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# Space–time observations in nested catchment experiments of representative basins—experiences gained and lessons learned to help the PUB initiative in the World's biomes

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**Abstract** Field experiences with a Nested Catchment Experiment (NCE) layout sited in a biome of a developing country are outlined in terms of both space–time observational hydrology and modelling constraints. This NCE encompasses scales of 0.125 km$^2$, 1.1 km$^2$, 19.9 km$^2$, 165 km$^2$ and 560 km$^2$, aided by experimental plots of 1 m$^2$ under different land uses. To address the prediction in ungauged basins (PUB), the paper depicts how to handle with field hydrology, regionalization scaling, and the constraints for uncertainty-based modelling. At the headwater scale, runoff generation hypotheses are contrasted with field evidence. At higher scales, hydrograph types support uncertainty bounds for information transfer. To help PUB objectives, novel approaches emerge from this NCE, namely the *scale transferability scheme*, at the hillslope scale, and the *integrating process hypothesis* for higher scales.

**Key words** field evidence; nested catchment experiment; prediction in ungauged basins

## THE MOTIVATION—THE PUB INITIATIVE IN WORLD'S BIOMES

The IAHS initiative of Predictions of Ungauged Basins (PUB) attempts to integrate previous experiments and novel strategies for river basin monitoring. *How could we link traditional ways of addressing problems with new blueprints for PUBs, thereby scaling our uncertain data and our equifinality-based models into the World's biomes?* By addressing this question, regionalization thresholds could be grasped by practical methods of gauging. For instance, the nested catchment experiment (NCE) sets up observational layouts of gauging catchments in nested spatial scales, i.e. from headwaters to lowlands. The NCE's focus is on streamflow measurement from multiple spatial gauges, as well as on measurement of hydrological variables. By using representative basins NCE was performed to understand space–time hydrological variabilities, which allows PUB to study a specific World biome. This paper briefly presents some experiences gained with a NCE layout sited in a biome of a developing country, in terms of both space–time observational hydrology and modelling constraints. Summarized results are presented, with discussions looking for some lessons learned in this NCE layout, showing what helpful yardsticks could collaborate with the IAHS PUB initiative in the World's biomes.

## THE LAYOUT—A NESTED CATCHMENT EXPERIMENT IN A DEVELOPING COUNTRY'S BIOME

Since 1989 the Potiribu Project (initially granted IPH-CNPq-ORSTOM and FINEP Programs) has been gathering an interdisciplinary task force working under a NCE layout. It envisages space–time water and sediment balance for making PUB in the South Brazilian Basaltic Plateau. It is a subtropical 300 000 km$^2$ biome of La Plata Basin, sited between 49–56ºW and 24–30ºS in southern Brazil, northeast Argentina and Paraguay (Tucci & Clarke, 1998). The Potiribu Project integrates monitoring, field experiments, observational hydrology and regionalization. The Potiribu NCE monitoring encompasses scales of 0.125 km$^2$, 1.1 km$^2$, 19.9 km$^2$, 165 km$^2$ and 560 km$^2$, respectively, aided by experimental plots of 1 m$^2$ under different land uses. Soil erosion of cultivated land is significant and leads to high sediment concentrations in rivers and silting of reservoirs of the South Brazilian Plateau.

In a study based on rainfall erosivity, soil erodibility and relief, Bordas *et al.* (1988) estimate the mean annual soil loss for a standardized area of 15 000 km$^2$, at about 1 t ha$^{-1}$ year$^{-1}$ and the concentration of suspended sediment of 100 mg L$^{-1}$. This assessment made justification to the monitoring of water and erosion processes of nested catchments in the framework of PUB at other scales. The evaluation from field data in a cultivated headwater by Castro (1996) emphasizes the role of concentrated erosion and estimated the rill and gully erosion at 7 t ha$^{-1}$ year$^{-1}$. It clearly stressed the importance of Surface Flow Pathways (SFP), mainly associated with rills and gullies in cultivated uplands, but with high spatiotemporal dynamics (Mendiondo *et al.*, 1998). These SFP forms collect and concentrate the runoff from hillslopes to the stream network and allow the rapid transfer of sediments and pollutants. Spatiotemporal changes of SFPs patterns occur in all representative basins.

