# Perceptual Model of Coupled Hydrological and Biogeochemical Responses Based on Reconciliation of Multiscale, Multicomponent Observations

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**Abstract:** The paper presents a successful attempt to link patterns of hydrological and biogeochemical processes, deciphered from observations at catchment scale, with detailed process understanding obtained from a field experiment carried out at the hillslope scale. This work is ultimately aimed at developing a watershed-scale model of coupled hydrological and biogeochemical responses. To gain an understanding of the mechanisms of runoff generation at catchment scale, and to make inferences about internal hydrological processes, we initially carried out a systematic analysis of rainfall-runoff, isotopic (deuterium), and hydrochemical (chloride, nitrate) data at several spatial (6, 12, and 24 $km^2$) and temporal (event, seasonal, inter-annual) scales. Results from this analysis indicated the importance of a shallow perched aquifer (i.e. hydrologic state variable) in controlling both the mechanisms of runoff generation and the nitrate export to the stream. Guided by these findings and also motivated by unresolved questions arising from the analysis, a field experiment was carried out to investigate the temporal and spatial variability of hydrological and biogeochemical processes at hillslope and subcatchment scale. Results from the field experiment have: (1) confirmed the importance of the shallow perched system in controlling the hydrological and the biogeochemical responses at both hillslope and subcatchment scales, and (2) revealed the different roles, of upland and near-stream zones in relation to the two above mentioned responses. Both approaches complemented each other and helped us converge to a common perceptual model of the hydrological and biogeochemical responses, which is very encouraging for generalisation of the results to other catchments. Our future research aims to utilise these findings in a simple but robust modelling framework to describe nutrient cycling accurately and realistically, and to make catchment scale predictions of the hydrological and biogeochemical responses.

***Keywords:*** field experiments; tracer studies; perceptual models; process complexity; hydrological processes; biogeochemical processes.

## 1. INTRODUCTION

Linking hydrological and biogeochemical processes at the catchment scale, in particular the export of nutrients (e.g. nitrate, $NO_3^-$), has been recognized as one of the most challenging problems in catchment hydrology. The increasing need for the development of robust models of nutrient cycling processes in catchments, to enable prediction of the impact of land uses, has become a significant issue. The use of numerical models is limited due to lack of nutrient concentration data at the appropriate spatial and temporal scales and poor understanding of the key processes controlling $NO_3^-$ export at catchment scale. Cirmo and McDonnell (1997) presented a conceptual framework for modelling nitrogen cycling for temperate forested catchments. It considers three key aspects: (1) hydrological pathways (mechanisms of water flow within the catchment), (2) temporal scales associated with those pathways, and (3) biogeochemical processes (i.e. mineralization, nitrification, etc) controlling the availability of nitrogen species for transport.

Ambiguities in results from classical methodologies for separating hydrological pathways (i.e. graphical, numerical models) has led to the use of combined hydrometric-hydrochemical approaches for elucidating the flow pathways and $NO_3^-$ export from catchments (McHale et al., 2002). These approaches have been successful in providing perceptual models of hillslope-catchment flowpaths and $NO_3^-$ export. McGlynn et al. (2002) described how a perceptual model was affected by the methodology, antecedent moisture conditions and event characteristics, and the scale of the studies. Given the complexity of the hydrological and biogeochemical processes and the spatial and temporal scales involved, multi-scale and multi-component observations, and specific and highly focused studies, aimed at determining the spatial and temporal routing of water and nutrients within catchments, are needed.

This paper presents a successful attempt to link patterns of hydrological and biogeochemical processes deciphered from observations at catchment scale, with detailed process understanding obtained from a field experiment carried out at hillslope scale. Both approaches converged to a common perceptual model of the hydrological and biogeochemical responses, providing a sound basis for a robust modelling framework applicable at catchment scale.

## 2. SUSANNAH BROOK CATCHMENT

Susannah Brook (SB) is a 24 km$^2$ catchment, located approximately 25 km east of Perth, Western Australia (WA) (Figure 1). The major land use is devoted to sheep grazing and native pastures, with small areas for stock holding yards and stud farming. Approximately 35% is native forest. Rainfall, streamflow gauging and water quality sampling stations were established in 1981, and monitored since then.

