Identification of Internal Flow Dynamics in Two Experimental Catchments

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Abstract Identification of the internal flow dynamics in catchments is difficult because of the lack of information in precipitation-stream discharge time series alone. Two experimental catchments, Hydrohill and Nandadish, near Nanjing in China, have been set up to monitor internal flows reaching the catchment stream at various depths, from the surface runoff to the bedrock. With analysis of the precipitation against these internal discharges, it is possible to quantify the time constants and volumes associated with various flow paths in both catchments.

1. INTRODUCTION

Rainfall-runoff models are used extensively to gain an understanding of catchment dynamics. External time series data, the amount of precipitation and resultant runoff, are utilised in a "black box" approach to infer how the catchment "works". Often only two responses can be identified, one quick and the other slow, with no information gained about the internal flow dynamics of the catchment, such as subsurface flowpaths and how flowpaths may change during storm events. The question of whether the source of the runoff is new rain water or old pre-storm water, either from the saturated zone (groundwater) or pre-storm non flowing water from the unsaturated zone (soil water), also remains unresolved using rainfall-runoff models.

In this paper an Instantaneous Unit Hydrograph (IUH) black box model, in this case the model known as IHACRES (Jakeman et al., 1990; Jakeman and Hornberger, 1993), is used to gain an understanding of the internal flow dynamics of two small experimental catchments, Hydrohill and Nandadish, at the Chuzhou experimental station in southern China. Precipitation, surface flow and subsurface flow data for the two catchments at six (6) minute intervals and covering 3 separate storm events are used to gain some understanding of the flow dynamics of the water at various subsurface levels.

Other methods, using different physical data, can be used in conjunction with IUH models to gain a better understanding of the hydrological response and internal flow dynamics of the catchments. In particular tracer source models, such as isotopic and chemical tracers can be used to build on the hydrological understanding of the catchments gained from IUH models (Robson et al., 1992; Sklash et al., 1976). Isotope hydrograph separation models use conservative tracers, such as ^{18}O, D and tritium to give an indication of the source of the streamflow by separating the streamwater into new rain water and old, pre-storm water. Chemical hydrograph separation models use a variety of chemical tracers, including Cl, SiO^2 and conductivity, to give an indication of the flowpath of the water.

The main focus of this work is to gain as much information from the data about the internal flow dynamics of the catchments as is possible using the IUH model. Comparisons with isotopic and chemical hydrograph separations will be published separately (Kendall et al., in preparation, 1995).

2. MODELS

2.1 Unit Hydrograph Model

The unit hydrograph model used in this work is known as IHACRES. This model extends unit hydrograph theory by assuming a linear relationship not only between quick flow and effective rainfall, but between effective rainfall and other identifiable hydrograph response components. Full details of the model can be found in (Jakeman et al., 1990) and (Jakeman and Hornberger, 1993), and only a brief description is given here.

The model consists of a nonlinear rainfall loss module which converts observed rainfall, $\{r_N\} = (r_1...r_N)$, into effective, or excess rainfall, $\{u_N\} = (u_1...u_N)$, and a linear module which converts the excess rainfall into observed streamflow, $\{q_N\} = (q_1...q_N)$. Usually the two modules use six (6) parameters, also called dynamic response characteristics (Jakeman and Hornberger, 1993), to describe the way in which observed rainfall becomes observed streamflow. Should the linear module identify more (or less) than the usual two (slow and quick) flow components then the number of dynamic response characteristics, and hence parameters, will increase (or decrease).

The nonlinear rainfall loss module transforms the measured precipitation, r_k, into effective rainfall, u_k, using

$$u_k = s_k r_k \tag{1}$$

where s_k is the catchment wetness index, a function of T_k, the temperature at time k and three dynamic response characteristics - τ_w, a time constant for the decline in the catchment wetness index, f, which regulates the degree of temperature dependence of the loss time constant, and c, which is selected to conserve the mass-balance of the catchment. An extra parameter, p, may sometimes be required to account for extra loss of water within the catchment (Ye et al., in press, 1995), so that (1) is replaced by

$$u_k = s_k^p r_k \tag{2}$$

When there are no temperature data available, as is the case with this study, the parameter f, as described above, is not required, and the loss time constant, τ_w is estimated as a constant for all time steps.

