

Modeling runoff dynamics from zero-order basins: implications for hydrological pathways

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Abstract:

Although zero-order basins (geomorphic hollows) are important components of headwater catchments, their hydrologic regime has not been thoroughly investigated. A multi-tank model approach is used to simulate flow from zero-order basins in Hitachi Ohta Experimental Watershed, Japan, and simulations are compared with six months of wet season flows. A three-tank model accurately simulated runoff for the 6-month period from basin (FA) with two zero-order basins and deep soils, whereas a two-tank model performed satisfactorily in a zero-order basin with shallower soils (ZB). Characteristics of flow paths were evaluated and the concept of “threshold response” was assessed in simulations. In FA, preferential flow from the upper outlet of Tank 1 only occurred during the two largest storms; no overland flow was simulated. Less rapid subsurface flow emitted from the side outlet of Tank 2 during large and several moderate-size storms. During small storms, no overland, preferential, or subsurface flows occurred. Water depth in Tank 3, which indicates shallow groundwater storage in FA, is highly correlated with 30-day antecedent rainfall. The concept of “threshold response” is evidenced by intermittent quick and moderate flows from Tanks 1 and 2, respectively.

KEYWORDS hydrogeomorphic model; hydrologic threshold; stormflow; preferential flow; tank model

1. INTRODUCTION

Mountain headwaters often contain geomorphic hollows (zero-order basins) that are important source areas and sinks for runoff, solutes, sediment, and biota in headwater catchments (e.g., Dietrich and Dunne, 1978; Tsuboyama *et al.*, 2000). Several investigations in Japan found that zero-order basins with shallow soils generate significant storm runoff once a threshold of saturation is reached (Sidle *et al.*, 1995; Tsuboyama *et al.*, 2000). Although these hollows are often ignored in current land management, their importance to overall catchment function is gradually being recognized.

Herein we attempt to model the “threshold response” in zero-order basins as first suggested by Sidle *et al.* (1995) and later elaborated upon and expanded into a hydrogeomorphic conceptual model of stormflow in headwater catchments (Sidle *et al.*, 2000; Tsuboyama *et al.*, 2000).

These earlier investigations found that zero-order basins exhibited hydrologic “response” once antecedent moisture in soils reached a specific “threshold”; outflow from the basins rapidly increased thereafter. To approximate antecedent moisture in hollows for estimating hydrological thresholds, Sidle *et al.* (2000) used 30-day antecedent rainfall (API_{30}); this threshold was influenced by soil depth.

The motivation for this study is based on these earlier findings. Here we develop a storm-runoff model for zero-order basins that considers discrete flow pathways in zero-order basins – i.e., overland flow, biomat/preferential flow, subsurface flow, and shallow groundwater flow. The unique characteristics and variations of each pathway are evaluated and the concept of “threshold response” is assessed.

2. METHODOLOGY

2.1 Study area

To develop a model of hydrologic response from zero-order basins, we focus on two headwater components of the forested Hitachi Ohta Experimental Watershed located in the eastern portion of Honshu, Japan (latitude: 36°34'N; longitude 140°35'E; Figure S1 in Supplements). The catchment is deeply incised with metamorphic bedrock exposed in channels. Average annual precipitation is 1460 mm with two wet seasons: a rainy season (Baiu) in early summer and an autumn typhoon season. Clay loam soils are covered by a thin organic horizon and range in depth from 0.44 to 4.15 m throughout the catchment. Hillslope gradients range from 25 to 45°, with a mean gradient of 32.4°. A detailed description of this site can be found in Sidle *et al.* (1995).

Within the 2.48 ha basin FB at Hitachi Ohta are two gauged subcatchments comprised of zero-order basins. Basin ZB (0.25 ha) is a deeply incised, unchanneled hollow with steep (mean gradient 33°) sideslopes. Average soil depth in ZB is 1.4 m, ranging from 0.4 m in some locations near the hollow axis to 4.2 m near the topographic divide. Basin FA is larger (0.84 ha) and contains a very short perennial stream; more than 90% of this basin is comprised of two zero-order basins with gentler slopes (mean gradient 27°) and deeper soils (mean depth 2.1 m; range 0.4–4.7 m). We compare our simulations with flow records from ZB and FA for a 6-month period from 1 May to 31 October 1992.

