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Developing Interception and Root Uptake Systems in Conceptual Hydrological Modelling

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This research aimed at developing a conceptual hydrological model (tank model) with interception and root uptake. It was conducted in a sub-watershed of Coban Rondo located in an area with 89% forest and plantation land. 10-year rainfall and discharge data were used to perform calibration, verification and simulation. The calibration utilised a hybrid optimisation method of random search and genetic algorithm. A water balance equation was developed. The effect of interception and root uptake parameters on the modelling procedure was evaluated using the Nash-Sutcliffe efficiency (NSE) coefficient and paired sample t test. Results showed that, at a significance level of 5%, the interception and root uptake parameters had a significant effect on modelling (t Stat = 8.457 > t critical two-tail = 1.980). The modelling performance increased by 26.98% with an NSE value of 0.91.

Keywords: hydrological model, conceptual, interception, root uptake.

Introduction

A conceptual hydrological model refers to a model that presents a hydrological process in mathematical equations and differentiates between the production function and the search function (Harto, 1993).

Several conceptual rainfall-runoff models include the NAM model (Danish Hydraulic Institute, 1982), the tank model (Sugawara et al., 1983), and the HBV model (Harlin, 1991).

The conceptual model lies between the physically-based model and the black-box model. This type of model is commonly applied to represent essential components that connect hydrological inputs with outputs. In general, the term 'conceptual' is used to refer to models that involve a simple arrangement of a small number of interrelated conceptual elements, each representing the land phase of the hydrological cycle. The most frequently used element in the conceptual model is the storage component. Each storage consists of one input and one or more outputs and is used to represent watershed storage such as surface detention, soil moisture and so forth. Linear storages and channels are used for routing purposes. Fundamentally, conceptual modelling comprises a set of moisture flow equations from one element to the next (Jain, 1993).

Conceptual models were originally developed for modelling small and homogeneous watersheds. Nevertheless, they have been successfully implemented to watersheds that have variations in topography, vegetation and watershed with an area of thousands of square kilometres. The input data required by the conceptual models are very simple and easy to collect (Jain, 1993). These conceptual models started to develop around the 1950s as hydrologists began to understand the approach of a hydrological system (Xu, 2002). Later in the 1960s, lumped conceptual rainfall-runoff models began to develop rapidly with the emergence of a clearer physical understanding of the components of the hydrological cycle (conceptual elements). The interpretation of these interconnected conceptual elements contributes to the determination of the rainfall-runoff relationship of a particular subsystem. The development of the hydrological models in the 1980s led to more complex models aiming to make predictions of changes in land uses and spatial effects of inputs and outputs. Distributed-parameter hydrological models with two- and three-dimensional modelling emerged and developed. Elevation models using maps or satellite imagery began to be applied in hydrological modelling. After the 1980s, hydrological models evolved on a global scale into macro-scale hydrologic models.

This research aimed to develop a conceptual hydrological model with interception and root uptake. The conceptual hydrological model developed is the tank model. The tank model has been extensively developed to analyse various cases of rainfall and discharge relationships (Basri, 2013; Chen et al., 2014; Ou et al., 2017; Phuong et al., 2018). In this study, the development of models was carried out to improve the ability of models in the management of forest and plantation land use. The role of forests and plantations in the hydrological cycle affects the availability of water in the watershed. The availability of groundwater is the amount of water that can be stored in the soil and discharged in a certain period of time (Purbawa and Wirajaya, 2009).

Research on interception, pioneered by Hoppe in 1896, has been conducted for more than a century (Swank, 1968); interception is, in fact, the most widely studied component of water balance in forests. Chaffe et al. (2010) conducted research on the importance of interception data for rainfall-runoff modelling and concluded that the interception information could improve the performance of the model.