The linear module uses a transfer function to allow the rainfall to pass through any combination of stores, in parallel and series, in becoming streamflow. The most common configuration uses two stores in parallel, one attributed to quick flow, $x_k^{(q)}$, and one to slow flow, $x_k^{(s)}$. These combine to yield the streamflow, q_k,

$$q_k = x_k^{(q)} + x_k^{(s)}, \tag{3}$$

with

$$x_k^{(q)} = \alpha_q x_{k-1}^{(q)} + \beta_q u_k \tag{4}$$

and

$$x_k^{(s)} = \alpha_s x_{k-1}^{(s)} + \beta_s u_k. \tag{5}$$

This can be rewritten to give an easier physical interpretation in terms of time constants, τ_q and τ_s, and relative volumetric throughputs, v_q and v_s,

$$\tau_q = -\triangle / \log_e(-\alpha_q) \tag{6}$$

$$v_q = \beta_q/(1+\alpha_q) \tag{7}$$

$$\tau_s = -\triangle / \log_e(-\alpha_s) \tag{8}$$

$$v_s = \beta_s/(1+\alpha_s) = 1 - v_q \tag{9}$$

where $\triangle$ is the sampling interval for the precipitation and streamflow time series. In this case the linear module has three response characteristics, τ_q, τ_s and v_q ($v_s = 1 - v_q$), making a total of 6 parameters for the model. Sometimes all the flow can be explained using just one store. This is the case for the surface flow and shallow interflows in these catchments, and hence only one time constant, τ_q, is needed, and the model then reduces to 4 parameters.

To measure the performance of the model estimate of streamflow, $\hat{q}_i$, three performance statistics are used, the absolute deviation (A), the bias (B) and the observed streamflow variance explained (R^2). These are defined as,

$$A = 1/n \sum_{i=1}^{N} |q_i - \hat{q}_i| \tag{10}$$

$$B = 1/n \sum_{i=1}^{N} (q_i - \hat{q}_i) \tag{11}$$

$$R^2 = 1 - \alpha_e^2/\alpha_q^2, \tag{12}$$

where α_e^2 and α_q^2 are the variance of the model residuals $(q_i - \hat{q}_i)$ and of the observed streamflow respectively.

To find or calibrate the appropriate values of the parameters for a particular data set, the parameter space of two of the parameters, τ_w and f, from the nonlinear module is sampled. The effective rainfall series is then calculated and a simple refined instrumental variable technique (SRIV) used to estimate the linear module parameters (Jakeman et al., 1990). The model output statistics are calculated in the SRIV step. Usually a subperiod of the entire data set is used to calibrate the model, and then those parameters can be used to simulate over other subperiods, with output statistics again being calculated.

2.2 Tracer Separation Models

Tracer separation models (both isotope and chemical) are based on solutions of two simple mass balance equations for stormflow :

$$Q_S = Q_O + Q_N \tag{13}$$

$$Q_S C_S = Q_O C_O + Q_N Q_N \tag{14}$$

where Q is the stream discharge, C is the concentration of the tracer and the subscripts S,O and N indicate stream water, old pre-storm water and new rain water respectively. It should be noted in using tracer separation models several assumptions need to be made about the composition and spatial homogeneity of the ground water and rain water (Sklash et al., 1976).

Results using these mthods will be published separataely (Kendall et al., in preparation, 1995).

3. CATCHMENT DESCRIPTIONS AND DATA

3.1 Catchment Descriptions

The Hydrohill and Nandadish catchments are two of several instrumented catchments located at the Chuzhou Hydrology Laboratory in Chuzhou Province, near Nanjing in China (Kendall and Weizu, 1991).