2.2 Field methods

Precipitation was measured with recording and storage gauges at a meteorological station located in an open site

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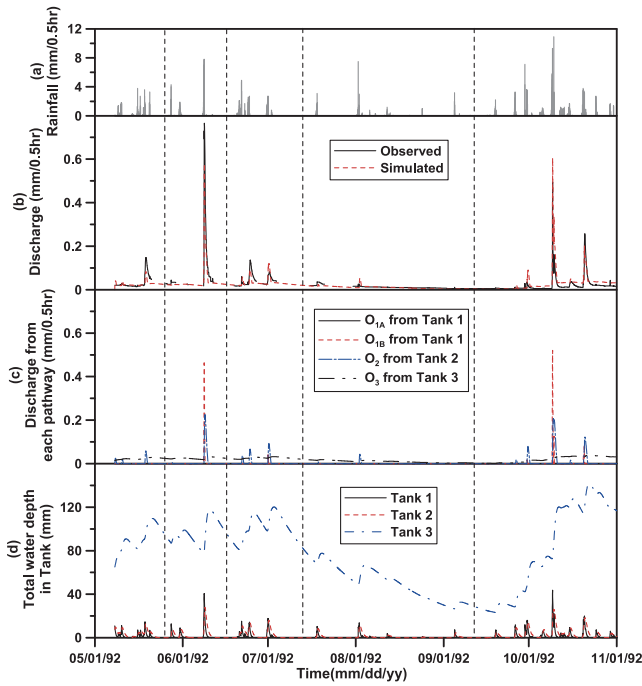


Figure 1. Observed and simulated runoff from FA by the three tank model for the 1992 wet season

about 250 m north of the outlet of ZB. Tsuboyama (2006) correlated these rainfall records with short-term data collected at a canopy interception plot near ZB and concluded that rainfall was uniform over the catchment. Rainfall data were collected every 10 min and aggregated into 30 min intervals for use in our modeling study (Figures 1a and 2a).

Discharge was continuously recorded at calibrated 60° V-notch weirs at the outlets of FA and ZB. In ZB there was no perennial stream, thus outflow from this basin only occurred during selected storms. Streamflow data were collected and aggregated for the same time intervals as rainfall for use in our model (Figures 1b and 2b).

3. MODELING CONCEPT

3.1 Modeling justification and concepts

We used a modified tank model to simulate long-term storm runoff processes at Hitachi Ohta. The tank model is a conceptual lumped hydrologic model introduced by Sugawara (1961). The model consists of a combination of linear or non-linear tanks in which runoff and infiltration occur from the side and bottom outlets of the tanks, and tanks include a storage component (Yoon, 2007). Tank models are becoming popular due to their simple structure, easy calculations, and better performance in simulating runoff compared to other models (e.g., Yokoo *et al.*, 2001).

Tank models have been widely applied to various aspects of storm-runoff modeling, including integrating artificial neural networks for parameter optimization (Chen and Adams, 2006), inserting a conceptual rainfall-infiltration process (Park and Cho, 2006), improving the unit hydrograph concept (Yue and Hashino, 2000), and establishing a method for evaluating model parameters (Yokoo *et al.*, 2001). While

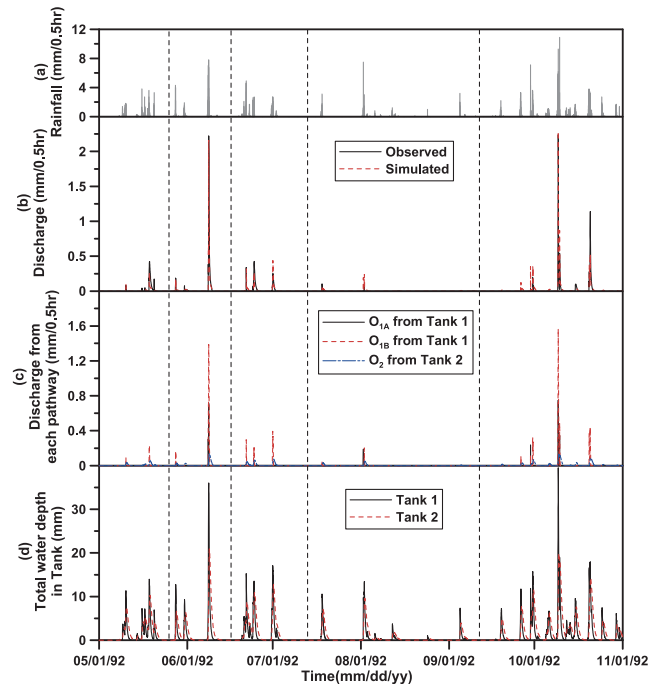


Figure 2. Observed and simulated runoff from ZB by the two tank model for the 1992 wet season