The Turcato basin (Fig. 1), approx. 20 km$^2$ area, is chosen as one representative basin of Potiribu NCE and of 230 000 km$^2$ of the Brazilian Basaltic Plateau. Mean annual rainfall is 1700 mm, well distributed. The annual average temperature is close to 19ºC. The substratum consists of continental basaltic flows in horizontal layers about 15 m thick. According to Brazilian classification, the soils are *Latossolo roxo*, rich in clay (>60%), deep, well structured with microaggregates, well-drained, and not hydromorphic. Since 1970, the area has been largely transformed by soyabean production with conventional tillage (ploughing, harrowing, and sowing along contours between terraces). Approximately <1% of native vegetation remains as riparian forest. Poor cultivation practices, forest clearance, and excessive use of agrochemicals have caused soil erosion and water quality problems in streams. On basaltic uplands, concentrated flow forms SFPs are associated with rills and gullies from terracing (Fig. 2). They form a network often connected to the rivers. Rills and gullies appeared to be formed where runoff velocities and discharge exceeded critical values, but gullies also appeared to be affected by other processes such as piping and mass movement, particularly at the riparian boundary where the bedrock emerged. Since 1994, there has been a change from conventional to no-tillage practices in approximately 90% of the Turcato basin, to reduce soil losses from concentrated flows.

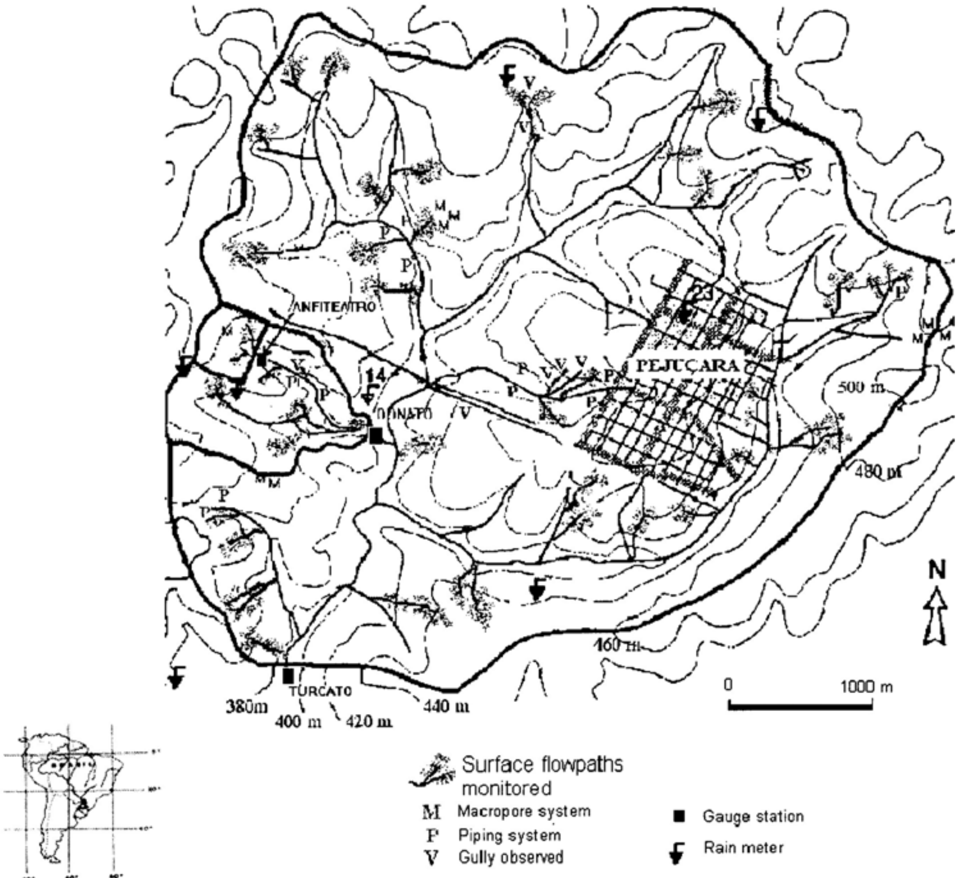


**Fig. 1** A Nested Catchment Experiment layout at 20 km$^2$ scale (*Turcato* basin), with basin of 1 km$^2$ (*Donato*), a hillslope of 0.125 km$^2$ (*Anfiteatro*), experimental plots of 1 m$^2$ at the hillslope scale. Spatiotemporal changes of Surface Flow Pathways (SFP) observed in headwaters as well as macropore and piping networks. Source: Mendiondo (1995).

