Some science questions for Predictions in Ungauged Basins (PUB) – Part II: Thoughts to constrain the predictive uncertainty

(brainstormed by E M Mendiondo, RT Clarke, E S Martins – 25 Jan., 2003)

The central theme of the PUB initiative will be heterogeneity and the uncertainty of the hydrologic predictions in ungauged basins. The overall objective of PUB is to constrain the predictive uncertainty through improved ways to characterise the effects of heterogeneity, process understanding and through access to new data resources. This is a commissioned task under deep discussion in the Science Steering Group of IAHS' PUB, concerning experiences gained and lessons learned in topics on hydrologic uncertainty. Of course this kind of new portfolio is an adaptive, non-stop process with share a plurality of insights. Thus scientific questions are to be further developed in terms of the role of theory, basins, field experiments, process understanding and new data base required. Research pathways to be feasibly advanced on hydrologic uncertainty and how they will be integrated into the entire PUB programme are briefly outlined in the following paragraphs as a text with subtitles.

1. ***Key research questions (revisited)*** **–** Previous contributions to the SSG enclosing scientific questions were released between 15 and 17 Jan. 2003, and herein enclosed in Appendix I and II, respectively. Some PUB topics that complement those previous scientific questions are outlined as follows.

2. ***PUB Theory I. Definition*** (quoting E. Nash): a distinction between Prediction and Forecasting needs for revision. 'Prediction' is concerned with estimating the frequency of occurrence, in the future, of events of any given magnitude, without reference to the times at which they would occur. Nash used the term 'forecasting' to denote the estimation of what will be happening at a stated point of time in the future, such as discharge tomorrow, or runoff in the coming month. If this usage, initially adopted as standard, is to be replaced, it should be done with care. In PUB, we are really concerned, with both Prediction and Forecasting.

3. ***PUB basins I: A retrospective*** **-** PUB initiative should rescue experiences gained and lessons learned from previous international hydrological programs. For instance, the International Hydrological Decade (IHD, 1965-74) was a leader partnership program that set up a high number of worldwide basins gauged. One of the primary aims of IHD was "…to foster more detailed research into physical process occurring in natural basins and at the same time to attack the elements of **uncertainty** in hydrology…" (UNESCO & IAHS, 1970; p. 6).

4. ***PUB basins II: A prospective*** **-** Since this type of research is both time-consuming and expensive, real or future basins of PUB programme should be studied in detail and should allow for as accurate-standardized as alternative data, observation and processing. In terms of constraining uncertainties, other kind of knowledge, either local or regionally-developed, that is still non-standardized worldwide, should be included as an alternative helper and contributor to PUB. Concurrent research of

modelling and statistical techniques may be utilized to test hypotheses and to develop models for constraining uncertainty, but not to displace alternative knowledge that local water practitioners gained throughout their experience with basins that are also suitable for PUB programme. Moreover, the ongoing UN-HELP (Hydrology for Environment, Life and Policy) could perhaps better link the PUB programme when that local/regional knowledge is also regarded as one main alternative issue to constrain uncertainty in river basin.

5. ***PUB basins III. Nested Catchment Experiment* –** PUB programme will encompass both representative and experimental catchments. **Representative basins** are to be selected as representative of a hydrological region, i.e. a region within which hydrologic similarity is assumed under relatively stable, natural conditions. They should have minimal natural or cultural changes during the period of study and, if changes occur, they should be carefully recorded. **Experimental basins** are relatively homogeneous in soil and vegetation and which have uniform physical characteristics. On such basins the natural conditions could be under modification and the effects of these modifications on the hydrological characteristics are studied. The PUB programme should coherently encourage robust studies, of gauging, prediction as well forecasting in nested hydrologic spatiotemporal scales. To constrain the predictive uncertainty, improved ways of studying nested experiments should characterise the effects of basin heterogeneity, process understanding and the access to new data resources. The set up of Nested Catchment Experiment (NCE), whether in representative or in experimental basins, should be studied by in a win-to-win cooperation through interdisciplinary task groups.

6. ***Data base requirements I: sources of information*** - GIS, DTM, RS databases need for a hydrology theory suitable to interprete these data in term of good hydrologic information. For instance, future advances of remote sensing technology and DTM need to include more physically-based techniques, whether direct or indirect (i.e. pedotransfer functions, tracers, time-domain reflectrometry, etc.) oriented by scale dependent model objects at the subpixel (raster based) as well at hillslope-process functioning (vector derived). The reliability of (a) integration of physically-based techniques with (b) landscape attributes could give hydrologically useful information on the underlying uncertainty due to basin heterogenous features.