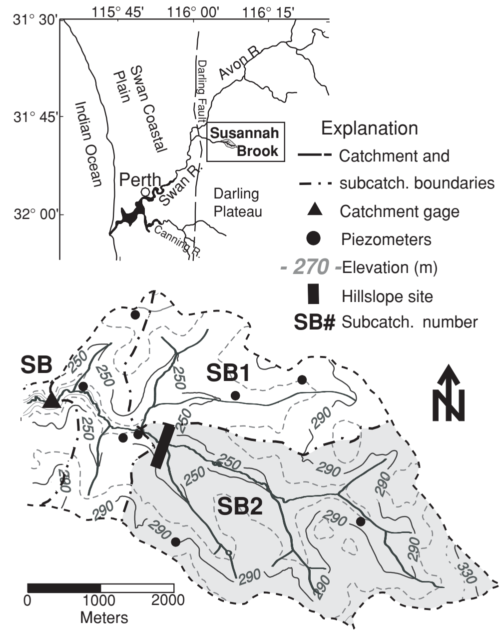


**Figure 1.** Location and map of Susannah Brook.

The catchment has a mean annual rainfall and potential evaporation of 850 and 2000 mm, respectively. Both exhibit strong seasonality, and about 90% of the annual rainfall (a.r) falls between May and November. Streamflow reflects this seasonality and tends to be ephemeral, drying up during summer periods. The soil of the catchment consists of a lateritic profile formed on deeply weathered basement rock. It comprises three zones: ferruginous (gravels), mottled (mottled kaolinitic clays), and pallid (white kaolinitic clay). A perched ephemeral aquifer develops during the rainy season due to differences in hydraulic conductivity between the surficial lateritic layer and the deeper clay zone. There is a strong relationship between soil mapping units and local topography. The lateritic uplands (Dwellingup) occupy the crest and gently undulating terrain. The valley floors are mottled yellow sandy and gravelly duplex soils (Yarragil). The catchment is a tributary of the Swan-Canning estuary system, itself the subject of a large-scale nutrient cycling study and extensive nutrient management strategies. A detailed description of the catchment and instrumentation is given by Turner and Macpherson (1990).

## 3. THE CATCHMENT SCALE ANALYSIS

### 3.1. Previous Study

In a major experimental study, Turner and Macpherson (1990) related hydrological pathways to stream water quality. Stable isotope (deuterium, $^2H$) and hydrochemical (chloride, $Cl^-$, $NO_3^-$) data from rainfall, streamflow, and shallow and deep groundwater, were used to develop an understanding of the mechanisms of runoff generation and $NO_3^-$ discharge. The sampling program provided the hydrological and tracer data at different spatial (SB, and subcatchments SB1 and SB2) and temporal (event, seasonal, and inter-annual) scales. The 1987-1989 study period encompassed a broad range of antecedent conditions for the events monitored: 1987 was an average year (849 mm), 1988 was a wet year (957 mm), and 1989 was a dry year (726 mm). Our catchment scale analysis was an extension of this work, identifying the hydrological controls on the seasonal and inter-annual patterns of $NO_3^-$ export, by addressing the water source contributions to the streamflow at those time scales.

### 3.2. Multi-scale Analysis of the Water Sources

Standard isotopic and chemical hydrograph separation techniques were applied to quantify water sources within the catchment. These methods were used to identify the time source components of the streamflow, separating it into pre-event water (old), and event (new) water. Two mass balance equations were used, one for water and one for the tracer ($^2$H or $Cl^-$):

$$Q_{\mathrm{streamflow}} = Q_{\mathrm{pre-event}} + Q_{\mathrm{event}} \tag{1}$$

$$C_{\mathrm{str}} Q_{\mathrm{str}} = C_{\mathrm{event}} Q_{\mathrm{event}} + C_{\mathrm{pre-event}} Q_{\mathrm{pre-event}} \tag{2}$$

where $Q$ is the volumetric flow rate, $C$ is the tracer concentration, *event*, *pre-event*, and *str* subscripts refer to each time-source component and (combined) streamflow respectively, $C_{event}$ is the tracer concentration from rainfall, and $C_{pre\text{-}event}$ is the tracer concentration in streamflow prior to each rainfall event. Equations (1) and (2) were solved to estimate the pre-event water components of streamflow at each time step, generating the event and pre-event water hydrographs. These hydrographs were integrated over the duration of the events, to obtain estimates of their volumetric contributions to total event flow. An estimate of the area contributing to saturated overland flow ($A_{SOF}$), for each rainfall event, was obtained according to Eshleman et al. (1993):

$$A_{SOF} = \frac{V_{event}}{P} = \frac{\int_{t_b} Q_{event}(t) \cdot dt}{P} \qquad (3)$$

where $P$ is total rainfall and $t_b$ the duration of the event hydrograph.