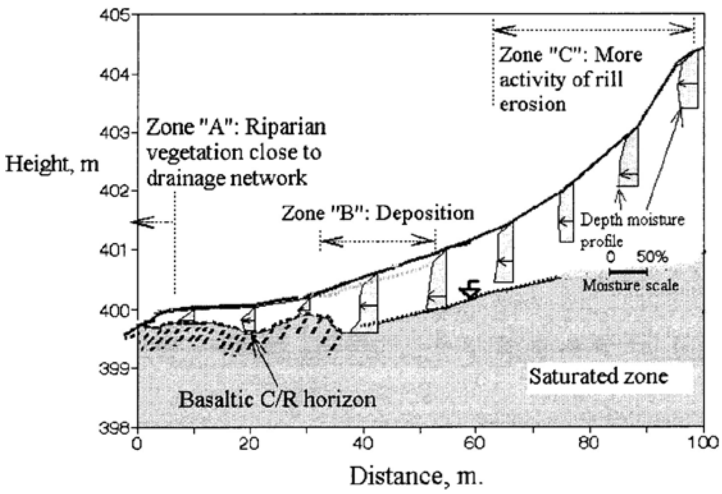


**Fig. 2** Typical profile of Potiribu NCE's headwaters. The PUB problem at hillslope scale recognizes that both Hortonian runoff generation and Hewlett-Dunnian runoff mechanisms are equally likely during storm flows. The combination of rill-erosion and gully-erosion, close to basaltic horizons, determines the plant erosion pattern of surface flow pathways (see Fig. 3). Source: Mendiondo (1995).

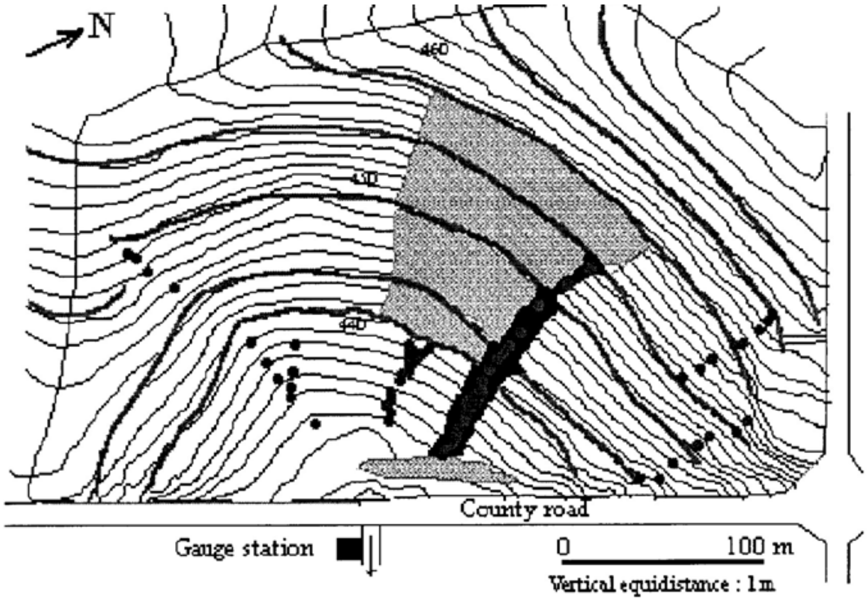


**Fig. 3** Monitoring of surface flow pathways (dots) at *Anfiteatro* hillslope of 0.125 km$^2$ with tillage practices (bold lines show terracing). Light shaded areas depict both upslope contributing area and deposit areas during extreme ENSO rainfalls. Bold shaded areas outline erosion patterns augmented after ENSO events of May 1992 that destroyed terraces.

## ONE RESULT—FIELD HYDROLOGY, REGIONALIZATION SCALING AND UNCERTAINTY-BASED MODELS

We present some results from the Potiribu NCE layout from results of Mendiondo (1995) and Mendiondo & Tucci (1997), partly inspired by monitoring methodology developed by ORSTOM researchers (see e.g. Chevallier, 1990). The framework, adopted in order to integrate the hydrological responses in a range of scales from 1m$^2$ to 564 km$^2$, is especially relevant to hydrograph-driven parameters. The approach is lumped, permitting the comparison between basins and relating factors from hydrological storm-based events. Several variables are studied for PUB purposes, i.e. runoff coefficient (runoff volume ÷ precipitation volume); (2) runoff thresholds according to Antecedent Precipitation Index (API); (3) fraction of partial contributing areas; and (4) maximum specific discharges, time-to-peak and observed base duration.