The interception process has small to medium scale impacts on the water balance of a watershed due to a local moisture deficit as a result of a decrease in the amount of precipitation and throughfall that reach the soil surface. Xiao and McPherson (2002) found that interception could reduce flooding runoffs. The bigger and shadier the trees, the greater the interception; hence, the smaller the risk of a flooding runoff. This is in line with Slamet (2015) who pointed out that the transformation of natural forests into rubber and oil palm plantations could result in decreased interception and infiltration capacity of saturated soils and increased surface flow. The impact of interception is, in fact, highly influential on the availability of river water in semi-arid watersheds with an ephemeral river system (Love et al., 2010).

Water transport in roots has been studied since the 17th century by Harvey and Malpighi as the earliest pioneers of plant anatomy. Research on the relationship between transpiration and water transport in plants was pioneered by Hales in the mid-18th century (Richter and Cruiziat, 2015). In 1949, Kramer explained that root uptake process might occur with passive absorption through the pull of transpiration (Soni and Soni, 2010). Also, passive absorption plays a more critical role than active absorption (FAPERTA UGM, 2014).

Interception and root uptake in the hydrological cycle consist of different intricate elements. The involvement of contributing factors in both processes results makes the conceptual model a highly complex model. This paper discusses the development of a tank model involving interception and root uptake and an effort to work towards the initial goal of developing a conceptual hydrological model with benefits of simplicity, ease of use, effectiveness and efficiency.

Methods

Study area

The research was conducted in Malang regency, namely at Coban Rondo sub-watershed, which has an area of 18.14 km^2. The research setting was located at an elevation between +900 m and +1100 m above the sea level with the coordinates of longitude between 112.44976° to 112.48768° east and latitude between 7.83841° to 7.94661° south. The land uses in 2017 consisted of forests (59%), plantations (30%), and settlements (11%).

Interception

Interception is a process of rain falling to the surface of vegetation, being held for a moment and then evaporated into the atmosphere or absorbed by the vegetation (Asdak, 2004). Dunne and Leopold (1978) in Hadisusanto (2006) stated that the calculation of rainfall (P) reaches the soil through the canopy (C) or effective rainfall (P-C) can be done using the following equation:

Forest plants:

$$(P\text{-}C)_{forest} = 0.887\ .\ P + 0.088 \quad (1)$$

Mixed plantations:

$$(P\text{-}C)_{mixed\ plantation} = 0.928\ .\ P + 0.269 \quad (2)$$

Interception by annual crop canopies

$$(C) = 0 \quad (3)$$

Root uptake

Root uptake is the movement of water from the soil to the plant. The process is executed by roots of the plant. The uptake of groundwater by roots is related to evapotranspiration, plant growth, soil moisture and oxygen, and groundwater infiltration (Dam, 2013). According to Kramer, the process of root uptake consists of two types of absorption, i.e., active and passive (1949, cited in Soni and Soni, 2010). The active absorption occurs through osmotic and non-osmotic mechanisms (via root respiration), while the passive absorption takes place due to the pull from transpiration.

The application of the concept of water absorption in rainfall-runoff modelling, among others, was implemented by Nurhayati (2008), namely by using the concept of passive absorption in the tank model. The equation used to estimate the root uptake is as follows (Nurhayati, 2008):

$$Uptake = ETo\ .\ \mu\ .\ Kc \quad (4)$$

Where: ETo – evapotranspiration (mm); μ – root uptake coefficient; Kc – crop coefficient.

Model development

a Net rainfall rate ($Pnet_{(t)}$) based on different land uses

$$Pnet_{(t)} = P1_{(t)} + P2_{(t)} + P3_{(t)} + P4_{(t)} \quad (5)$$

Where: *Pb* – rainfall (mm); $P1_{(t)}$ – rainfall on settlements = kl1.$Pb_{(t)}$ (mm); $P2_{(t)}$ – rainfall intercepted in mixed plantations = 0.928 . (kl2.$Pb_{(t)}$) + 0.269 (mm); $P3_{(t)}$ – rainfall on rice fields = kl3.$Pb_{(t)}$ (mm); $P4_{(t)}$ – rainfall intercepted in forests = 0.887 . (kl4.$Pb_{(t)}$) + 0.088 (mm); kl1 – percentage of settlement area; kl2 – percentage of mixed plantation area; kl3 – percentage of rice field area; kl4 – percentage of forest area; subscript (t) = at n^{th} time.