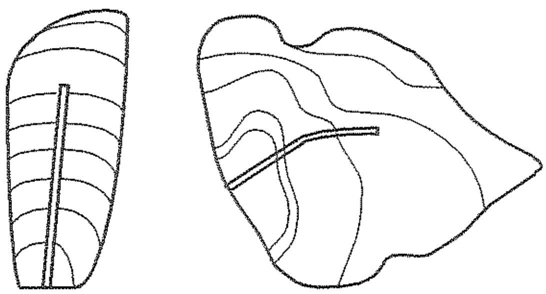

Figure 1: The Hydrohill and Nandadish catchments. The troughs can be seen in the middle of the catchments.

The Hydrohill #2 catchment (herein referred to as Hydrohill) is a totally artificial catchment constructed for the purpose of studying rainfall-runoff processes in detail. The Hydrohill catchment, with an area of 4900 m^2, was constructed with a concrete aquiclude consisting of two intersecting slopes with 14 degree gradients overlaying bedrock covered with 1 metre of silty loam and enclosed with impermeable walls on all sides. The catchment was then filled with enough soil to approximate the natural soil profile, and then grass planted on the surface.

After three years of settling, a drainage trench was dug at the intersection of the two slopes, and the water sampling instrumentation installed. The water sampling instrument consists of five fibreglass troughs, each 40 cm wide and 40 m long, installed longitudinally in the trench (Figure 2). These troughs were stacked on top of each other to create a set of long zero-tension lysimeters, with each trough having a 20 cm lip extending horizontally into the soil to prevent leakage between layers. The water is routed through v-notch weirs located in the gauging station under the hill where discharge is continuously monitored. Water samples were also collected for the purposes of chemical and isotopic analysis.

As illustrated in Figure 2, the first trough collects rain, the next, surface flow and the next three, subsurface flows, 0-30cm, 30-60cm and 60-100 cm respectively. Two smaller lysimeters were installed at a 1-m depth, 1 inside the catchment and one just outside the catchment.

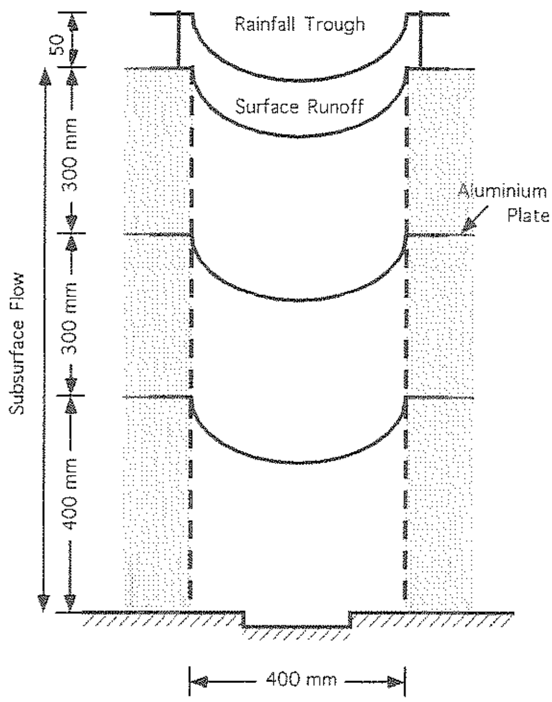

Figure 2: System of troughs and lysimeters used to collect rainfall, surface flow and subsurface interflow.

The Nandadish catchment, with an area of 7800 m^2, is approximately 16 times larger than the Hydrohill catchment and is located 300 metres away. It is a natural catchment with soil cover ranging from 0.5 m to 7 m in depth and is covered by grass, shrubs and small trees. A similar lysimeter system to that used to monitor rain, surface and subsurface flows in the Hydrohill catchment is used, except there are only two subsurface levels, 0-30cm and 30-100cm.

In both catchments a network of access tubes allows for the soil moisture to be measured by neutron gauge, and piezometer wells allow for the water table height to be monitored. The piezometer wells also allow for water sample collection.

3.2 Data

The hydrological data for these catchments include the rainfall, surface and subsurface flows at six (6) minute intervals over 16 days at the catchments and includes three storm events. Due to several problems during collection the data were occasionally inconsistent and various small adjustments were made to correct obvious timing problems.

