for Vegetative Cover or CN_v:

Zone	Vegetative cover	CNv	Remarks
I	Mixed Deciduous +Tea forest	9	Deep soil
II	+Mixed Deciduous forest Shrubs	14	Shallow soil
III	ds, Cash crop, orchar lages and shrubs	16	Relatively flat

4.4 CN for Surface storage or CN_{ss}:

Zone	Surface storage	CNss	Remarks
I	Forest cover	17	Steep slope
II	range land +Forest	15	+ Sloping estrfo
III	Few ponds or marshes	10	Flat area

4.5 All of the CN in each zone were added up and then adjusted with AMC to obtain a CN to be used as an initial API

Zone	ΣCN	AMC	$API_{initial}$
I	62	60-	2
II	64	60-	4
III	66	60-	6

Table 5: Recession coefficient (k) used in adjusting API for flow estimation.

API range	Recession coefficient (k)
0 – 10	0.91
11 – 20	0.86
21 – 30	0.78
31 – 40	0.72
41 – 80	0.65
> 80	0.49

The API $_{initial}$ of each zone is next adjusted by using k value and daily rainfall to be daily API of each zone by using Equation (2) and (3). The average daily API for the whole watershed is then obtained from weighted API of each zone. The weighting API is needed because soil water will move down to accumulate at stream bank and near the outlet causing the API to be high at the lower part of the watershed and getting lower as going higher up to the ridge (Hewlett and Nutter, 1969).

Using Equation (3) with the k values from Table 5, the $API_{initial}$ from Table 4.5 and the daily rainfall data, the daily API is estimated. The average daily API for the whole watershed is obtained from the weighted API of each zone by trial and error method as in Equation (1). By using coefficient of determination, r^2, and given API for zone I, II, and III for P. 37 Watershed as 0.20, 0.34 and 0.45, respectively, the most suitable model is found to be as follows:

$$Q_{ij} = 0.0332 - 0.0092\, R_{ij} + 0.0092\, API_{ij} \quad (r^2 = 0.5712) \qquad (7)$$

The daily flow out of the catchment is estimated using Equation (5). The estimated flow is plotted against the actual flow and the coefficients adjusted by trail and error method in order that the estimated flow are close to the actual flow (see Figure1) and the coefficient of determination higher. The best model was found to be as follows:

$$Q_W = 1.1151\, [\Sigma(TI_{ij}\, Q_{ij})]^{1.1315} \quad (r^2 = 0.7078) \qquad (8)$$

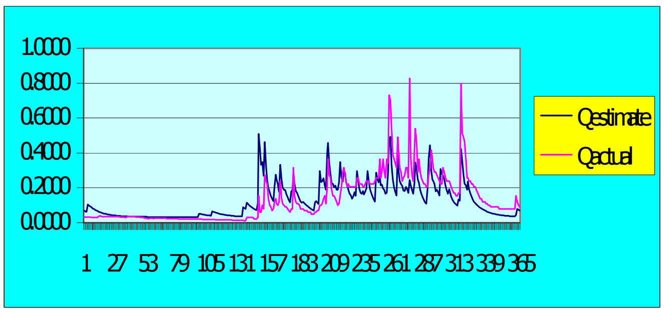

Figure1: The plot of estimated and actual daily streamflow of P.37 Watershed

5 MODEL VERIFICATION

The model was verified by running it with the data used in its development. It was found that in the dry season the result agreed well with the actual values. However, during the rainy season the model underestimated the flow. The total flow of the watershed was 48.7 mm and the model predicted a lower by 6.3 mm. The relationship between actual and estimated flow was moderately high as shown in the following equation.

$$Q_{actual} = 1.0125\, Q_{estimated} + 0.0158 \quad (r^2 = 0.5914) \qquad (9)$$

However, in testing for sensitivity of coefficient of sub-model and the coefficient was adjusted again, the sub-model was found to work well. Therefore, the coefficients of Equation (8) were readjusted to be as follows:

$$Q_W = 0.80\, [\Sigma(TI_{ij}\, Q_{ij})]^{0.85} \qquad (10)$$

By using Equation (10), both total quantity and the fluctuation of estimated flow were closer to the actual one. In the rainy season, the model gave very close estimates and only slightly higher in the dry season. The annual flow was estimated to be 49.9 mm or only about 1.2 mm higher than the actual one. The result was shown in Figure2 and the new equation obtained was as follows:

$$Q_{wr} = 1.1394\, Q_{we} - 0.0223, \quad (r^2 = 0.6083) \qquad (11)$$

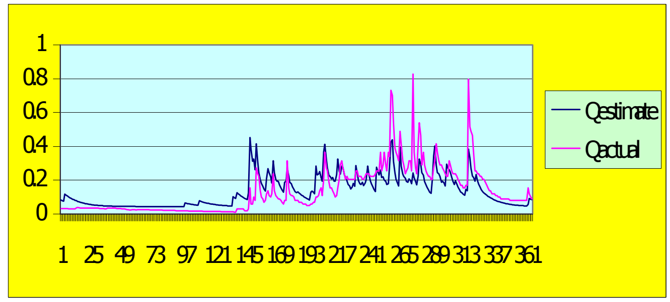

Figure 2: The Plot of P.37 Watershed Daily Flow Estimated by Equation (10) and Actual Daily Flow

Next, the model was validated by using P.37 Watershed daily flow data of 1978, 1979 and 1980, which had a record of high, moderate and relatively low flows, respectively. In 1978 had a high outflow of 80.4 mm because of a continuous heavy rain, the model underestimated the flow by 21.8 mm and gave a relatively low coefficient of determination (r^2) of 0.2523.

For 1979, the model gave an estimate of 85.5 mm which was slightly lower than the actual flow of 94.5 mm with a high coefficient of determination of 0.8145. But in 1980, which had low flow, the model gave a very close estimate of 59.4 mm, only one millimeter lower than an actual runoff with a coefficient of determination of 0.4452 as shown in Figure 3.

6 HOW THE MODEL WORK ?

The model developed here works in two routes at the same time. The first route, the model will go to each zone of the watershed of physical homogeneous characteristics such as topography, soil type and moisture contents by assigning the value to each factor called topographic index (TI). In each zone, the values for different factors concerning outflow of the area consisting of (1) topography or CN_t, (2) infiltration or CN_s, (3) vegetative cover or CN_v and (4) surface storage or CN_{ss}, will be assigned. The CN value of the 4 factors will be added to be representative of the all the factors having roles on the releasing of runoff of the watershed or runoff curve number (CN).

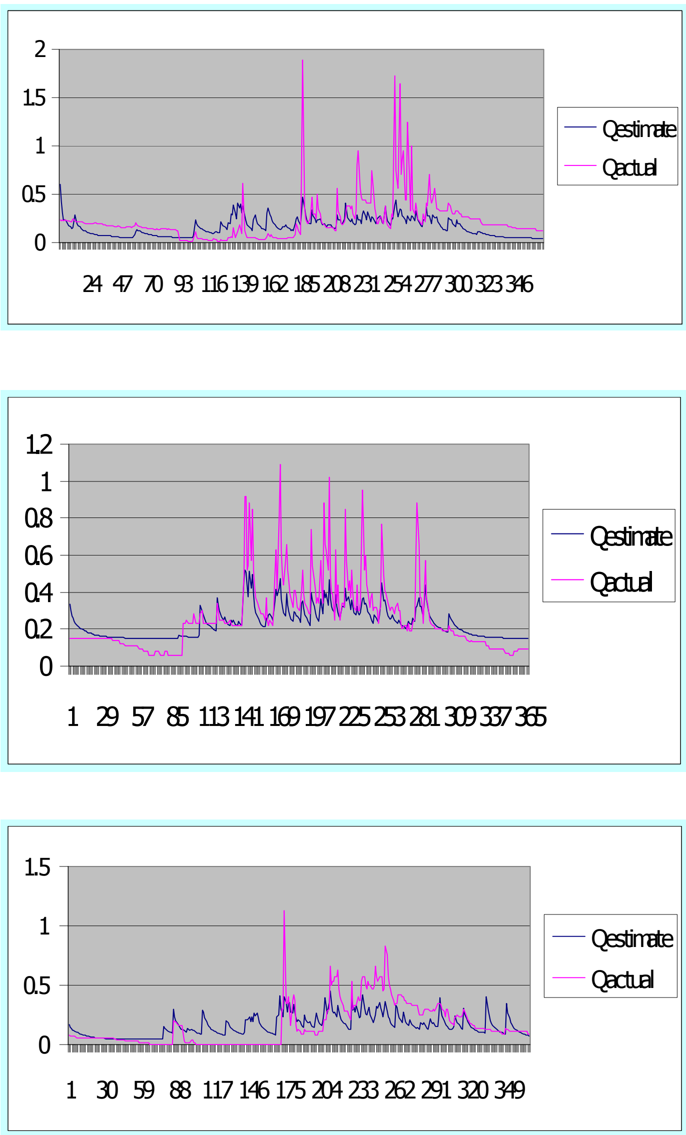

Figure 3: Plot of P.37 watershed estimated and actual daily flow of 1978, 1979 and 1980.