these studies applied tank models for different purposes, all applications included hydrologic pathways such as overland flow, subsurface flow, and groundwater flow. Each pathway can be expressed as a side outlet of a particular tank. Each outlet has different characteristics associated with different runoff coefficients, storage components, and delay times for the occurrence of outflow. To represent various flow pathways, each with their own pattern of outflow, storage, and delay time, a multi-tank approach is needed.

3.2 Development of an appropriate tank model for zero-order basins

To simulate storm runoff processes, a model with three tanks in series was employed for simulations in FA (Figure 3); a simpler two tank model was used for ZB. In the three tank model, Tank 1 represents rapid runoff near the ground surface. The lower side outlet of Tank 1 simulates overland flow. Overland flow is not produced unless the water depth in Tank 1 exceeds the specified depth threshold (d_{1A} in mm) or the rate of increase of water depth in Tank 1 exceeds the specified threshold (I_t in mm/0.5 h) throughout the entire water depth. The former would denote saturated overland flow while the latter implies infiltration-excess overland flow. The upper outlet of Tank 1 represents rapid discharge through near-surface flow paths such as biomat flow (Sidle *et al.*, 2007) and other preferential flow paths. Preferential flow appears to need a separate outlet because water flowing through via these pathways will be more rapid than subsurface stormflow in the mineral soil, but much slower than overland flow. Preferential flow is not produced unless the water depth in Tank 1 exceeds the specified threshold of the upper side outlet (d_{1B} in mm). The bottom outlet of Tank 1 represents infiltration into subsurface soil layers.

The side outlet of Tank 2 represents subsurface flow which is slower than both overland and preferential flows.

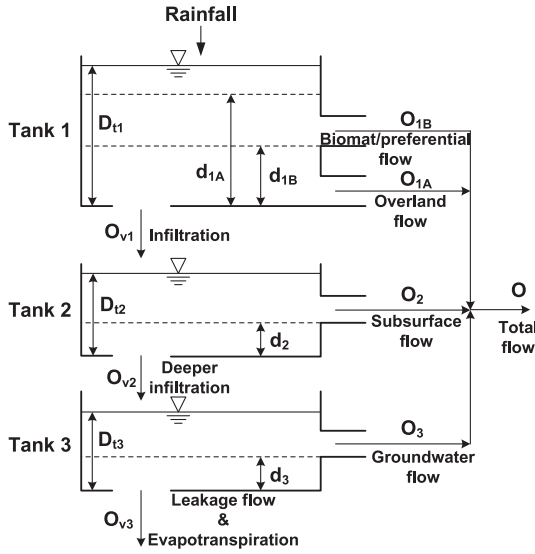


Figure 3. Structure of the tank model with three serial tanks

Subsurface flow is not produced unless the water depth in Tank 2 exceeds the threshold of the side outlet (d_2 in mm), generally creating a lag. Shallow groundwater infiltration occurs through the bottom outlet of Tank 2. The side outlet of Tank 3 represents shallow groundwater flow; slower than subsurface flow. The process of generating shallow groundwater flow is the same as for subsurface flow from Tank 2 (i.e., using parameter d_3 for the specified threshold). The bottom outlet of Tank 3 represents a combination of: (1) ‘leakage’ via deep percolation or rerouting of this ‘leakage’ downstream of the basin outlet; and (2) evapotranspiration (ET) losses. A simpler two tank model, with the same structure (excluding Tank 3) as the three tank model, was employed in ZB to reduce the number of parameters. In this model, the side outlet of Tank 2 depicts combined subsurface and shallow groundwater flow because segregating these two flows becomes ambiguous due to the shallow soil depth in ZB. Also, the concept of deeper groundwater flow contributing to discharge from ZB is irrelevant because no baseflow occurs in this hollow. Thus, in the two tank model, the bottom outlet of Tank 2 has the same function as the bottom outlet of Tank 3 (in the three tank model) – i.e., leakage and ET. In reality, evaporation of intercepted rainfall occurs above the soil surface (i.e., in the canopy) and transpiration occurs within the soil down to bedrock. At Hitachi Ohta, ET usually varies from 0.04 to 0.0625 mm/0.5 h; the maximum value for the entire 6-month period was 0.084 mm/0.5 h. Also, during drier periods there would be no water stored in Tank 1 and most of the ET would actually come from the lower tanks. During wet periods the combined leakage/ET estimate from the lowest tank would likely affect the proportion of surface/preferential flow versus baseflow, but the magnitude of this effect would not be great because of the high rainfall inputs.