7. ***PUB Theory II: simple starting*** - New theory needs to be developed for prediction in ungauged basins, where the hydrological regime in gauged basins is changing. Where hydrological records are non-stationary, whether because of climate or land-use change, we do not know how to transfer information from gauged to ungauged basins. The use of <u>existing</u> Bayesian methodology, for choosing between models, possibly with different numbers of parameters, needs to be explored in the context of ungauged basins. This new theory should envisage either a new reflection on how to use tools both available and under developing. For example, the use of existing Bayesian methodology, for choosing between models, possibly with different numbers of parameters, needs to be explored in the context of PUB. Bayesian analysis is concerned with obtaining posterior probability distributions [i.e. P(*theta* | *X*), where *X* consists of observations, and '*theta*' consists of parameters and other

unobservable quantities like missing values]. In the context of PUB, it would be possible, in theory, to write Theta = [phi, *Y*], where '*phi*' are model parameters and *Y* are the missing values in the ungauged basins; then integrating the post. probability P(*theta* | *X*) = P ([*phi*, *Y*] | *X*) over the parameters 'phi' would give the contribution of the missing data in the ungauged basin. the posterior distribution of the missing values *Y* of the ungauged basin would give prediction intervals. This is all straightforward Bayesian theory, and PUB Science Plan should deepen in how it works in real practice, gathering working groups to study this application in different changing biomes.

8. ***PUB Theory III: a priori uncertainty from data:*** It is worth noting that the former approach is not so straightforward characterizing all sources of errors in modeling. That is crucial when *a priori* estimations of errors are required to feed an intensive computer task on uncertainty (Markov Chain Monte Carlo, Bootstrap, etc). In this way, we could attack different kind of constraining uncertainty in gauged basins, for example the gauging discharge at a cross-section of river basin. There are multiple sources of error assessment in a discharge rating curve, whether from different internal errors in one single gauged discharge, *Error #1*, or from the residual from fitting a mathematical relationship of the rating curve to a gauged discharge set, *Error #2*. However, rarely are these errors integrated to constrain the predictive uncertainty and published in technical or modelling papers. Novel scientific pathways are needed to improve this kind of prior uncertainty in a gauged basin and how it is envisaged for ungauged basins. These uncertainty priors also apply to precipitation gauges and evaporation pans. In this case *Y* is spatially distributed through spatial fields of hydrologic variables, as well their parameters, that are to be upscaled. In the case of discharge gauging, uncertainty priors should be downscaled. In the midway is how to tackle them into through concepts that encompass the basin heterogeneity and observational layouts in field.

9. ***PUB Theory IV: prior uncertainty from observational hydrology*** – For the mentioned example of discharges, field hydrologists know well how *Error #1* integrates ancillary errors, i.e. from measurement of local hydraulic slope, roughness as well geometric factors in Manning or Chézy equations, etc. Field hydrologists are also aware of how *Error #1* and *Error #2* could be integrated into a physical reasoning for constraining uncertainty. There are novel scientific insights that link the uncertainty integration of *Error #1* and *Error #2* to the underlying resilience in basin flow regimes. This opens a big scientific opportunity for innovating through PUB programme in order to explore predictive uncertainty under interdisciplinary tasks among traditional areas like flooding, ecohydrology, biogeochemical cycling, and the demand of observational hydrology.

10. ***PUB Theory V: posterior uncertainty transference -*** Confidence intervals of the priors, *Error #1* and *Error #2,* should be further studied in how either hydrologic prediction or forecasting could assess the likelihood of *Y*. New scientific efforts must be addressed in the context of complex models that acknowledge posterior uncertainty transference, in terms of both resilient devices (RD) and adaptive management (AM), and when a **learning process** is looked for PUB. That posterior

uncertainty transference could seek the value of knowing how little the conceptual tools (i.e. hydrologic models) know when they do put more emphasis to have well-behaved runs for mimicking the perceptual heterogeneous system (i.e. river basin). For that, two topics could be further studied: the Expected Value of Including Uncertainty (EVIU) and the Expected Value of Perfect Information (EVPI). Both EVIU and EVPI compare the expected value of Bayesian outcome with another outcome made without regarding uncertainty. This later outcome comes from a non-resilient device that does not accept an adaptive (recursive, learning) process. The EVPI is the expected *cost* of begin uncertain about *Y*, whereas the EVIU is the additional expected cost of pretending we are not uncertain. Both of them depend on the degree of the uncertainty of the priors, *Error #1* and *Error #2,* giving emergent hypothesis-testing of how this uncertainty transference, across the basin, is statistically expected.