As an example, we present here a survey carried out from November 1989 to November 1993. Detailed events are taken from the hydrological period from August 1992 until September 1993 with 1 m$^2$ plots also installed. Results come from nested scales, i.e. from one hillslope of 0.125 km$^2$ (called *Anfiteatro*), a two order basin of 1.1 km$^2$ (*Donato*), a composite rural-urban fourth-order basin of 19.9 km$^2$ (*Turcato*, Fig. 1) and a medium basin of 563 km$^2$ (*Andorinhas*). In the example presented here, rainfall–runoff events are selected according to: (1) precipitation higher than 5 mm; (2) non-existence of errors in synchronization between pluviograph and limnigraph time series; (3) suitability of analysing single events (if complex events with several discharge peaks occur, special hydrograph component identification techniques were applied).

A detailed interpretation of hydrographs is studied with variables selected from storm flow events: discharge previous to rising limb (*Qini*), total peak discharge (*Qmt*) and superficial peak discharge (*QmS*), discharge at the end of recession curve (*Qfim*), direct runoff depth (*LES*), runoff coefficient ($C = LES \div P$), time-to-peak (*Tp*), base time (*Tb*), and the subsurface flux contribution to the total hydrograph (*Dsub*), defined as $Dsub = \{0.5\ [(Qfim - Qini).Tb] \div (LES.\ Aj)\}.k$, with *k* as a dimension constant and *Aj* as the basin area. In short, *Dsub* expresses the fraction between rapid and slow components in observed hydrographs. The working hypothesis is that hydrograph parts could be discriminated between *Qini* and *Qmt*. This assumption is initially simple, however it could serve as a first yardstick to the comparison among various storm events analysed in a common period. Similarity between hydrographs is identified through multivariable study, statistical principal components as well as multi-dimensional scaling techniques. In this paper, we briefly present a simple classification based upon *Tp*, *Tb* and *QmsU* ($= QmS \div LES$), defined as the maximum direct discharge per unit of direct runoff depth. Furthermore, synthetic hydrographs are used in the hydrology regionalization from the NCE approach to predict ungauged basins at intermediate scales.

The following variables are shown in Table 1: (1) the total precipitation registered in Turcato basin; (2) its relation to the annual average precipitation in Cruz Alta town, sited 60 km away of the NCE layout, and with long time series records; and (3) the corresponding annual average precipitation in the whole Potiribu NCE layout. There is a slight trend in wet years for the period (1989–1992), depicted with a depth difference of 168 mm, between the long-term average in Cruz Alta, *Pm*(CA), and the annual average of Potiribu NCE, *Pm*(NCE). Although the year 1992 had fewer rainy days, the extreme rainfalls due to El Nino Southern Oscilation, ENSO, on 26 and 27 May, 390 mm in 36 h, caused high economic losses. Results are depicted in Fig. 4, showing the observed relationships of hydrograph variables according to different basin areas of Potiribu NCE. There are two types of observed hydrograph distinguished, namely Type-A events, with circles, and Type-B events, with asterisks. Every point in the aforementioned figures outlines the expected value of events observed in each basin: for instance, *Anfiteatro* at 0.124 km$^2$, *Donato* at 1.1 km$^2$, *Turcato* at 19.9 km$^2$, *Taboao* at 165 km$^2$ and *Andorinhas* at 563 km$^2$, with a standard deviation in the respective sample of events analysed. The interrogation sign calls for a prediction of an ungauged basin, PUB.

The Type-A events are representative of rapid hydrographs, more related to Hortonian mechanisms. They are characterized by shorter times-to-peak and base times (*Tp* and *Tb*) and with higher *QmsU*. The ratio *Tp:Tb* rapidly rises from 0.20 ± 0.07 at the hillslope scale (12.5 ha) to 0.35 ± 0.11 at the 1.1 km$^2$ basin (Table 2).