The three tank model has five threshold parameters (d_{1A} , d_{1B} , d_2 , d_3 , I_t) and the two tank model has four threshold parameters (d_{1A} , d_{1B} , d_2 , I_t). These thresholds trigger the outflow from each flow pathway (Figure 3). Thus, these thresholds exemplify “threshold hydrologic response”. Each tank outlet has an associated parameter to calculate outflow

using a linear proportionality:

$$\begin{aligned} O_m(t) &= K_m \cdot D_m(t) && \text{for side outlet} \\ O_{v_n}(t) &= f_n \cdot Dt_n(t) && \text{for bottom outlet} \end{aligned} \quad (1)$$

where, $O_m(t)$ and $O_{v_n}(t)$ are outflows from the m th side and n th bottom outlets at time t (mm), respectively; k_m and f_n are the coefficients of the m th side and n th bottom outlets, respectively; $D_m(t)$ is depth from the water surface to the m th outlet (positive in the downward direction) at time t (mm); and $Dt_n(t)$ is total water depth in the n th Tank at time t (mm). Outflow from the m th outlet only occurs when $D_m(t)$ is positive, and k_m and f_n have values from 0 to 1. $O_m(t)$ is calculated by Eq. (1) for each time step. Thus basin runoff is

$$O_{sim}(t) = \Sigma O_m(t) \quad (2)$$

The parameters used in the tank model were optimized by the genetic algorithm (GA; Holland, 1975) and the objective function of R^2 was employed as

$$\text{minimize } 1 - R^2 = \frac{\Sigma(Q_{obs} - Q_{sim})^2}{\Sigma(Q_{obs} - \overline{Q_{obs}})^2} \quad (3)$$

where, Q_{obs} , $\overline{Q_{obs}}$ are the observed outflows and their mean values, respectively, and Q_{sim} is the simulated runoff by the tank model.

The result of sensitivity analysis for the 12 parameters (Figure S2 in Supplements) shows the variation of error in total runoff during the 6-month period plotted against variations of each parameter with other parameters fixed to their optimal values. As threshold parameters (d_{1A} , d_{1B} , d_2 , d_3 , I_t in black) and infiltration coefficients (f_1 , f_2 , f_3 in blue) increase, total runoff decreases; runoff increases as runoff coefficients (k_1 , k_2 , k_3 in red) increase. In general, variations in parameters of Tank 3 have the greatest influence on runoff response (Figure S2 in Supplements).

4. RESULTS AND DISCUSSION

4.1 Seasonal hydrographs of ZB and FA

Runoff from the outlets of FA and ZB was simulated by tank models for the period from 1 May to 31 October 1992 when detailed flow records were available. Model parameters were optimized for the entire period and for five arbitrarily defined sub-intervals within this 6-month period (Table S1 in Supplements). Runoff for the 6-month period simulated by tank models at the outlets of FA and ZB agrees with observed runoff (Figures 1b and 2b, respectively). Many storms during Periods 1, 2, and 3 were a bit under-predicted because of high antecedent moisture; in contrast, storms during Periods 4 and 5 tend to be over-estimated (Figures 1b and 2b). Ratios of observed to simulated runoff from ZB for individual sub-intervals vary from 0.7 to 1.1, however, with the exceptions of periods 4 and 5, all ratios range between 0.9 and 1.1, i.e., $\pm 10\%$ (Table 1). In FA, ratios of observed to simulated runoff ranged from 0.74 to 1.02; excluding period 4, this range is 0.9 to 1.02. As such, model performance was slightly better in FA than ZB, but reasonable in both basins.

