Space-time observations in nested catchment experiments of representative basins – Experiences gained and lessons learned to help PUB initiative in world's biomes

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The Motivation – the PUB initiative in world's biomes

The IAHS initiative of Predictions of Ungaged 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 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 hydrologic variables. By using with representative basins is NCE performed to understand space-time hydrologic variabilities which allows PUB to study a specific world's 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 modeling 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 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 Southbrazilian Basaltic Plateau. It is a subtropical 300,000 km^2 biome of La Plata Basin, sited between 49-56 W and 24-30 S in Southern Brazil, north-east 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 expressive and leads to high sediment concentrations in rivers and silting of reservoirs Southbrazilian Plateau.

In a study based on rainfall erosivity, soil erodibility and relief, Bordas et al (1988) estimate the mean annual soil loss for a standardised area of 15000 km² at about 1 t ha^{-1}y^{-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}.y^{-1}. It clearly stressed the importance of Surface Flow Pathways (SFP), mainly associated with rills and gullies in cultivated uplands, but with high spatio-temporal dynamics (Mendiondo et al, 1998). These SFP forms collect and concentrate the runoff from hill-slopes to the stream network and allow the rapid transfer of sediments and pollutants. Spatiotemporal changes of SFP's patterns occur in all representative basins.

The Turcato basin (Figure 1), ca. 20 km² area, is chosen as one representative basin of Potiribu NCE and of 230,000 km² of the Brazilian Basaltic Plateau. Mean annual rainfall is 1700 mm, well distributed. The annual average temperature is close to 19°C. The substratum consists of continental basaltic flows in horizontal layers about 15 m thick. According to Brazilian classification, the soils are *Latossolos roxo,* rich in clay (>60 %), deep, well structured with micro-aggregates, well-drained, and not hydromorphic. Since 1970, the area has been largely transformed by soya-bean production with conventional tillage (ploughing, harrowing, sowing along contours between terraces). Approximately less than 10 % 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 SFPs are associated with rills and gullies from terracing (Figure 2 and Figure 3). 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 appeared also 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 ca. 90 % of the Turcato basin, to reduce soil losses from concentrated flows.