b Actual evapotranspiration (ETc) based on different land uses

$$ETc_{(t)} = ETc1_{(t)} + ETc2_{(t)} + ETc3_{(t)} + ETc4_{(t)} \quad (6)$$

Where: $ETo_{(t)}$ – potentials evapotranspiration (mm); Kc – crop coefficient; $ETc1_{(t)}$ – actual evapotranspiration in settlements = kl1.Kc1.Eto $_{(t)}$ (mm), Kc1 = 1; $ETc2_{(t)}$ –actual evapotranspiration in mixed plantations = kl2.Kc2.Eto $_{(t)}$ (mm); $ETc3_{(t)}$ – actual evapotranspiration in rice fields = kl3.Kc3.Eto$_{(t)}$ (mm); $ETc4_{(t)}$ – actual evapotranspiration in forests = kl4.Kc4.Eto$_{(t)}$ (mm).

c Root uptake based on different land uses

$$\text{Uptake (t)} = \text{CUptake . ETc(t)} \quad (7)$$

Where: CUptake – root uptake coefficient.

Table 1

Crop Coefficient (Kc)

No	Kc value	Wet season	Dry season
1	2	3	4
1	Kc2	0.68	0.75
2	Kc3	0.85	1.20
3	Kc4	0.60	0.60

Source: Nurhayati (2008)

d The following is the water balance in tank 1:

Changes in the water storage in tank 1 ($\Delta Ha_{(t)}$)

$$\Delta Ha_{(t)} = \begin{cases} 0, \ if \ \mathrm{Ha}_{(t)} + \mathrm{Pnet}_{(t)} - \mathrm{Uptake}_{(t)} \leq 0 \\ \mathrm{Ha}_{(t)} + \mathrm{Pnet}_{(t)} - \mathrm{Uptake}_{(t)}, \ if \ \mathrm{Ha}_{(t)} + \mathrm{Pnet}_{(t)} - \mathrm{Uptake}_{(t)} > 0 \end{cases} \quad (8)$$

Where: $Ha_{(t)}$ – water storage at period t (mm); $net_{(t)}$ – Pnet rainfall rate (mm).

Surface flow ($Qa1_{(t)}$)

$$\mathrm{Qa1}_{(t)} = \begin{cases} 0, \ if \ \Delta\mathrm{Ha}_{(t)} < Da_1 \\ (\Delta Ha_{(t)} - Da_1).CQa_1, \ if \ \Delta\mathrm{Ha}_{(t)} \geq Da_1 \end{cases} \quad (9)$$

Sub-surface runoff ($Qa2_{(t)}$)

$$\mathrm{Qa2}_{(t)} = \begin{cases} 0, \ if \ \Delta\mathrm{Ha}_{(t)} < Da_2 \\ (\Delta Ha_{(t)} - Da_2).CQa_2, \ if \ \Delta\mathrm{Ha}_{(t)} \geq Da_2 \end{cases} \quad (10)$$

Subtotal runoff (Qa tot $_{(t)}$)