Fifty rainfall events, covering a wide range of intensity, duration and discharge, were selected. The $^2$H and $Cl^-$ data from 1987 (Figure 2a,b) and 1988, and $Cl^-$ data from 1989, were used to separate the streamflow into two components. This separation was combined with hydrometric data (water table level) and then used to identify the dominant flow pathways within the catchment, their temporal variability and their dependence on antecedent conditions.

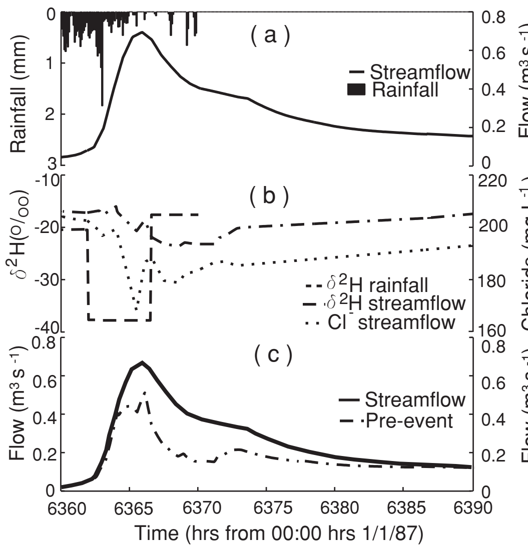


**Figure 2.** Time series in 5-min intervals: ( a ) rainfall and streamflow, ( b ) $\delta^2 H$ ( $^o/_{oo}$, Vienna Standard Mean Ocean Water) and $Cl^-$ , ( c ) streamflow and pre-event hydrographs.

Results clearly indicated that, on a whole-event basis, pre-event water dominated the event response in Susannah Brook (Figure 2c). Event water contributions become significant only during short periods of high rainfall intensities, and wet antecedent conditions. Only 27% of the rainfall events analysed had a volume fraction of pre-event water less than 70%. Similar results were obtained at sub-catchment scale.

On a seasonal scale, there was considerable variability in the contribution of pre-event water to total streamflow and most of the variability appears to be random or event dominated. There was also significant inter-annual variability, which reflected the antecedent wetness of the catchment. The mean annual contribution of pre-event water to streamflow varied between 68% in 1988 (wet year) and 86% in 1989 (dry year). The smaller magnitude in the wet year most likely arises from the higher antecedent wetness, which increases the ability to generate more event water through saturation excess overland flow. The $A_{SOF}$ values showed a clear seasonal trend (Figure 3a). $A_{SOF}$ values increased during the autumn and early winter periods, reaching a maximum value that persisted during the rest of winter, and then slowly declined towards the end of the year. There was also a distinct inter-annual variability with $A_{SOF}$ values reaching a maximum of 13.3% and 7% (of SB area) for the wet and dry years respectively. The above pattern of variability was also observed at SB1 and SB2 (Figure 3b). The shallow subsurface system provided further confirmation of the temporal variability in $A_{SOF}$, as high values were reached when the perched aquifer reached ground level (Figure 3c).

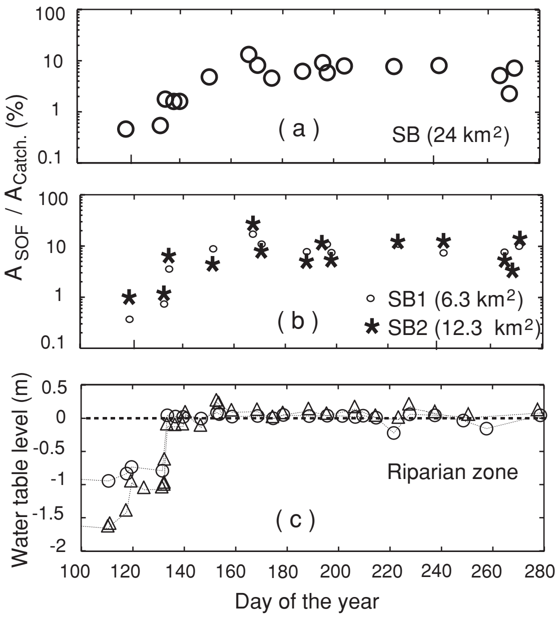


**Figure 3.** Seasonal variation of $A_{SOF}$ and water table levels (1988): (a, b) $A_{SOF}$ for SB, SB1, and SB2, (c) water table level relative to ground surface.