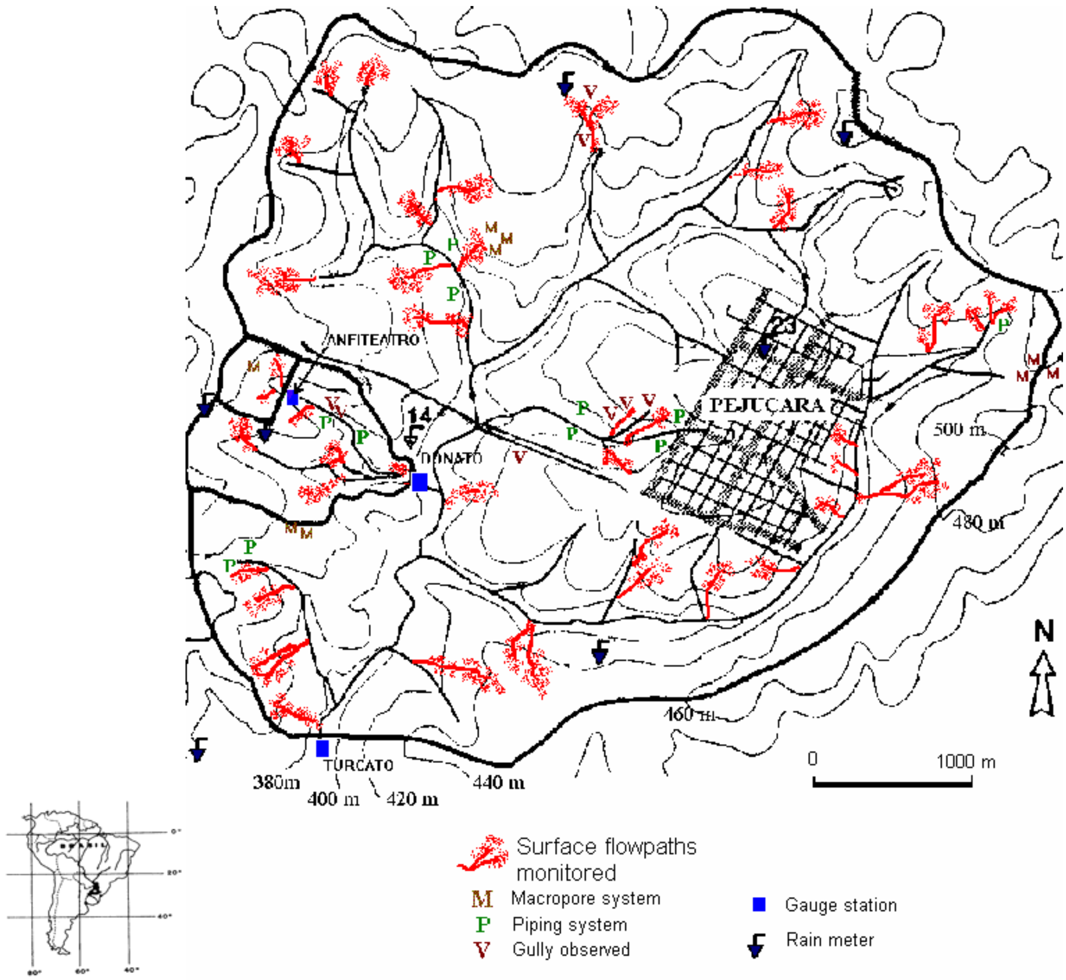

Figure 1- A Nested Catchment Experiment layout at 20 km^2 scale (*Turcato* basin), with basin of 1 km^2 (*Donato*), a hillslope of 0.125 km^2 (*Anfiteatro*), and experimental plots of 1 m^2 at hillslope scale. Spatiotemporal changes of Surface Flow Pathways (SFP) observed in headwaters as well as macropore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

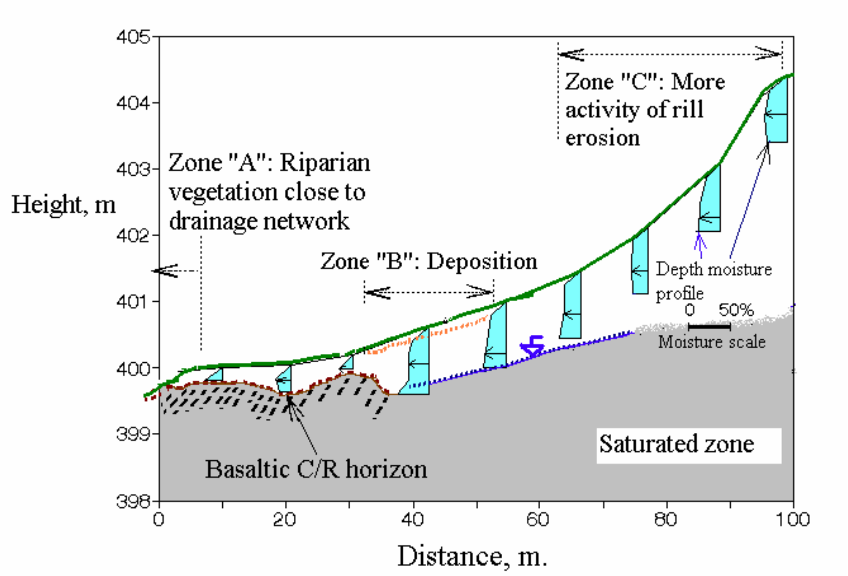

Figure 2- Typical profile of Potiribu NCE's headwaters. The PUB problem at hillslope scale attempts that both Hortonian runoff generation and Hewlett-Dunnian runoff mechanisms are equally likely during stormflows. The combination of rill-erosion and gully-erosion, close to basaltic horizons, determines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