Water samples were also collected periodically from all the troughs, as well as the rain gauge, to allow for oxygen isotopic composition analysis, at the US Geological Survey's stable isotope laboratory in Reston, Virginia, and chemical composition analysis, at the Panola Mountain Research Project laboratory in Atlanta, Georgia (Kendall et al., in preparation, 1995; Kendall and Weizu, 1991).

4. IDENTIFYING WATER SOURCES AND FLOWPATHS.

To understand the dynamics of a catchment during a storm event, the sources of flows and the flowpaths of the water, both new rain water and old pre-storm water, must be understood. This includes understanding the mixing of waters from various sources, on the surface and in the unsaturated and saturated zones, and the mechanisms by which these waters contribute to surface flow, interflow, unsaturated zone flow and groundwater flow, including macropore and matrix flow.

The unit hydrographs of storm events obtained from previous hydrologic response studies have shown that quick flow dominates slow flow. Meanwhile isotope and chemical hydrograph separations have shown that most stormflow is old, pre-storm water (Bishop et al., 1990; Kendall and Weizu, 1991) as opposed to new rain water. It is unclear whether this old water comes from ground water or soil water (non flowing pre-storm water in the unsaturated zone) and by what mechanism it becomes storm flow. The height of the water table, Figure 3, at various times during the storm event, measured using the access tubes, can help in identifying the source of the storm runoff and interflow.

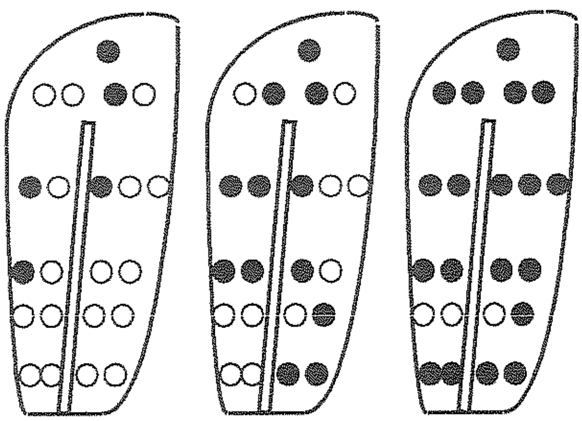

Figure 3: Access tubes which are saturated (filled in circles) in the Hydrohill catchment at 3 different times - from left to right at 105, 110 and 119 hours after midnight July 1.

It is also important to understand the relationship between the dynamic response characteristics and the physical catchment attributes, such as the slope of the catchment, soil depth, vegetation cover etc. Once these relationships are understood any physical change in the catchment can be accounted for by altering the appropriate dynamic response characteristics (Post and Jakeman, in press, 1995). This will also help in predicting what changes in runoff may occur as a result of climate or environmental change.