A remarkable finding was the agreement between the temporal dynamics of $A_{SOF}$ values and $NO_3^-$ discharge. The total mass of nitrate discharged (from SB) during each rainfall event was obtained by integrating the product of the instantaneous flow discharge and the nitrate concentrations, over the event duration. Increased $NO_3^-$ discharge occurred during periods when the saturation areas were rapidly increasing (Figure 4). An early $NO_3^-$ discharge occurred on day 135 coincident with the first sharp increase in $A_{SOF}$, and water level of shallow piezometers. The highest $NO_3^-$ discharge occurred on day 153, coincident with another increase in $A_{SOF}$, and the ground manifestation of the perched system. However, after day 153, a sharp decline in $NO_3^-$ discharge was observed while $A_{SOF}$ values remained high. A similar response was observed for SB1 and SB2.

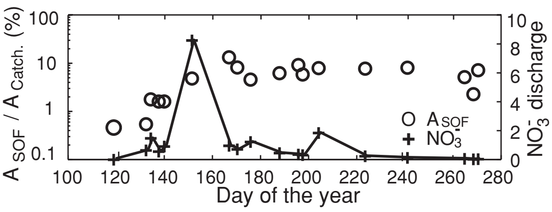


**Figure 4.** Seasonal variation of $A_{SOF}$ and $NO_3^-$ discharge ($NO_3^-$ mass for each rainfall event normalized by the mean annual $NO_3^-$ mass).

This multi-scale analysis was useful in identifying water sources and pathways at different spatial and temporal scales. Firstly, it identified the dominance of the pre-event water component in the stormflow hydrograph at all scales. Significant discharge of pre-event water during storms is an unequivocal proof of the importance of subsurface flow in generating streamflow (Genereux and Hooper, 1998). Secondly, hydrometric data suggested a saturated throughflow mechanism that is coupled to the shallow aquifer. These results and the agreement between the dynamics of $A_{SOF}$ values and $NO_3^-$ discharge signals a flushing mechanism of $NO_3^-$ export from the catchment (Creed et al., 1996), which relates the export of $NO_3^-$ and the rate of expansion of variable source areas.

A number of further questions arose from this analysis. Firstly, similar temporal patterns of $NO_3^-$ concentration among first-order streams, SB1, SB2, and SB were observed. This suggests that the controls on $NO_3^-$ export could occur at the hillslope scale. Secondly, the spatial extent of $A_{SOF}$ appears to be limited to the near-stream zones, and assuming a consistent flushing mechanism, $NO_3^-$ could only be flushed from those areas, as suggested by the decrease in $NO_3^-$ discharge (Figure 4). These observations led us to consider the spatial structure of the hillslope, its hydrological and biogeochemical response, and its relation to $NO_3^-$ export from the catchment.

# 4. HILLSLOPE SCALE EXPERIMENT

## 4.1. Study Site and Data Collection

The study site was located within SB2 near its outlet (Figure 1). Two representative hillslopes (steep and flat slopes) were selected, to investigate the dynamics of the shallow perched aquifer (hydrological state variable). The field experiment focused on the temporal and spatial distribution of water, conservative tracers, nitrogen species, and biogeochemical parameters along upland, mid-slope, and near-stream or riparian zones.

The hillslopes drained by the near-stream zones are mainly agricultural with crop and grass fields for grazing. Hillslope lengths are short (145 to 300 m) with slopes ranging from $10^o$ to $6^o$ (steep hillslope), and from $3^o$ to $1^o$ (flat hillslope), with the higher and lower values corresponding to upland and near-stream (riparian) zones respectively. Soil units at upland zones correspond to the Dwellingup unit, while Yarragil units (Yg4 duplex soils) are found at the riparian zones. Two transects of shallow piezometers from near-stream to upland zones were located perpendicular to the stream (Figure 5).