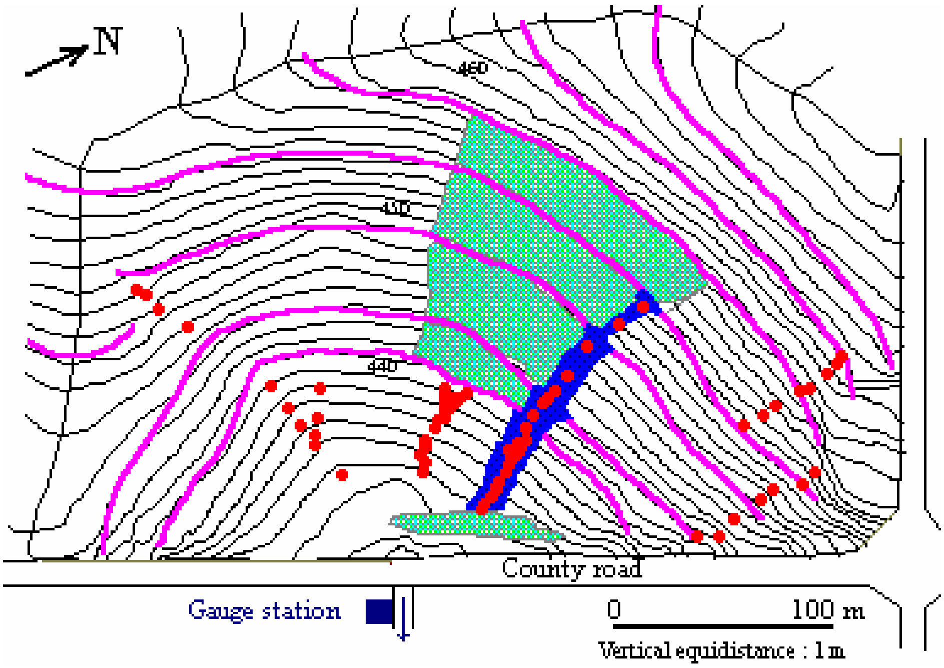

Figure 3- Monitoring of surface flow pathways (dots) at *Anfiteatro* hillslope of 0.125 km^2 with tillage practices (bold lines show terracing). Light shaded areas depict both upslope contributing area and deposit areas during extreme ENSO rainfalls. Bold shaded areas outline erosion patterns augmented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

One receipt - field hydrology, regionalization scaling and uncertainty-based models

We rapidly present some results from the Potiribu NCE layout from results of Mendiondo (1995) and Mendiondo & Tucci (1997) and partly inspired in monitoring methodology developed by ORSTOM researchers (see i.e. Chevallier, 1990). The framework, adopted in order to integrate the hydrologic responses in a range de scales from $1m^2$ to 564 km^2, is especially relevant to hydrograph-driven parameters. The approach is lumped, permiting the comparison between basins and relating factors from hydrologic 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, (4) maximum specific discharges, time-to-peak and observed base times.

As an example, we present here a survey carried out since November 1989 until November 1993. Detailed events are taken from the hydrologic 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*, Figure 1) and a medium basin of 563 km^2 (*Andorinhas*). In the example here presented, rainfall-runoff events are selected according to: (1) precipitation higher than 5 mm, (2) inexistence of errors in synchronization between pluviograph and limnigraph time series, (3) suitability of analyzing single events (if complex events with several discharge peaks occur, special hydrograph separation techniques were applied).

A detailed interpretation of hydrographs is studied with variables selected from stormflow events: discharge previous to rising limb (*Qini*), total peak discharge (*Qmt*) and superficial peak discharge (*QmS*), discharge at the end of recession curve (*Qfin*), direct runoff depth (*LES*), runoff coefficient (*C=LES÷P*), time-to-peak (*Tp*), base time (*Tb*), and the subsurface flux contribution to the total hydrograph (*Dsub*), defined as $Dsub = \{0{,}5\ [(Qfin\text{-}Qini).Tb] \div (LES.\ A_j)\ \}.k$, with k as a dimension constant and A_j 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 analyzed 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÷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 ungaged basins at intermediate scales.