**Table 1** Variation of annual precipitation in Potiribu NCE.

| Año | Pa (NCE) (mm) | Number of rainy days | Pa-Pm (CA, Record: 1939–1992) (mm) | Pa-Pm (Record: 1989–1992) (mm) |
|---|---|---|---|---|
| 1990 | 2256 | 110 | +545 | +377 |
| 1991 | 1063 | 63 | -647 | -815 |
| 1992 | 2112* | 93 | +402* | +233* |
| 1993 | 1611 | 75 | -100 | -277 |

*Extreme rains of 396 mm in 26 and 27 May, 1992 due to regional ENSO events.

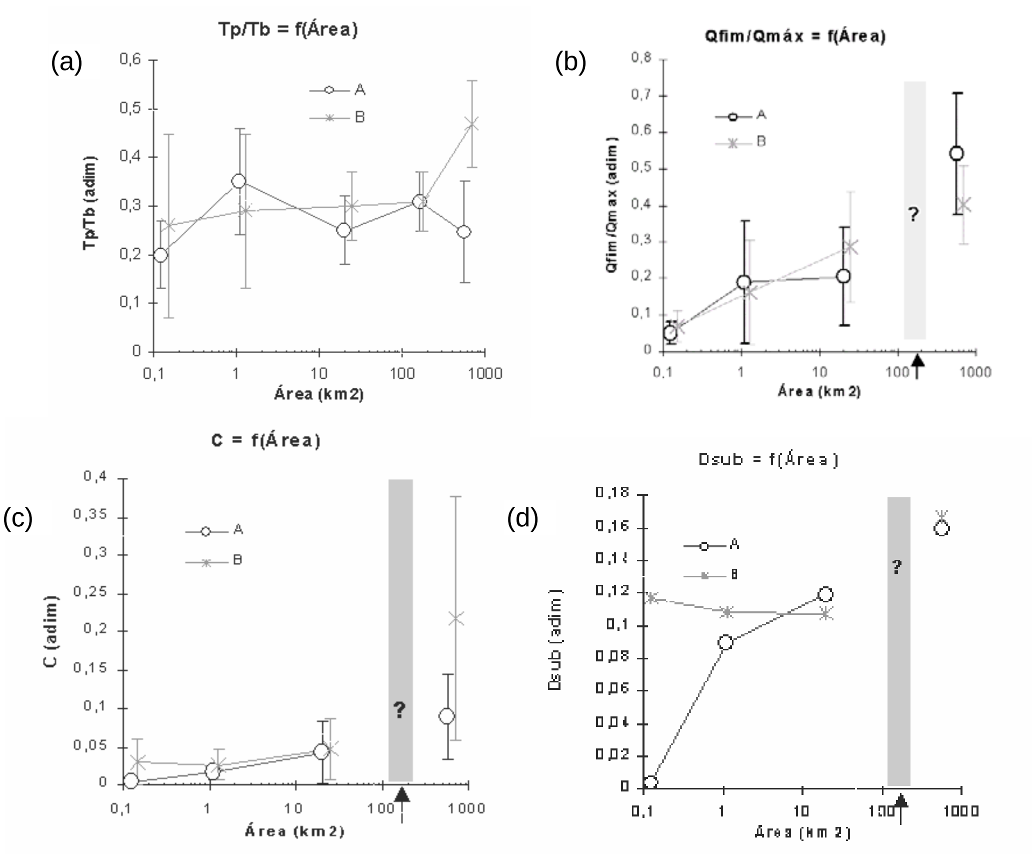


**Fig. 4** PUB regionalization example from Potiribu Nested Catchment Experiment, with scaling relationships of storm flow events between 0.125 and 563 $km^2$. Hydrographs are classified by Type-A (o) and Type-B (*) events, respectively. (a) ratio between time-to-peak and base time; (b) flow previous to rising limb divided by maximum flow; (c) runoff coefficient; (d) subsurface contribution during storm flow. Source: Mendiondo (1995).