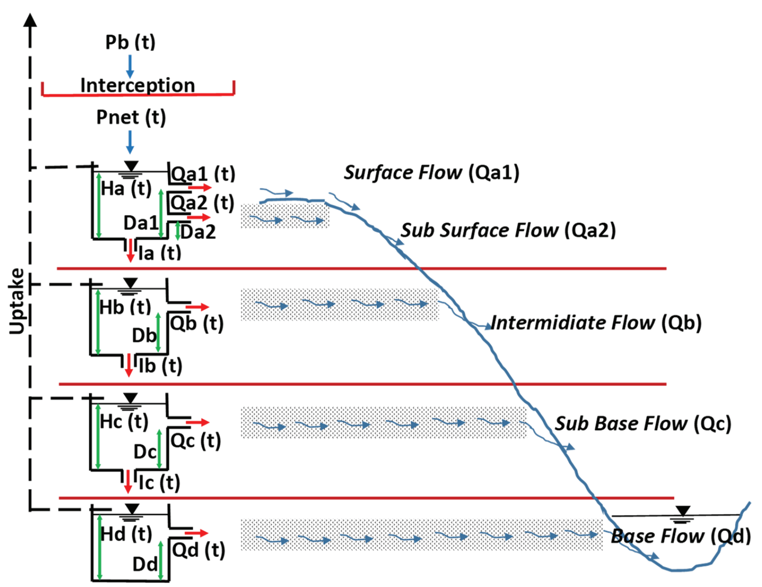
$$\text{Qa tot}_{(t)} = Qa1_{(t)} + Qa2_{(t)} \quad (11)$$

Infiltration ($Ia_{(t)}$)

$$\mathrm{Ia}_{(t)} = \begin{cases} 0, \ if \ \Delta\mathrm{Ha}_{(t)} = 0 \\ CI_a . \Delta Ha_{(t)}, \ if \ \Delta\mathrm{Ha}_{(t)} \neq 0 \end{cases} \quad (12)$$

Fig. 1

Schematic plan of the tank model (Source: own study)



Water balance in tank 1

$$Ha_{(t+1)} = \begin{cases} 0, \ if\ \Delta \mathrm{Ha}_{(t)} - Qa\ tot_{(t)} - Ia_{(t)} \le 0 \\ \Delta \mathrm{Ha}_{(t)} - Qa\ tot_{(t)} - Ia_{(t)},\ if\ \Delta \mathrm{Ha}_{(t)} - Qa\ tot_{(t)} - Ia_{(t)} > 0 \end{cases} \quad (13)$$

Where: CQa_1, CQa_2, CI_a – discharge coefficient of outlets Qa_1, Qa_2, and Ia; Da_1, Da_2 height of outlets Da_1 and Da_2.

The procedure was repeated on tanks 2, 3 and 4 consecutively and for the next simulation time.

The total outflow from the outlet (Q) of each sidewall of the tank is considered as the accumulation of water flow from the system in the watershed, and the equation is as follows:

$$Q_{(t)} = Qa\ tot_{(t)} + Qb_{(t)} + Qc_{(t)} + Qd_{(t)} \quad (14)$$

Model calibration

A hybrid optimisation algorithm model of random search (RS) and genetic algorithm (GA) was developed to accelerate the optimisation process of calibrating the model parameters. The optimisation process began with implementing the RS method up to a certain iteration limit with fitness value under certain criteria. In this study, the criteria of fitness value were Nash parameters with positive values close to one. In the next stage, the accuracy of the optimisation results by the RS method was improved by using the GA method and hence obtaining the best and homogenous population.

Model evaluation

a Nash–Sutcliffe efficiency coefficient (NSE)

The model performance was evaluated using NSE proposed by Nash and Sutcliffe (1970), as follows:

$$NSE = 1 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2} \quad (15)$$

Where: n is the total number of observed data during the period of observation, Oi is the data of ith observation, is the average of the observation data, and Pi the output value of the ith model. The NSE values range between 1.0 and - ∞, in which a value of 1.0 indicates a very well performed model.

b Paired sample t test

Differences in the model before and after modification were examined by a paired sample t test.

$$t = \frac{\bar{X}_1 - \bar{X}_2}{\sqrt{\frac{S_1^2}{n_1} + \frac{S_2^2}{n_2} - 2r\left(\frac{S_1}{\sqrt{n_1}}\right)\left(\frac{S_2}{\sqrt{n_2}}\right)}} \quad (16)$$

Where: x = mean of sample 1, $\bar{x}_2$ = mean of sample 2, S_1 = standard deviation of sample 1, S_2 = standard deviation of sample 2, S_1^2 = variance of sample 1, S_2^2 = variance of sample 2, r = correlation between the two samples. The statistical analysis was carried out using the Analysis ToolPak in Excel.