11. ***PUB Theory VI: Representative Elementary Area revisited -*** Basin heterogeneity, both structural heterogeneity (‘phi_1’ sets) and functional heterogeneity (‘phi_2’sets), will be gathered into recursive mapping/assessment through an intensive batch of runs, where EVIU and EVPI are calculated using multi-dimensional hydrologic attributes. These ‘*phi*’ sets could be assisted by either remotely-sensed captured or nestedly-scaled observed predictions (or forecasting), or by both. For example, some upscaling approaches for ‘phi_1’ sets *walk* from micro to macroscale using the distributed attributes self-related to their level of similarity (or dissimilarity). More dissimilar the attributes, more uncertainty transference accomplished by entropy (variance assessed) upwards. There are novel hypotheses, i.e. the Scale Transition Scheme (STS), that let obtain dynamic Representative Elementary Area (REA) for similarity or entropy levels. Such dynamic REAs are also related to the uncertainty of multivariate processes which depict moving confidence intervals.

12. ***PUB Theory VI: constraining uncertainty -*** To constrain uncertainty, a new set of physical formulae is expected to derived, thereby showing how the uncertainty transference upscales the prior uncertainty from microscale, or downscales confidence intervals from the macroscale. Due to non-linear processes of hydrologic phenomena, hysteresis or regionalisation loops (between up-and-downscaling approaches) are expected to occur because of this uncertainty transference in the same basin. Thresholds and erratic behaviours are also expected to appear, due to non-linear processes, in this kind of heterogeneity-uncertainty hysteresis scaling. Those new, wanted formulae should properly address this behavior, especially regarded to multidimensional fractals that weigh heterogeneity and uncertainty transference. But different dynamic REAs (wheter upscaled or downscaled derived through STS) could also be self compared. This is a preliminary looking-forward yardstick of how to constrain uncertainty or enhance heterogeneity for the basin under a Nested Catchment Experiment layout.

13. ***PUB’s timeline and activities I: broad participation*** – It could be initially stated that we need a framework to handle the situation of constraining uncertainty issues being overtaken only by computer power and legislative guidelines to have predictions everywhere. Other also suitable proposal is that field hydrologists, who

better know *a priori* uncertainty in river basin gauged or ungauged, were strongly encouraged to participate of the PUB programme to avoid any knowledge encapsulation for modelling purposes exclusively. This broad participation should begin in the initial phases of PUB Decade. This kick-off will contribute a lot for future computational modelling and budgetary limits, because field hydrologists usually have developed own expertise on better economically suited layouts or experiments in river basin.

14. ***Linking the PUB to ongoing activities I -*** From the above reasons, novel linking with existing programmes HELP, GEWEX, WWAP, etc are expected. It is high recommended that PUB does promote the need of an integration of the uncertainty coming from errors-in-data (*Error #1* and *Error #2)* to be clearly taken into account under a new generation of hydrologic papers and integrated programmes.

15. ***PUB Timeline and activities II: exercises and authoring -*** Forthcoming PUB activities should firstly attend the physical hydrology through a pool of motivating academic exercises as well pragmatic praxis.

16. ***The 'Hidden basin' exercise for PUB*** - Much can be done using data from existing basins, by leaving one basin out of the data set, and regarding the omitted basin as ungauged. This can be repeated for each basin in turn. This kind of exercise behaves as a yardstick in PUB context, showing regionalisation and some simple pathways on **predictive uncertainty**.

17. ***Ethics and publishing duties under PUB*** - Existing experimental and representative basins could be safeguard and used for PUB activity. It will be essential to make full recognition of the contribution of local persons and field hydrologists who manage those basins when results are published, not merely in terms of a footnote of acknowledgements at the end of the paper, but by including them as authors. PUB initiative should take care to avoid the too often practice that those who do the fieldwork, and who superbly know the **sources of uncertainty** of hydrological data records, receive inadequate recognition. One of the reasons why the PUB initiative is required is because fieldwork is in fact indispensable for **constraining uncertainty** in hydrological processes.

18. ***Linking the PUB to ongoing activities II: land use scenarios -*** Many worldwide basins, especially those from water scarcity regions, have major land use change which plays a major role on the hydrological regime of our basins. For instance, small reservoirs are built every year to attend urgent water demand (household, livestock, irrigation) and some of them do not last long. How to take into account these small reservoirs in physical modelling? Generally you don't have good information about them. They are built without project ! How NCE (Nested Catchment Experiment) is suitable to overcome this manmade externality?