In Table 1 are shown the following variables: (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 Potiribú NCE, *Pm*(NCE). Although the year 1992 had fewer rainy days, the extreme rainfalls due to El Nino Southern Oscilation, ENSO, in 26 and 27 May raised to 390 mm in 36 hours, causing high economy losses. Results are depicted in Figure 4, showing the observed relationships of hydrograph variables according to different basin areas of Potiribu NCE. There are two types of hydrograph distinguished, namely Type-A Events, with circles, and Type-B Events, with asterisks, respectively. Every point in the fore mentioned 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, *Taboão* at 165 km^2 and *Andorinhas* at 563 km^2, with a standard deviation in the respective sample of events analyzed. The interrogation sign calls for a prediction of an ungaged basin PUB.

The Type-A Events are representative of rapid hydrographs, more related to Hortonian mechanisms. They are characterised 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). Generally, Type-A Events occur in Summer or in 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 Winter season or in low temperature periods, and with higher *API*.

In Type-B Events, the relation *Tp÷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), ranging until 199 minutes (at 19,9 km^2), and ending in 4042 minutes (at 565 km^2). Although *Tp÷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 *Qfin÷Qmt* for the PUB problem at 165 km^2 scale.

In the one hand, the relationships *Qfin÷Qmt* versus *C* grows slower in Type-A than Type-B (Figure 4). Thus *Qfin÷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 expressive constraint points out how is the process of flow generation from headwaters to the lowlands in NCE layout. At small scales, *Qfin÷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 influence of saturated areas near the exutory, 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. In the other hand, the subsurface dynamics (*Dsub*) 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 stormflow 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).

Table 1- Variation of annual precipitation in Potiribu NCE

Año	*Pa* (NCE) [mm]	Number of rainy days	*Pa-Pm* (CA, Record: 1939-92) [mm]	*Pa-Pm* (Record: 1989-92)[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.