4.2 Within-basin responses

The function and response of the various flow pathways

Table 1. Outflow simulated from various outlets in different periods and zero-order basins

Basin	Period	Total outflow from each outlet (mm)						
		O _{1A}	O _{1B}	O ₂	O ₃	O _{sim}	O _{obs}	O _{sim} /O _{obs}
Zero Order Basin (ZB)	1	0.00	7.78	4.88	—	12.66	12.40	1.02
	2	2.49	21.54	4.82	—	28.85	31.09	0.93
	3	0.00	3.23	13.52	—	16.75	16.50	1.02
	4	0.00	0.80	0.00	—	0.80	0.95	0.84
	5	0.76	27.28	2.43	—	30.47	42.18	0.72
	Entire	3.19	57.95	41.37	—	102.51	103.12	0.99
Forest Basin A (FA)	1	0.00	0.00	8.96	12.35	18.04	20.03	0.90
	2	0.00	1.28	18.70	26.90	32.54	33.91	0.96
	3	0.00	0.29	7.26	30.97	25.41	25.70	0.99
	4	0.00	1.11	0.00	28.49	19.39	26.30	0.74
	5	0.00	3.31	16.50	22.47	42.26	46.30	0.91
	Entire	0.00	12.15	36.11	155.91	155.01	151.89	1.02

The parameters of each sub-period or the entire period shown in Table S1 were used.

in FA is illustrated by simulated discharge from the different tank outlets (Figure 1c). Quick flow from the upper side outlet of Tank 1 (O_{1B}; preferential flow) only occurred during the two largest storms in which discharge increased and declined rapidly (Figure 1c). Less rapid subsurface flow response (mostly via the soil matrix) emits from the side outlet of Tank 2; subsurface flow occurred during several moderate-sized storms in addition to larger storms. During small storms, no flow occurred from the side outlets of either Tanks 1 or 2, indicating no overland, preferential, or lateral subsurface flow. Rainfall during small storms infiltrates into Tank 3 through the bottom outlets of Tanks 1 and 2, and contributes to baseflow from the side outlet of Tank 3. The side outlet of Tank 3 is critical in controlling the generation of slower baseflow; Tank 3 stores more water compared to the other tanks. Also, the concept of “threshold response” (Sidle *et al.*, 2000) can be explained by intermittent occurrences of quick and moderate discharge from Tanks 1 and 2, respectively.

Perennial discharge does not occur from the shallow soils in ZB (Figure 2c). As such a three-tank model is not necessary in ZB because Tank 3 plays no role in generating baseflow. A three tank model is appropriate in FA because Tank 3 controls the dynamics of the reservoir related to both storage and slow release of baseflow. The water depth in Tank 3 at the onset of each event during the 6-month period of 1992 is highly correlated with 30-day antecedent rainfall (API₃₀) (Figure S3 in Supplements). Thus, FA has a larger storage capacity due to its deeper soils compared to ZB with shallower soils. These results agree with the findings of Sidle *et al.* (2000).

4.3 Comparison of total outflows from each pathway

The proportions of total outflow through each pathway relative to total outflow from the basins vary seasonally (Table 1). For ZB, the proportions of total outflow through the outlets of Tank 1 in Periods 2 and 5, during which large storms occurred, are larger than these proportions of rapid flow (overland and preferential flows) during other periods. Similarly in FA, the proportions of total outflow through the outlets of Tanks 1 and 2 (preferential and subsurface flows) during Periods 2 and 5 are larger than the proportions during the other periods. These proportional variations in

both FA and ZB appear to be strongly associated with storm size; i.e., larger storms increase of the proportion of relatively quick flow.

Overland flow from ZB (lower side outlet of Tank 1; Table 1) was only simulated during the two largest storms. During the periods with the two largest storms (Periods 2 and 5), overland flow only comprised $\approx 10\%$ and $\approx 2.5\%$, respectively, of total discharge from Tank 1 (overland flow plus preferential flow). No overland flow was simulated for any storms in FA (deeper soils). The paucity of simulated overland flow in these forested basins agrees with field observations (Sidle *et al.*, 1995).