If new 'turning points' are being brainstormed in hydrological sciences,
how should they be cross-puzzled under a context of PUB?

uncertainly-adapted	?	models	?
heterogeneously-oriented	?	experiments	?
hydrologically-better regarded	?	data	?

Appendix I – Science questions for Predictions in Ungauged Basins (PUB) – Part I

(Eduardo Mario Mendiondo, 15 Jan. 2003)

1. **PUB settings: coping with errors & uncertain variables** – How could we rapidly profit from previous experiences gained working with sources of errors of hydrological observations in basin experiments? Regarding the PUB perspective, which lessons learned should we underpin from the uncertainty at gauged basins?

2. **PUB regionalisation upwards** - In which manner effective parameters of hydrological processes at the hillslope, which have both structural and functional heterogeneity, are to be upscaled towards higher scales (as PUB needs) with the appropriate assessment of predictive uncertainty transfer? How could we better use alternative information of linking functions and evidences (i.e. pedo-transfer, tracers) in this scaling view? How do likelihood-based schemes robustly help for it?

3. **PUB regionalisation downwards** - Which are the suitable pathways of accounting the uncertainty underlying in records at a lumped scale, moving through a downscaling process into new spatiotemporal scales? Is remote sensing architecture (pixel based) appropriate for this PUB downscaling? How much new uncertainty is “added” by these raster (grid) elements rather than working on hydrotope units (hillslope based, and better scientifically-oriented for PUB)?

4. **Budget constraints in PUB scaling** – In what way could we optimise resources, such that any selected conceptually-based scaling yardstick (either down or upwards) would be feasibly recognised by decision-makers as less expensive than other existing approaches of making PUB? How much cost the transference of predictive uncertainty of hydrological parameters (down/upwards)? What type of initial investments might PUB experiments, fund-constrained due to different local conditions, firstly assure in order to get reliable bounds of uncertainty?

5. **Regionalised PUB loops/hysteresis** - Either upscaling or downscaling process in hydrology (i.e. parameters) is intrinsically related to the underlying variability observed at the point scale—also known as “nugget variability” from geostatistics jargon, and derived from micro-scale measurements and direct observations. How much hysteretic behaviour, called as “regionalisation loop” (RL), between up-and-downscaling approaches, is expected at micro, meso and macroscales of PUB? How does nugget (point) variability play a role of an “end-member” in RL? In what explicit form both predictive uncertainty and landscape heterogeneity could be included in RLs? What type of physical RL thresholds are admissible and have applied consequences for water practitioners that need of making PUB?

6. **Resilient-based, ecologically-oriented PUB**- Are RLs a kind of yardstick for river basins as resilient systems? If so, how can hydrological resilience help the applied,

pragmatic regionalisation envisaged for PUB? In what explicit way is related RL to inner landscape heterogeneity and to outer predictive uncertainty of a basin?

7. **Biome-based prediction (PUB extrapolation/interpolation)** - How could we interpret those expected RLs in any basin experiment? What are the scientific implications of "RL" for a given ungauged basin that needs for extrapolation from proxy basins, or for interpolation from nearest gauged scales? Are these "RLs" expected to be equally-behaved for all basins of worldwide biomes; if not, how local climatic constraints could affect them and show new clues for making PUB?

8. **Plurality of insights (PUB value loading)** - How do we build up alternative PUB science assets aided by from stakeholder visions, such that model inter-comparison (scientifically-based) could be also checked with local knowledge information (societal-oriented, but usually not related in hydrological journals!), thereby linking oral testimonies from country people who better know about historic marks as well equally probable scenarios of making PUB? How much money could we save when those "Value Loadings and Plurality of Insights" (VL&PI) are also firstly set into traditional PUB modelling? How do they properly avoid future time-consuming educational guess (i.e. calibration), when we, alone, usually ask the wrong question (or pose the false hypothesis testing) to our models?

9. **PUB parameter parsimony (model set up)** - What are the minimum number of parameters better suitable to make a first trial for PUB in a range of scales, and that might permit to follow a construction of hydrologically-universal models (hybrid, conceptually-based in processes' likelihood) at different biomes? If models are to be scale dependent, how should they assure evidences of leading with uncertainty and heterogeneity into new formulae that comprise "Regionalisation Loops" (RL), as specific features of a river system? What kind of advantages and limitations do RLs carry out for both water modellers and practitioners? How could "Value Loadings and Plurality of Insights" (VL&PI) help on parameter parsimony selection when PUB exercises are expected to be different because of a great diversity of world biome situations?