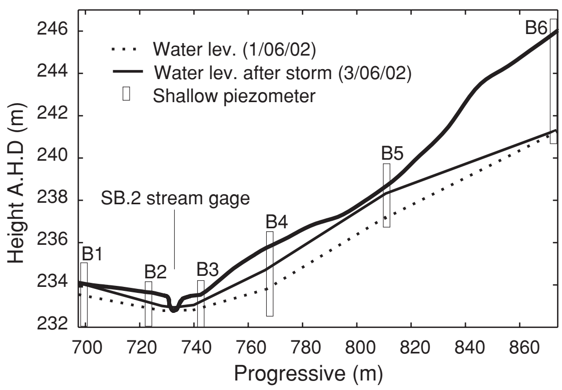


**Figure 5.** Hillsope transects at SB2. Topography, stream stage, and water table elevation are all referred to the Australian Height Datum (A.H.D).

The sampling program was designed to provide information at event scale through the entire study period (May-Dec 2002). Shallow groundwater levels were recorded using pressure water level probes at 10 to 15 min intervals during rainfall events, and 30 min to hourly intervals during intra-event periods. Groundwater quality parameters (i.e. electrical conductivity, pH, redox potential) and samples were measured and collected on a daily basis during rainfall events and every two or three days during intra-event periods. Water samples (filtered and unfiltered) were immediately refrigerated, and stored for analysis. Samples were analysed for Total nitrogen (TN), Ammonia ($NH_3$), Nitrite ($NO_2^-$), Nitrate ($NO_3^-$), and Chloride ($Cl^-$) using an Alpkem Segmented Flow Autoanalyser.

## 4.2.Hydrological and Biogeochemical Response

Different temporal patterns in the dynamics of the shallow aquifer from near-stream and upland zones were observed (Figure 6). Water table levels were more responsive to rainfall events in the near-stream (B1 and B3) than in the upland zones (B6). Water levels exhibited a sharp increase on day 153 in response to the first rainfall event, and surfaced at B1 (flat hillslope), remaining in that position for approximately 70 days. At B3 (steep hillslope) the water table responded to all the rainfall events without reaching the ground surface. In contrast, no response was recorded at B6 (upland) for approximately 8 days after the occurrence of the first event. From around day 160, water table levels continuously increased reaching a maximum around day 200. There were also differences in the event recession limbs of the shallow groundwater hydrographs, with pronounced and undetected changes in the near-stream and upland zones, respectively.

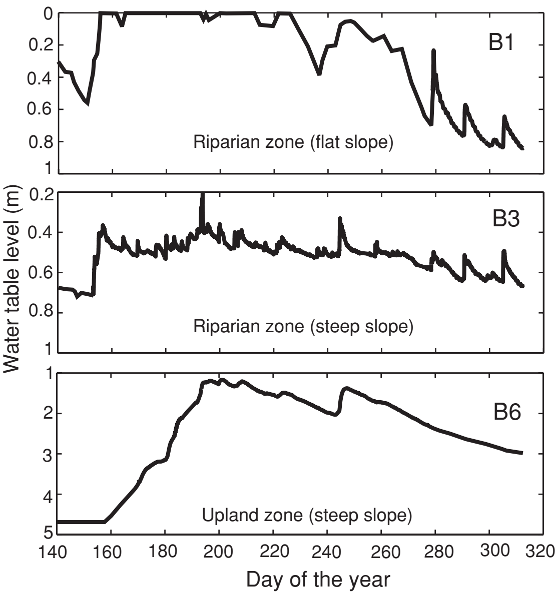


**Figure 6.** Shallow water table levels relative to the ground surface at 3 locations in the hillslope.

The differences in behavior may in fact highlight the role of upland and near-stream zones within SB, in relation to the mechanisms of runoff generation and hydrological pathways. As can be seen from Figure 5, the water table profile after the first storm indicates a water contribution from the near-stream zones with a poor, if any, connection to the upland parts. Hydrochemical and streamflow stage data (not shown) indicated that the connection between upland and near-stream zones occurred around day 180. The data also indicate the presence of a "storm event zone", approximately 60 m out from the stream, which is a major water source contributing to the streamflow during rainfall events. The different role of upland and riparian zones is also reflected in the $NO_3^-$ concentration data (Figure 7). Initially, $NO_3^-$ concentrations were low (around 2 mg $L^{-1}$) among all the shallow bores and the streamflow prior the event on day 153 (1/06/02). After the rainfall event, concentrations increased in all the bores, and the streamflow $NO_3^-$ concentrations were identical to those of the near-stream zones (data not shown).