Responses from each pathway of the tank model are shown for small, moderate, and large storms in FA (Figure 4). During the storm on 30 May 1992, no outflow occurred from the side outlets of either Tanks 1 or 2, indicating that rainfall during the small storm infiltrates into Tank 3 and contributes to baseflow (Figure 4a). The slight increase in baseflow (side outlet of Tank 3) confirms this response and is consistent with field observations. During the moderate-size storm on 20 June 1992, again no overland or preferential flow was simulated (side outlets of Tank 1), while subsurface flow (side outlet of Tank 2) occurred after the rainfall peak. The discharge hydrograph from Tank 2 is clearly distinguishable from the baseflow hydrograph from Tank 3 (Figure 4b). Subsurface flow from Tank 2 rises and declines rapidly and persists only briefly after the storm peak. In contrast, baseflow discharge is elevated both during and after the storm due to groundwater recharge. During the large storm on 8 June 1992, preferential flow finally emerged (O_{1B} side outlet of Tank 1) because of the high water depth in Tank 1 (Figure 4c). Outflows from Tanks 1, 2, and 3 are remarkably different in their hydrologic response. In contrast to outflow from Tank 1, which occurred mostly during the storm, outflow from Tank 2 occurred both during and after the storm and was considerably delayed compared to Tank 1. Furthermore, outflow from Tank 3 (baseflow) responded much more slowly than subsurface flow (Tank 2); baseflow increased slightly during and after the storm and total water depth in Tank 3 continued to increase after the storm (Figure 4c). These simulation results are consistent with field observations in FA.

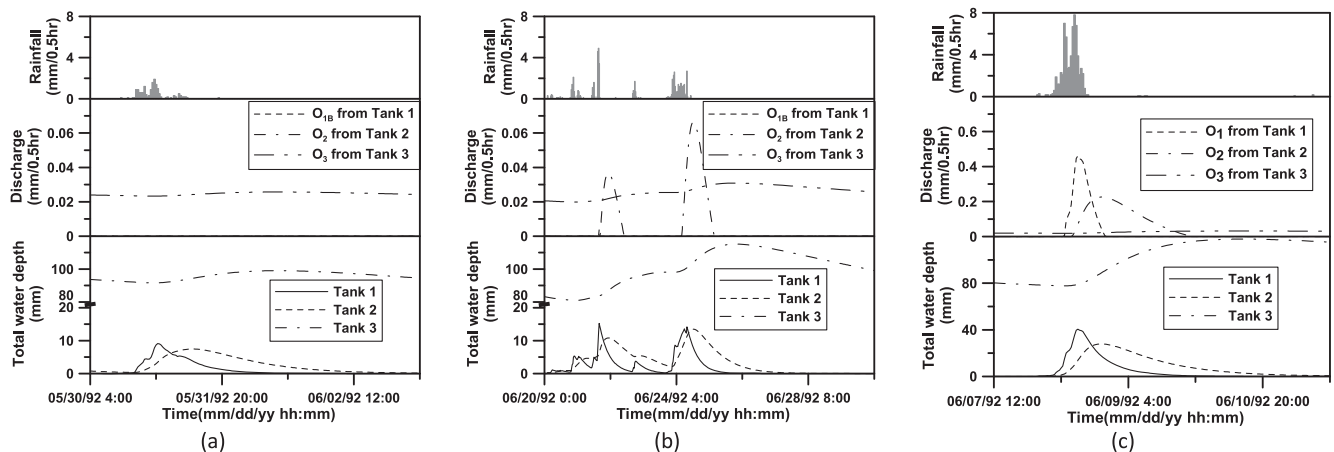


Figure 4. Simulated outflow from each pathway for (a) small, (b) moderate, and (c) large storms

5. SUMMARY AND CONCLUSIONS

Herein we used an innovative application of the tank model to simulate storm-runoff via various pathways from zero-order basins in a catchment where extensive hydrological investigations have been conducted. Also, the concept of “threshold hydrological response” was elucidated from the model simulations. Comparing simulated runoff with observations, the tank model performed well in both FA and ZB; ratios of observed to simulated runoff varied mostly within $\pm 10\%$ or less.