Results and Discussion

The analysis results of the effect of interception and root uptake on conceptual hydrological modelling are presented in Tables 2 and 3 and Fig. 2.

Table 2

Paired sample t test between the discharge of the model without interception-root uptake and the model with interception-root uptake

Parameters	Without interception-uptake	With interception-uptake
1	2	3
Mean	0.615	0.485
Variance	0.107	0.061
Observations	120	120
Pearson correlation	0.862	
Hypothesised mean difference	0	
Df	119	
t Stat	8.457	
P(T<=t) one-tail	4.034E-14	
t Critical one-tail	1.657	
P(T<=t) two-tail	8.068E-14	
t Critical two-tail	1.980	

Testing at α = 0.05

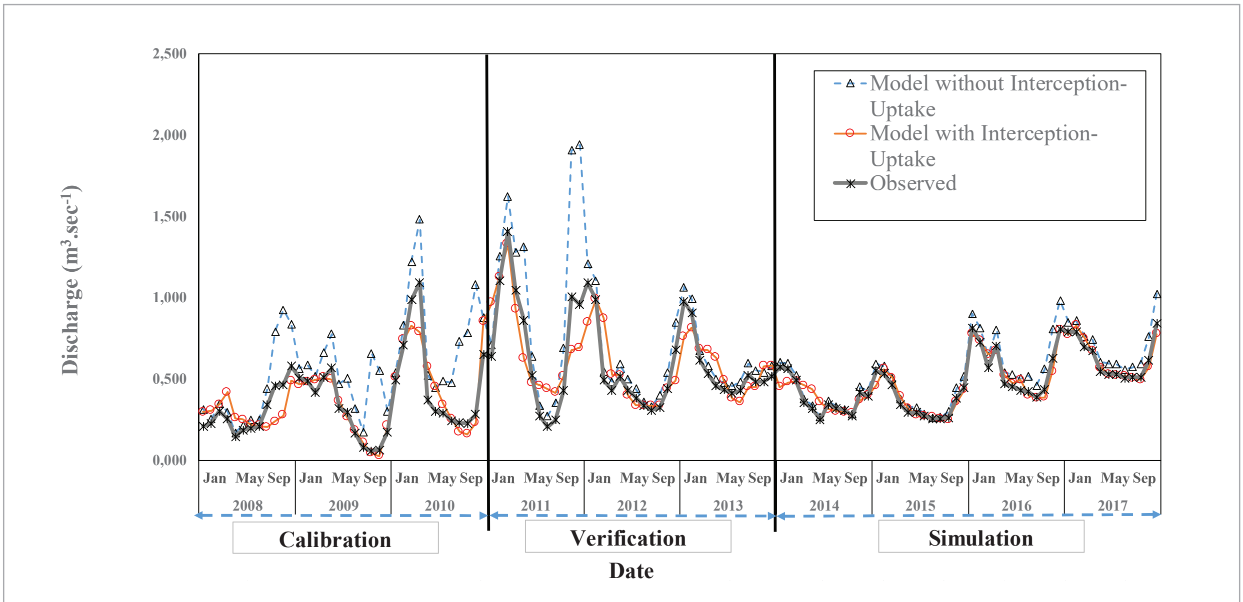
Testing result: t Stat = 8.457 > t Critical two tail = 1.980, thus H0 was rejected.

Conclusion: the tank model with interception-root uptake made a significant difference to the modelling performance, i.e., it increased by 26.98%.

Source: own study.