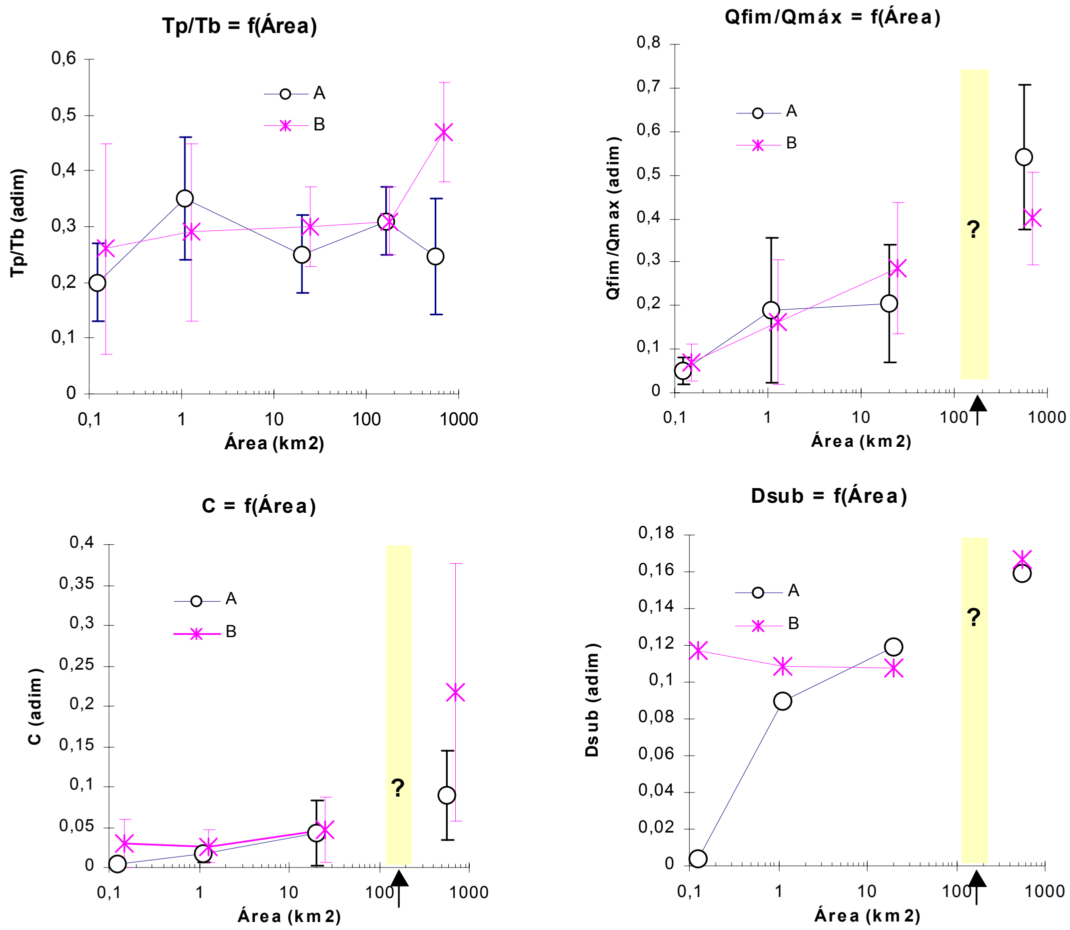

Figure 4 – PUB regionalization example from Potiribu Nested Catchment Experiment, with scaling relationships of stormflow events between 0.125 and 563 km^2. Hydrographs are classified by Type-A (o) and Type-B events (*), respectively. Upper left panel: ratio between time-to-peak and base time; Upper right: flow previous to rising limb divided by maximum flow; Lower left: runoff coefficient; Lower right: subsurface contribution during stormflow. Source: Mendiondo (1995).

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

Area	Time-to-peak, *Tp* [min]		Base Time, *Tb* [min]	
[Km^2]	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 Figure 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

Figure 5 outlines experimental results of simulated rains over a 1 m^2 plot at hillslope scale (see Figure 1). Using a two-parameter Green-Ampt model, scanning likelihood surfaces are plotted such that uncertainty-based models could be discussed in perspective of PUB. Our working assumption of 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 modeling in basins (see i.e. Beven, 1996; Sivapalan, 2002, and others). In short, the regionalization relationships among scales of Figure 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 above mentioned 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 to be shortly discussed for PUB. Of course they are initial, open to brainstorms and suggestions from many colleagues during this Kick-off Workshop. In the representative basins of Potiribu NCE, water and sediment yields are used to changing 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 draw distinctive rills and gullies which need for conservation. In 1994, no-tillage practices were introduced with erosion rate reduction. In 2001, basin restoration was coped with uncertainties derived from a complementary theory towards Ecohydrology. In this way, spatiotemporal observations of subsurface fluxes from macropore or piping and saturated areas play a complex role such that different runoff generation hypotheses may coexist during storms (see i.e. Figure 2). After 1997 observational hydrology and field evidences depicted that Hortonian runoffs were rather 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.