The role of various flow pathways was assessed through modeling simulations and compared with findings from field investigations even though the field data were derived from a soil pit, not the entire hillslope or zero-order basin, so that quantitative validation could not be conducted. In FA (deeper soils), rapid runoff (preferential flow), moderate subsurface flow through the soil matrix, and slow shallow groundwater flow (supporting baseflow) occurred through the outlets of Tanks 1, 2, and 3, respectively. Both rapid and moderate flows were intermittent and affected by “threshold responses”. Simulations in ZB (shallower soils) indicate that a two tank approach is sufficient to model runoff because no shallow groundwater flow contributed to baseflow. Thus, the shallower soil in ZB has a smaller storage capacity than FA. Very importantly, the proportion of total outflow from each pathway varies strongly with storm size. Large storms increase of the proportion of relatively rapid flow and rainfall from small storms mostly contributes to baseflow. Simulations are corroborated by field results (e.g. Sidle *et al.*, 1995) and have important implications for flood prediction, solute transport, and erosion processes. The models described herein that characterize flow pathways and quantify storm runoff from zero-order basins provide a useful component for developing a catchment-wide model that focuses on these hydrogeomorphic concepts of stormflow that can be tested against field data.

REFERENCES

- Chen J, Adams BJ. 2006. Integration of artificial neural networks with conceptual models in rainfall-runoff modeling. *Journal of Hydrology* **318**: 232–249. doi:10.1016/j.jhydrol. 2005.06.017.
- Dietrich WE, Dunne T. 1978. Sediment budget for a small catchment in mountainous terrain. *Zeitschrift für Geomorphologie N.F. Suppl.* **29**: 191–206.
- Holland J. 1975. Adaptation in natural and artificial systems. The University of Michigan Press: Ann Arbor.
- Park H, Cho W. 2006. Derivation of a tank model with conceptual rainfall-infiltration process. *Journal of Korea Water Resources Association* **39**(1): 47–57 (in Korean). doi: 10.3741/JKWRA.2006.39.1.047.
- Sidle RC, Tsuboyama Y, Noguchi S, Hosoda I, Fujieda M, Shimizu T. 1995. Seasonal hydrologic response at various spatial scales in a small forested catchment, Hitachi Ohta, Japan. *Journal of Hydrology* **168**: 227–250. doi:10.1016/0022-1694(94)02639-S.
- Sidle RC, Tsuboyama Y, Noguchi S, Hosoda I, Fujieda M, Shimizu T. 2000. Stormflow generation in steep forested headwaters: a linked hydrogeomorphic paradigm. *Hydrological Processes* **14**: 369–385. doi:10.1002/(SICI)1099-1085(20000228)14:3<369::AID-HYP943>3.0.CO;2-P.
- Sidle RC, Hirano T, Gomi T, Terajima T. 2007. Hortonian overland flow from Japanese forest plantations – An aberration, the real thing, or something in between? *Hydrological Processes* **21**: 3237–3247. doi:10.1002/hyp.6876.
- Sugawara M. 1961. On the analysis of runoff structure about several Japanese rivers. *Japanese Journal of Geophysics* **2**(4): 1–76.
- Tsuboyama Y, Sidle RC, Noguchi S, Murakami S, Shimizu T. 2000. A zero-order basin – its contribution to catchment hydrology and internal hydrological processes. *Hydrological Processes* **14**: 387–401. doi:10.1002/(SICI)1099-1085(20000228)14:3<387::AID-HYP944>3.3.CO;2-H.
- Tsuboyama Y. 2006. An experimental study on temporal and spatial variability of flow pathways in a small forested catchment. *Bulletin of the Forestry and Forest Products Research Institute* **5**(2): 135–174.
- Yokoo Y, Kazuma S, Sawamoto M, Nishimura H. 2001. Regionalization of lumped water balance model parameters based on multiple regression. *Journal of Hydrology* **246**: 209–222. doi:10.1016/S0022-1694(01)00372-9.
- Yoon YN. 2007. Hydrology: Fundamental and application. Cheong Moon Gak Publishers: Gyeonggido, Korea (in Korean).
- Yue S, Hashino M. 2000. Unit hydrographs to model quick and slow runoff components of streamflow. *Journal of Hydrology* **227**: 195–206. doi:10.1016/S0022-1694(99)00185-7.