In the second route, the model will search for daily rainfall data and compile it. The data will be used in evaluating soil antecedent moisture content (AMC), which is needed for adjusting CN value to be an initial value of API of each zone (API_{ij}). In addition to API_{ij} value, daily rainfall ($R_{(t)}$) will also be applied in estimating flow of each zone(Q_{ij}) by using Equation (7). The model will calculate flow for every zone in the watershed.

The flow values obtained will be subtracted from rainfall as part of the rainfall infiltrated into the soil. The remaining rainfall from subtraction information will be (1) sent to the CROP MODEL and (2) used in calculation of total outflow that drains from the watershed (Q_w) on the given day by using Equation (10), which is a result of introduction of topographic index (TI_{ij}) into each zone.

In calculating flow for the next day, the model will first find a recession constant (k) for API_{ij} and then adjust it to be API_{ij} of the next day. In adjusting the API_{ij}, Equation (2) will be used in case of no rain and Equation (3) will be used in stead in case of rain on the next day. The adjusted API_{ij} will be applied in calculation of flow for each zone first and then the total flow of the watershed. The detail of how the model works is shown in Figure 4.

7 CONCLUSION AND SUGGESTION

In conclusion, the hydrological model developed can be applied to any watershed. This is because in the structure of the model, all the factors controlling streamflow have been included rather completely. However, the model still needs factors concerning watershed storage of rainwater before the water is released into the stream. Usually, the storage will be differed with space and time resulting in a close estimate in flow quantity is obtained when there is little rain and a close in timing and fluctuation of flow when the rainfall is moderate. As for continuous heavy rain conditions, the prediction of both quantity and the fluctuation of flow will be greatly varied.

Therefore, in order to obtain accuracy in prediction both quantity and fluctuation of flow, a separation of model into low flow and for high flow sub models should be studied by creating conditions involved for using each model such as moisture content or soil water condition in soil profile. The result of the study is then compared with the present model.