Fig. 2

Comparison of discharge between the model and observation



Source: own study

Table 3

Nash-Sutcliffe efficiency (NSE) coefficient

Process	Nash-Sutcliffe Efficiency (NSE) Coefficient		% of NSE improvement
	Without interception-root uptake	With interception-root uptake	
1	2	3	4
Calibration	-0.49	0.77	259%
Verification	0.23	0.71	208%
Simulation	0.81	0.91	14%

Source: own study

The analysis results showed the pronounced effect of interception and root uptake on conceptual hydrological modelling. The finding concurs well with that of Gerrits (2010) studying the role of interception in the hydrological cycle. Interception is a key process in a hydrological cycle that involves significant changes in the water balance and affects subsequent processes in both quantity and time. It is the major cause of the nonlinearity of the hydrological processes in the watershed. It occupies a crucial place in the hydrological cycle. Gerrits (2010) also pointed out that interception had different roles in the hydrological cycle. The most important role is to reduce rainwater through evaporating the water stored on the canopy so that infiltration is minimised. The second role is to influence the spatial distribution of infiltration that affects the soil moisture pattern and the sub-surface flow path. The last role is to redistribute the flow of water over time since the spatial variability of storage capacity and rainfall causes spatially different delay times.

Root uptake is one of the functions of transpiration. Hirasawa et al. (1987) found how the transpiration rate was nearly equal to the root uptake rate. Root uptake, in various hydrological models, is described as a sink term in the Richards' equation of water flow in unsaturated soils (Richards, 1931). Nurhayati (2008) developed a root uptake model based on the concept of passive absorption, meaning that the absorption of water by roots is a function of actual evapotranspiration. The amount of water absorbed by plant roots is determined by multiplying the root uptake coefficient (C_{Uptake}) by the actual evapotranspiration. The root uptake coefficient is assumed to represent plant and soil characteristics that affect the root uptake process. The process of modeling the root uptake begins with water absorption by the roots in the first tank. If the water requirement in the first tank cannot be fulfilled, the roots will absorb water from the second tank according to the movement of capillary water in the soil. The process will be repeated up to the fourth tank to meet the water requirement.

This research also revealed that interception and root uptake contributed to a decrease in the water volume of the model's water balance.

Conclusions

The results of this study proved that the parameters of interception and root uptake exerted a significant effect on the conceptual hydrological modelling. The findings of this research are in line with previous results put forward, among others, by Hirasawa et al. (1987), Nurhayati (2008), Chaffe et al. (2010), and Gerrits (2010), namely: 1) by entering interception and root uptake parameters can improve the performance of hydrological models, 2) interception and root uptake affect the water balance in hydrological modelling, and 3) passive root uptake is affected by evapotranspiration.

The tank model was developed by incorporating interception and root uptake factors while keeping working towards the initial goal of developing a conceptual hydrological model with benefits of simplicity, ease of use, effectiveness and efficiency.

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Konceptualaus hidrologinio modeliavimo sulaikymo ir įvedimo sistemų kūrimas

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Šio tyrimo tikslas - sukurti koncepcinį hidrologinį modelį (bako modelį) su perėmimu ir šaknų įsisavinimu. Jis buvo vykdomas Coban Rondo baseine, esančiame rajone, kuriame yra 89% miško ir plantacijų. Kalibravimui, patikrinimui ir modeliavimui atlikti buvo naudojami 10 metų kritulių kiekio ir išleidimo duomenys. Kalibravime naudojamas hibridinis atsitiktinės paieškos ir genetinio algoritmo optimizavimo metodas. Buvo sukurta vandens balanso lygtis. Perėmimo ir šaknies įsisavinimo parametrų poveikis modeliavimo procedūrai buvo įvertintas naudojant Nash-Sutcliffe efektyvumo (NSE) koeficientą ir suporuotą mėginio t testą. Rezultatai parodė, kad reikšmingumo lygis 5%, perėmimo ir šaknies įsisavinimo parametrai turėjo reikšmingą įtaką modeliavimui (t Stat = 8.457> t kritinis dviejų ašių = 1.980). Modeliavimo efektyvumas padidėjo 26,98%, o NSE vertė - 0,91.

Raktiniai žodžiai: hidrologinis modelis, šaknies įsisavinimas.