**Table 2** Characteristic times of hydrographs observed in Potiribu NCE layout.

| Area | Time-to-peak (min) | | Base Time, Tb (min) | |
|---|---|---|---|---|
| | Type-A | Type-B | Type-A | Type-B |
| 0.125 | 12 ± 2 | 42 ± 35 | 50 | 161 |
| 1.1 | 31 ± 12 | 58 ± 35 | 88 | 200 |
| 19.9 | 123 ± 34 | 199 ± 29 | 492 | 663 |
| 165 | 960 ± 534 | 960 ± 534 | 3060 | 3060 |
| 563 | 1558 ± 742 | 4042 ± 1059 | 5231 | 9216 |

**Table 3** PUB at 165 $km^2$ scale from observed Potiribu's NCE regionalization (see Fig. 4).

| *Qfin* ÷ *Qmt* (%) | | *C* (%) | | *Dsub* (%) |
|---|---|---|---|---|
| Type-A | Type-B | Type-A | Type-B | Type-A & Type-B |
| 38 ± 15 | 35 ± 13 | 7 ± 5 | 14 ± 11 | 13–14 |

Generally, Type-A events occur in summer or hot periods, caused by convective storms, and with low *API*. The Type-B events are associated with storms of moderate intensity, with longer durations, usually in the winter season or low temperature periods, and with higher *API*.

In Type-B events, the relation $Tp \div Tb$ increases from 0.26 ± 0.19 (at 12.5 ha) to 0.33 ± 0.07 (19.9 $km^2$). Expected values of *Tp* varies between 42 minutes (at 0.125 $km^2$), and 199 minutes (at 19.9 $km^2$), and ending in 4042 minutes (at 565 $km^2$). Although $Tp \div Tb$ itself uniformly maintains a proportional increase with basin area, it could show changing thresholds in time intervals. According to Table 3, estimations could also be made for nested basins, regarding *C*, *Dsub* and $Qfim \div Qmt$ for the PUB problem at 165 $km^2$ scale.

On one hand, the relationships $Qfim \div Qmt$ with C grows slower in Type-A than Type-B (Fig. 2). Thus $Qfim \div Qmt$ of Type-B is 20% bigger than Type-A at a scale of 560 $km^2$ (i.e. at *Andorinhas* basin), however, the runoff coefficient *C* has a different increase of 110% between Type-A and Type-B at the same scale. This significant constraint points out how the process of flow generation from headwaters to the low-lands in NCE layout. At small scales, $Qfim \div Qmt$ approximately ranges between 20 and 30%, for Type-A and Type-B, respectively. The coefficient *C* close to 5% at 20 $km^2$ (at *Turcato* Basin) shows the influence of saturated areas near the outlet, with a delivery of quite similar volumes under very different circumstances (Type-A and Type-B) and masking the attenuation capacity inside the river channel. On the other hand, the subsurface dynamics outlines values between 0% (at 0.125 $km^2$ scale) and 16% (at 563 $km^2$ scale) for Type-A hydrographs. On the contrary, the hydrographs of Type-B show non-saturated mechanisms directly linked with highly dynamic saturated areas of near 12% at the hillslope (at 0.125 $km^2$) in respect to direct runoff with $C <$ 5%. For scales higher than a 500 $km^2$, the subsurface dynamics during storm flow is close to 18% with $C > 20\%$. This case, as other regionalized constraints in the NCE, depicts that simple relationships are better identified when hydrographs are selected under different conditions (Mendiondo & Tucci, 1997).

Figure 5 outlines experimental results of simulated rains over a 1 $m^2$ plot at hillslope scale (see Fig. 1). Using a two-parameter Green-Ampt model, scanning likelihood surfaces are plotted such that uncertainty-based models could be discussed in the perspective of PUB. Our working assumption that a particular error model structure can result in a likelihood function, as traditional maximum likelihood theory (Clarke, 1998). These results depict that uncertainty-based models are extremely dependent on Antecedent Precipitation Index (API), thereby regarding the equifinality paradigm of modelling in basins (see e.g. Beven, 1996; Sivapalan, 2002, and others). In short, the regionalization relationships among scales of Fig. 4 should be able to address the PUB problem if we are capable to recognize they are confident in experimental results, but with uncertainty-based data.