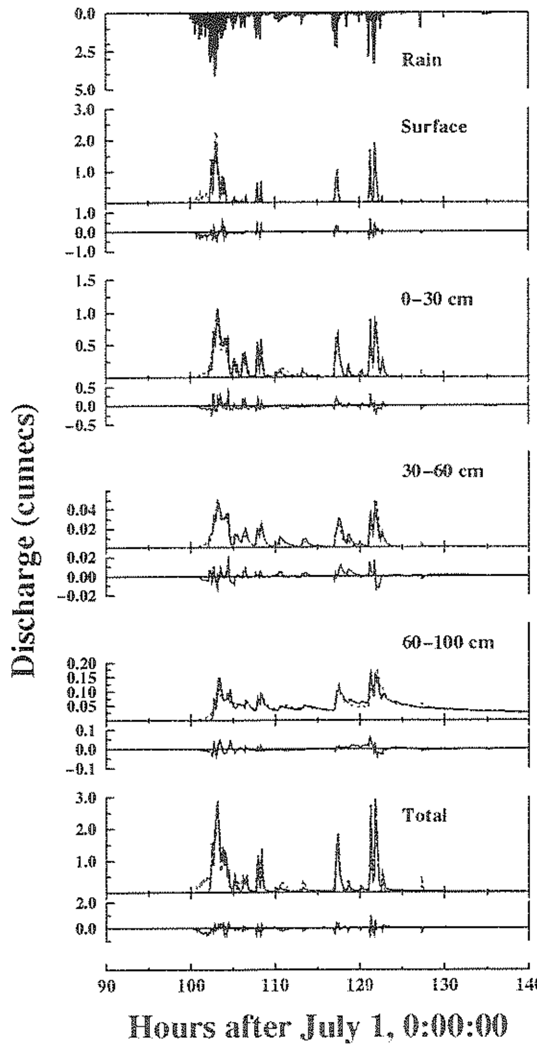

Figure 4: The calibration plots for the Hydrohill catchment, showing the observed (solid line) and modelled (dashed line) flow for each level, with the error below each graph.

4.1 Processes in the Hydrohill Catchment

The Hydrohill catchment is very responsive to precipitation, with the surface and subsurface flows strongly resembling the rainfall hydrographs (Figure4). Flow peaks in the saturated zone (60-100 cm level) are observed shortly after (within 60-90 minutes) the rain and their appearance on the surface and in the shallow subsurface levels.

The height of the water table throughout a storm event will give an indication of the composition of the various flows and interflows being measured. Figure3 shows the state of some of the wells at three different times throughout the first storm event in the Hydrohill catchment, with filled in circles indicating the wells are saturated. At the beginning of the storm all wells were unsaturated. However over the duration of the storm event, almost the entire catchment becomes saturated, with the upslope wells and wells nearest the drainage troughs achieving saturation first (Kendall and Weizu, 1991).

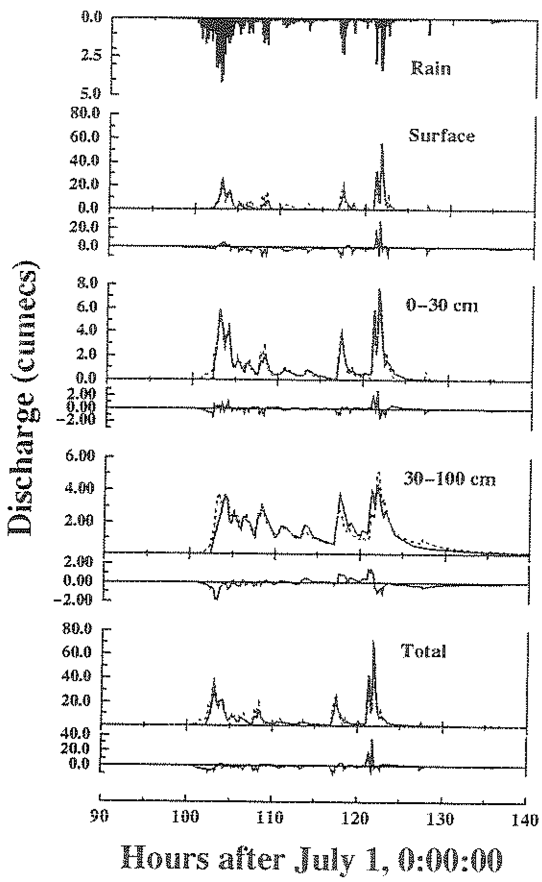

Figure 5: The calibration plots for the Nandadish catchment, showing the observed (solid line) and modelled (dashed line) flow for each level, with the error below each graph.

5. HYDROGRAPH SEPARATIONS

5.1 IUH Separations

The model was calibrated over the first storm event, from 97.5 hours to 140 hours after July 1, 0:00:00. For the surface flow, 0-30 cm and 30-60 cm subsurface flows, it was found that the linear module could best model the catchment response when only one store was used, indicating that almost all the flow at these levels was quick flow. However, for the 60-100 cm level (the 30-100 cm level in the case of Nandadish) two stores, quick and slow components, in parallel were needed to model the catchment response. The model was also calibrated on the total flow, using two stores in parallel to model the catchment responses.