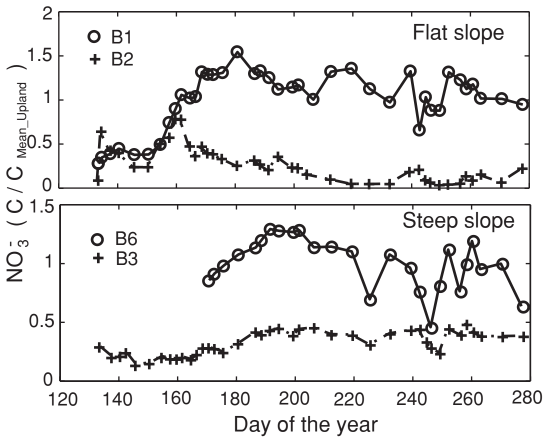


**Figure 7.** Seasonal variation of $NO_3^-$ concentrations (normalized by the mean $NO_3^-$ upland concentration).

A remarkable increase in concentration occurred around day 180, which coincided with the connection to the upland portion of the hillslope. Concentrations increased reaching a peak around day 200, and then declined towards the end of the season, alternating between high and low values. Although $NO_3^-$ concentrations have the same temporal patterns in most of the shallow piezometers (except for B2), there are differences in their magnitude. Concentrations decrease along the shallow aquifer pathway towards the near-stream zones. The $NO_3^-$ depletions in those zones range from 30% (steep slope) to 90% (flat slope). The match between $NO_3^-$ concentrations in near-stream zones in the flat slope and those corresponding to the streamflow at SB2 outlet, suggests that flat slope areas (17% of SB2) play an important role in controlling the $NO_3^-$ export from the catchment. The $NO_3^-$ data provides an independent confirmation of our results from the catchment scale analysis. The rapid response of shallow water table levels on day 153, and the agreement in $NO_3^-$ concentrations between the perched aquifer (at near-stream zones) and the streamflow, indicate that the flushing of $NO_3^-$ occurs from those near-stream zones.

### 4.3. A Common Perceptual Model

In order to realistically represent the hydrological and biogeochemical catchment responses in SB, a model needs to account for the different roles of upland and riparian zones. The hydrological roles of these two landscape units are clearly different: riparian zones control the catchment storm response while upland zones can be considered storage units with longer residence times, controlling the baseflow component of the stream once they connect to the riparian zones. The biogeochemical nature of these landscape units, in relation to $NO_3^-$, is also clear. Upland zones constitute the sources of $NO_3^-$ and participate in the downslope transport. Riparian areas are responsible for the depletion of $NO_3^-$. Our current research effort is aimed to build a modelling framework that will allow us to link, mechanistically, the upland and near stream zones in terms of water and solute fluxes. The biogeochemical data collected from the field experiment will be used to establish the mechanisms of $NO_3^-$ removal (dilution, denitrification, uptake) within the riparian zones.

## 5. CONCLUSIONS

Our understanding of the dominant hydrological and biogeochemical processes governing runoff generation and $NO_3^-$ export at the catchment scale, has been improved by combining catchment and hillslope scale observations. The use of a combined hydrometric-hydrochemical approach has led us to a confirmation of the dominance of subsurface stormflow at all spatial and temporal scales, and the role of antecedent wetness conditions. A shallow perched aquifer was identified as being the major source of water contributing to streamflows during rainfall events. The $NO_3^-$ export from the catchment has also been linked to the dynamics of the shallow aquifer. The analysis of both spatial scales converge to "an unifying perceptual model" of hydrological and biogeochemical catchment response. The data show that a realistic representation of both responses can only be obtained by considering the roles of upland and riparian zones. These results are encouraging and crucial for generalization to other catchments. More research is needed to connect the different units of the hillslope into a numerical modelling framework and thus improve our ability to make catchment scale predictions.


## 6. ACKNOWLEDGEMENTS

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