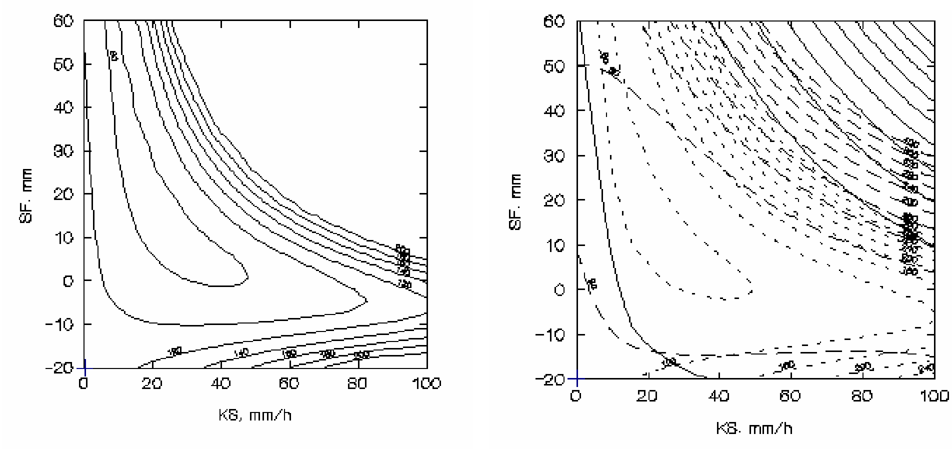

Figure 5. Uncertainty-based models constrained by temporal variations of state variables at the microscale of Potiribu NCE layout. Results show likelihood surfaces of calibration experiments based on two-parameter Green-Ampt model at 1m^2 plots. Left: likelihood suface after first simulated rain. Right: changes in likelihood surface after the second, third and fourth simulated rain. Source: Mendiondo & Tucci (1997)

In this way, two new blueprints emerges 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 multi-dimensional scaling with similarity thresholds, as a 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 Figure 5, into an upscaling process within the hillslope scale. In the other hand, IPH approach regionalizes synthetic hydrographs, i.e. normalized discharges and times-to-peak of Figure 4, interpreting what hydrographs *could say* regarding space-time observational evidences of representative basins under a PUB perspective.

The perspective – supporting the PUB initiative

If IAHS Program poses new challenges at global scales, then promissory advances of observational hydrology would be profited by PUB from understanding NCE's field experiments. That would allow both alternative scaling techniques and uncertainty standards to be underpinned from experiences gained and lessons learned on NCE and to be compared with other layouts. Using participatory programs, 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 the PUB of world's biomes.

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References

Borges,A., Bordas,M. (1988) Choix de bassins représentatifs expérimentaux sur le plateau basaltique sudaméricain. IAHS Publ.174, p.161-169.

Beven, K. (1996) Equifinality and uncertainty in geomorphological modeling, In: B. Rhoads & C. Thorn (eds). The scientific nature of geomorphology, Chichester: Wiley, p.291-313.

Castro, N. M. R. (1996) Ruissellement et erosion sur des basins versants de grandes cultures du Plateau Basaltic du sud du Brésil. Strasbourg: Univ. L. Pasteur, Th. Doctor, 178p.

Chevallier, P. (1990) *Complexité hydrologique du petit bassin versant.* Th. Dr. Paris: Éditions de l'Orstom, Collection Études et Thèses, 331p.

Clarke, R. T. (1998) *Stochastic processes for water scientists: development and applications*. Chichester: Wiley.

Mendiondo, E. M. (1995) Integration of hydrologic scales in nested basins of Potiribu River (in Portuguese). M Sc. Dissertation, Porto Alegre: IPH-UFRGS, 247p+an.

Mendiondo, E. M. (2001) Contribution of uncertainty analysis for basin restoration through an interdisciplinary approach of Geobiohydrology (in Portuguese). Dr. Thesis. Porto Alegre: IPH-UFRGS, 243p+an.

Mendiondo, E., Tucci,C. (1997) Hydrologic scales: Integrating Process Hypothesis (IPH) at the hillslope scale (in Portuguese) *Rev. Bras. Rec. Hídricos* I: 100-112

Mendiondo, E., Castro, N., Auzet, A., Chevallier, P. (1998) Surface Flow Pathways in Subtropical Agricultural Headwaters, In : M. Haigh et al (eds.) *Headwaters*, Baalkema, Rotterdam, Chapter 26, p.285-292.

Sivapalan, M. (2002) Prediction of Ungaged Basins. Preparatory Workshop on the IAHS Initiative for the Prediction in Ungaged Basins (PUBs) 28-29 March 2002 Yamanashi University, Kofu, Japan.

Sorooshian, S. (2002) Some comments for the IAHS PUBs Initiative Workshop. Preparatory Workshop on the IAHS Initiative for the Prediction in Ungaged Basins (PUBs) 28-29 March 2002 Yamanashi University, Kofu, Japan.

Tucci, C. E. & R. T. Clarke (1998) Environmental issues in the La Plata Basin. *Wat. Res. Dev*., v.14, n.2, p.157-173.