The model fits are judged on the output statistics mentioned above, and on how well the calculated hydrographs capture the important features of the observed flow.

Figures 4 and 5 shows the calibration plots for the Hydrohill and Nandadish catchments. These diagrams show that the model has captured the important features of the observed flow well - namely the timing and magnitude of large peaks and the slow flow characteristics.

Table 1a and 1b show the parameters used for these models. The time constants, τ_q and τ_s, show as expected, that the flow peaks from rain events recess more slowly at the deeper levels than the surface and shallow levels. It is interesting to note however, that the values of τ_w, the time constant for the decline in the catchment wetness index, is consistently larger at deeper depths for Hydrohill, while smaller at deeper depths for Nandadish.

level	τ_w	p	c	τ_q	τ_s	v_s
surface	2	0.8	0.805	0.8	-	-
0-30	97	1.0	0.059	1.9	-	-
30-60	102	1.0	0.064	2.9	-	-
60-100	188	1.0	0.025	3.0	171.4	0.786
total	96	0.5	0.826	1.2	72.0	0.006

Table 1a. The dynamic response characteristics for the Hydrohill catchment.

level	τ_w	p	c	τ_q	τ_s	v_s
surface	214	1.4	0.049	1.3	-	-
0-30	166	1.0	0.026	3.2	-	-
30-100	130	1.4	0.038	5.6	57.1	0.594
total	222	0.7	0.291	1.1	3.9	0.486

Table 1b. The dynamic response characteristics for the Nandadish catchment.

Another measure of the success of a model is the output statistics, as described in section 2. Tables 2a and 2b show the model output statistics for the two catchments. The R^2 values are all above 0.8, showing good agreement between observed and modelled streamflow and the absolute deviation and bias are both low for all models, with perhaps the exception of the total flow data for both catchments.

level	A	B	R^2
surface	0.45	-0.01	0.891
0-30 cm	0.09	-0.01	0.897
30-60 cm	0.07	0.0	0.896
60-100 cm	0.13	0.0	0.872
total flow	1.65	-0.01	0.909

Table 2a. The output statistics for the Hydrohill catchment when calibrating over the first storm event.

level	A	B	R^2
surface	0.25	-0.47	0.816
0-30 cm	0.05	0.01	0.920
30-100 cm	0.09	-0.06	0.867
total flow	6.88	-0.25	0.833

Table 2b. The output statistics for the Nandadish catchment when calibrating over the first storm event.

6. DISCUSSION AND CONCLUSION

Understanding the sources and flowpaths of storm water has important implications for water quality as well as the effects of climate change. An understanding of the Hydrohill catchment, and its similarities and differences in both dynamic response characteristics and physical catchment attributes to the natural Nandadish catchment is important in understanding how natural catchments work.

The difference in the time constants for the surface flow of the two catchments, with the quick flow time constant τ_q being larger for the Hydrohill than the Nandadish catchment, suggests that the differences in surface vegetation have a significant effect. Quick flow takes longer to reach the outlet of the Nandadish catchment, with its vegetation composed of shrubs etc, compared to the grass on the Hydrohill catchment. This has important implications for the clearing of catchments and the replacement of the vegetation which is cleared.

A similar relationship between the time constants τ_q and τ_s, at the subsurface levels, is observed between the two catchments. At the shallower subsurface levels this may be due to macropore flow, with possibly a more extensive macropore network allowing the water to flow more quickly through the unsaturated subsurface soil in the artificial Hydrohill catchment than the more natural Nandadish catchment.

The relationship between the time constant which regulates the catchment wetness index, τ_w, and any physical catchment descriptors is also important. In this case, the time constant for the catchment wetness index increases with subsurface depth in the Hydrohill catchment and decreases in the Nandadish catchment. This may be due to more hydraulically responsive soils in the Nandadish catchment.

While the artificial Hydrohill catchment has significantly different hydrological response characteristics to the natural Nandadish catchment a good deal about the behaviour of other catchments can be gained from their study. Comparing the hydrographs from the IHACRES model with hydrographs obtained from tracer separation models will give further understanding of these processes.

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