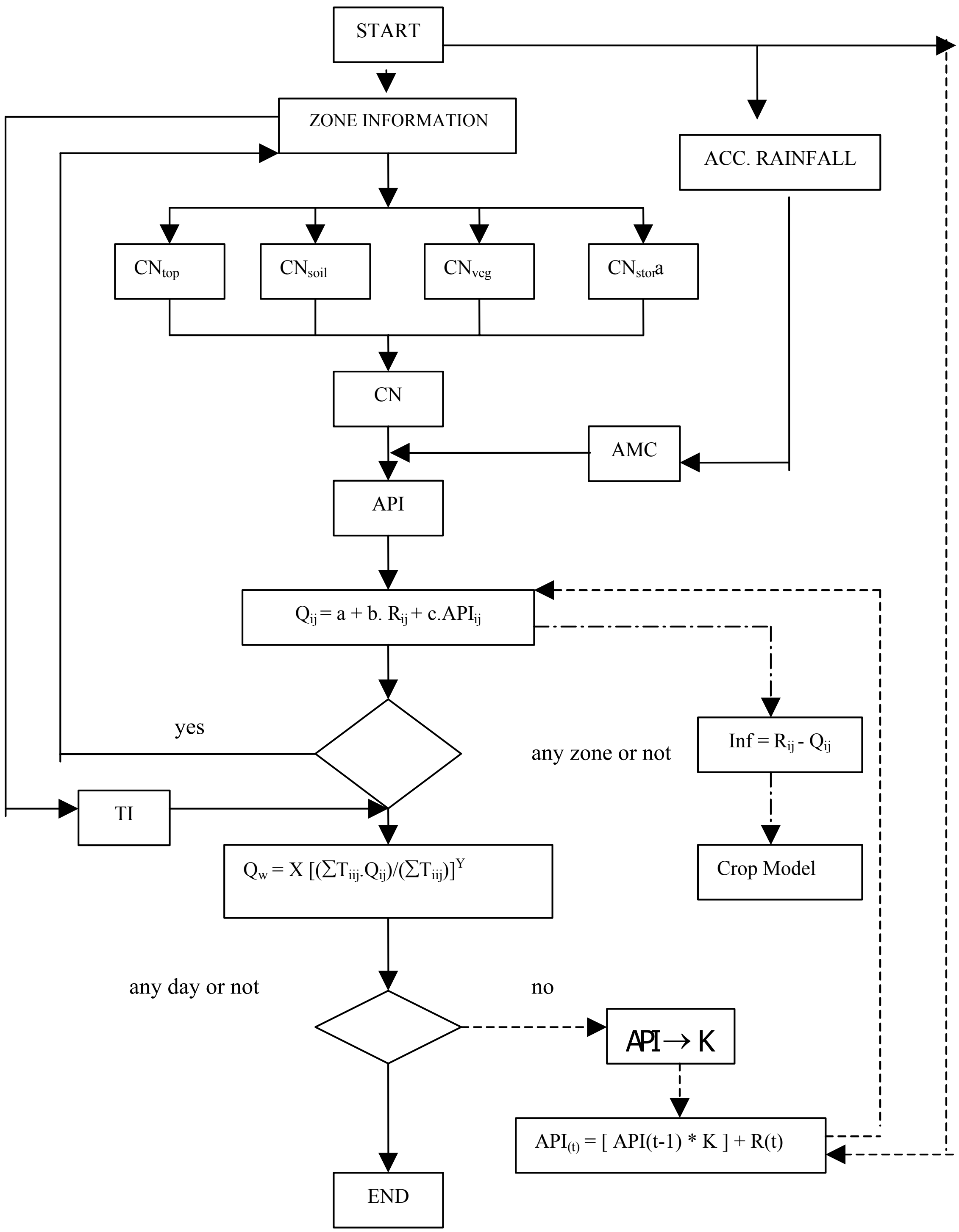

Figure 4. Flow chart of how the hydrological model work

ACKNOWLEDGMENT

We sincerely thank Dr. Barry Croke, Australian National University, Canberra, ACT. Australia, for his editing on a draft of this paper.

REFERENCES

Beven, K J and Kirkby, M J. 1979 A physically based variable contributing area model of basin hydrology Hydrol. Sci. Bull., 24(1):43-69.

Croke, B.F.W., W.S. Merritt and A.J. Jakeman. 2004. A Dynamic Model for Predicting Hydrologic Response to Land Cover Changes in Gauged and Ungauged Catchments, Journal of Hydrology, 291: 115-131.

Cuddy, S. Proceedings of the 2005 International Conference on Simulation and Modelling, V. Kachitvichyanukul, U. Purintrapoban and P. Utayopas (eds).

Hewlett, J. D. and W. L. Nutter. 1969. An Outline of Forest Hydrology. University of Georgia Press. Athens. 137 p.

Lee, R. 198. Forest Hydrology. Columbia University Press. New York. 349 p.

Linsley, Jr. R.K, M. A. Kohler and J. L. H. Paulhus. 1982. Hydrology for Engineer. McGraw-Hill Book. New York.

Ngamsomsuke, K. Ekasingh, B. and Letcher, R. 2005. Crop choise simulation model for integrated water resource assessment and management. Proceedings of the 2005 International Conference on Simulation and Modelling, V. Kachitvichyanukul, U. Purintrapoban and P. Utayopas (eds).

Schwab,G.O., K.K.Barner, R.K.Frevert and T.W. Edminter. 1971. Rainfall and Runoff, pp.63-81. *In* Elementary Soil and Water Engineering. John Wiley & Sons Inc., New York.

Viessman, Jr. W., G.L.Lewis and J.W. Knapp. 1989. Introduction to Hydrology. Harper & Row Publishers, Singapore. 780 p.

Witthawatchutikul, P. 1985. Watershed Research at Rayong, Thailand. pp.57-68. *In* Proceedings Seminar on Watershed Research and Management Practices Theme: Towards More Effective Watershed Management. ASEAN-US Watershed Project. Laguna, Philippines.

Witthawatchutikul, P. 1997. Modelling for Evaluation of Critical Condition of Watershed in Thailand. Ph.D. Thesis. Kasetsart University. 146 P.