10. **Observational hydrology, friendly-used in PUB** - How could field evidences, collected by direct observation on any ungauged catchment, be incorporated into a friendly manner and through a conceptually-based approach for the set up of a parsimonious number of parameters driving hydrological equal-suitable models?

11. **PUB multi-source validation** - In what way can we integrate hydrological measurements in a basin, i.e. soil moisture, rainfall, tracers, streamflow, etc., in order to both establish new multi-source layouts for validating models in gauged scales and infer predictive scenarios for PUB?

12. **PUB under non-stationarity and withdrawal effects -** How could models better address the new sources of uncertainty of the effective hydrological cycle at river basins that suffer seasonal land-use and with increasing water withdrawals from different water-consumer sectors? In what way these non-stationary components

(their business is also "water"!) could be approached scientifically for ungauged spatiotemporal scales? How these new "noise" and "uncertainty transfer" mechanisms, in real circumstances, should be decoupled from the traditional well-known approach of a "non-consuming water basin"? (Note: "non-consuming water basin" is the most known approach that frequently appears in current hydrological textbooks for educational purposes; only by having a basin isolated from manmade abstractions are "natural" hydrological components better approached—and wrongly knowable!)

13. **Variety of modelling opportunities under PUB** - In what way should the multi-finality of response scenarios at an ungauged basin be approached robustly (in terms of likelihood, a clone hydride system running both deterministically and with physically-based stochastic) and then confronted with equifinality-based models, in order to take account not only well-behavioural runs (as an exercise of approaching the *perceptual evidence* to the *conceptual model*) but even to foster emergent pathways of including resilient hydrological processes of the catchment?

14. **Hydrological equations updated for PUB** - What are the profits and limits of including heterogeneity and uncertainty as explicit factors, in an ensemble of new set of parameters (lumped approach) as well a matrix of parameters (distributed approach), that carry out a novel type of complementary hydrological equations for real world conditions of ungauged basins?

15. **PUB fitting of predictive uncertainty to data uncertainty -** By recognizing, in the worldwide hydrological praxis, the occurrence of (1) underlying uncertainty in hydrological time records (rainfall, streamflow, etc.) and of (2) predictive uncertainty of model runs (likelihood outcomes, scenario bounds, Bayes, Monte Carlo or bootstrap performances, etc), what new insights could emerge from the comparison of these two types of uncertainty (from data and from modelling)? What are the pro-and-cons of taking a phased analysis, i.e. at each time interval and/or at each spatial scale, thereby seeking for fitting predictive uncertainty to data uncertainty?

16. **Basin uncertainty revisited for PUB** - How robust and scientifically well-posed is the desired exercise (guess) of only trying of "reducing predictive uncertainty in our models" without regarding how big is the underlying uncertainty of the measurements adopted as "the truth" in river basins? By re-interpreting "what our database errors are possibly saying", what adaptive management should we begin in the short-term to counterpart the underlying data uncertainties in gauged basins? If applicable, how this management might be usefully profitable for new kind of experiment (that accept uncertainty and heterogeneity as basin milestones, but useful) in making PUB in worldwide biomes?

17. **PUB incentive for applied hydrological experiments and training** - Which kind of field composite layouts and best practices, i.e. Nested Catchment Experiments (NCE), are recommended to better assess data uncertainty in gauged basins? How "observational uncertainty" could be regarded into applied exercises on educational

textbooks, depicting its role played in front of predictive uncertainty of current modelling inter-comparison for PUB (i.e. distributed as well lumped)? How tracer science could be integrated and applied into the common hydrological gauging praxis, i.e. through composite automatic gauging stations, with both level and concentration records, gauged at NCE layouts?

18. **Learning layout for PUB** - How could we build up integrated hydrological models that include scale-transfer schemes that serve as boundary conditions for many the of biogeochemical processes with uncertainty, in data and in model outcomes?

19. **PUB capacity building & institution engagement** - How could leader hydrologists encourage undergraduate and postgraduate students through exercises inspired in real conditions of gaged or ungaged basins? How to set new experiments and logistic frameworks, capable of being adaptive in terms of incorporating future observations, alternative hypothesis-testing as well as acceptable bounds of uncertainty in hydrological processes? Because of being an emerging portfolio, how frequent are PUB workshops/ meetings needed, i.e. in a yearly basis?