## THE DISCUSSION—EXPERIENCES GAINED AND LESSONS LEARNED FOR PUB

*How to pose the abovementioned constraints in the context of either equifinality-based models or experimental hydrology to make PUB for other World biomes?* Some experiences gained and lessons learned from Potiribu NCE are suitable for brief discussion in the context of PUB. Of course they are initial ideas, open to brainstorms and suggestions from many colleagues during the PUB Decade. In the representative basins of Potiribu NCE, water and sediment yields change rapidly across spatial and temporal scales, producing gauging limitations, i.e. non-stationary rating curves due to ENSO events (Mendiondo, 2001). Preferential water pathways on hillslopes show compound patterns, especially before and after ENSOs, and create distinctive rills and gullies, which are needed for conservation. In 1994, no-tillage practices were introduced leading to erosion rate reduction. In 2001, basin restoration was related to uncertainties derived from a complementary theory towards Ecohydrology. In this way, spatiotemporal observations of subsurface fluxes from macropores, piping and saturated areas play a complex role such that different runoff generation hypotheses may co-exist during storms (see i.e. Fig. 2). After 1997, observational hydrology and field evidence showed that Hortonian runoffs were likely to occur with Hewlett-Dunnian runoffs (Mendiondo & Tucci, 1997). Further, dynamic runoff-contributing areas are monitored by riparian area delineation using remote sensing and GIS, confirming different spatiotemporal runoff generation patterns.

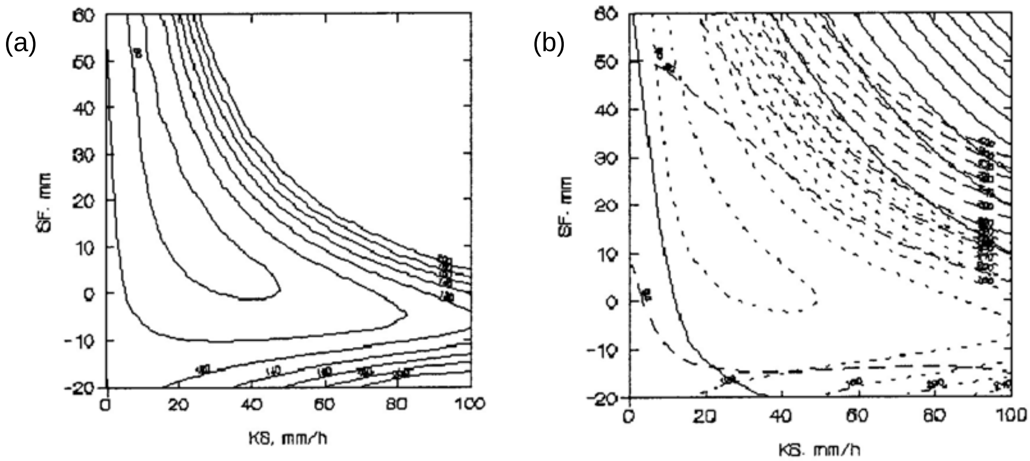


**Fig. 5** Uncertainty-based models constrained by temporal variations of state variables at the microscale for the Potiribu NCE layout. Results show likelihood surfaces of calibration experiments based on two-parameter Green-Ampt model at 1 m$^2$ plots. (a) Likelihood surface after first simulated rain. (b) Changes in likelihood surface after the second, third and fourth simulated rains. Source: Mendiondo & Tucci (1997).

In this way, two new blueprints emerge from this NCE for PUB, namely (1) *Scale Transferability Scheme* (*STS*), at the hillslope scale (< 0.125 km$^2$) and (2) *Integrating Process Hypothesis* (IPH) ranging from 0.125 km$^2$ to 563 km$^2$. The STS integrates a multidimensional scaling with similarity thresholds, like the Representative Elementary Area concept generalization (REA), using spatial correlation from point (distributed) to area (lumped) process (Mendiondo & Tucci, 1997). STS addresses uncertainty-bounds of model parameters, i.e. *Ks* of Fig. 5, into an upscaling process within the hillslope scale. On the other hand, the IPH approach regionalizes synthetic hydrographs, i.e. normalized discharges and times-to-peak of Fig. 4, interpreting what hydrographs could *say* regarding space-time observational evidence of representative basins under a PUB perspective.

## THE PERSPECTIVE—SUPPORTING THE PUB INITIATIVE

If the IAHS programme poses new challenges at global scales, then promissory advances of observational hydrology would be profited by PUB from understanding the NCE field experiments. That would allow both alternative scaling techniques and uncertainty standards to be underpinned from experiences gained and lessons learned on NCE, and would allow it to be compared with other layouts. Using participatory programmes, i.e. FRIENDS, GEWEX, IGBP, HELP, GWP and others, a NCE approach could permit novel win-to-win opportunities to sustain global partnerships on studying IAHS PUB of the World's biomes.

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