Appendix II - Some thoughts on PUB.

(Robin Clarke, 17 January 2003)

1. First, a comment on the word Prediction. Eamonn Nash (of blessed memory) always drew a distinction between Prediction and Forecasting: the former being concerned with estimating the frequency of occurrence, in the future, of events of any given magnitude, without reference to the times at which they would occur. He used the term 'forecasting' to denote the estimation of what will be happening at a stated point of time in the future, such as discharge tomorrow, or runoff in the coming month. I think this usage remains standard, and if it is to be replaced, it should be done with care. In PUB, we are really concerned, as I see it, with both Prediction and Forecasting, in the distinct senses defined by Nash.

2. Nash was concerned with prediction and forecasting of flow characteristics, but of course PUB will need (will it not?) to extend this to sediment transport, and water chemistry. It might be argued that methods are needed to identify the structure and behaviour of freshwater ecosystems in ungauged basins, but this seems to me to be a problem for the next generation of water scientists (or possibly the one after that).

3. For prediction and forecasting in an ungauged basin, there are at least three approaches:-

   (a) In this first approach, a re-construction is attempted of data sequences (e.g., monthly runoff) for the basin, which would have been observed if the basin had been gauged for flow; sediment yield; …. From the re-constructed series, frequencies of events could be calculated, and/or forecasts made of future runoff; sediment yield; …. Because the reconstructed series is a series of estimates, some of its characteristics (e.g., variance) will differ from those of the 'true' series, if it had been observed.

   (b) A second approach is to estimate the particular characteristic in which we are interested (e.g., mean annual flood, mean annual sediment yield,…) in gauged basins, and then extrapolate to the basin(s) without records by means of a regionalization procedure (see comments below on this).

   (c) For prediction (*sensu* Nash), a third approach is to obtain artificial ("synthetic") sequences of monthly runoff (sediment yield; ….), which have the same statistical characteristics as the flow sequence that would have been observed, if the basin had been gauged. This is similar to approach (b) in that the approach (c) would involve the regionalization of parameters from statistical time-series models of the characteristic of interest. It might work better for rainfall - for which data sequences are both more common and longer – than for flow or sediment sequences. For example, there are some well-tried statistical models for daily rainfall, and it should not be too difficult to extrapolate their parameters.

These three alternatives (together with any others) could be compared using the data that we have now, by leaving out, from a set of basins with records, each basin in turn, and treating the omitted basin as if it were ungauged.

4. Regionalization is mentioned above, and this widely-used technique has possibilities for further development, in my opinion. I will focus on the multiple-regression approach (regression of mean annual runoff; …. on catchment characteristics, usually after log-transformation of both dependent and independent variables), but I believe the same comments apply to the alternative "growth curve" approach in which records are pooled by dividing them all by the station means.

   (a) Current regionalization procedures do not take into account, as far as I can see, the fact that the gauged basins bear a geographical relationship one to another (or, to borrow Keith Beven's phrase, that they lie in a landscape). Some of the basins are closer together than others; and, relative to any one basin, the others lie at different distances and in different directions from it. Over the past twenty-five years or so, there have been major advances in statistical methods for the analysis of spatial data, and it should be possible to make use of this theory, the better to describe the variance-covariance matrix of the multiple-regression residuals (instead of simply assuming that this matrix is diagonal).

   (b) However, whilst the introduction of spatial-statistical methods into current regionalization procedures is (in my opinion) an area to be explored, it will not be completely straightforward, because: (i) stations, whether gauged or ungauged, lie on irregular linear features (river channels) within the two- or three-dimensional landscape, so that Euclidean distance and direction are not the only variables to be considered; (ii) the description of the variance-covariance matrix of residuals will need to take into account the fact that the correlation between flows, at two sites on the same river, is likely to be greater than the correlation between flows at two sites lying in different river basins, even when the distance between them is the same.

   (c) As used in regionalization, multiple regression procedures assume that independent variables are free from measurement error. But this is clearly not the case; there are errors involved in calculating drainage basin area – perhaps the most important variable used in regionalization – and in calculating mean areal rainfall, where this is used. Both in the gauged basins used to calculate the multiple regression, and in the ungauged (for flow) basins to which it is applied, mean areal rainfall will be calculated from differing numbers of raingauges, bearing different spatial relationships to each other. Regionalization needs to take these spatial relationships into account.

   (d) The 'log-transformation' of variables is invariably used without any study of whether it is the most appropriate transformation for the data. Also de-transformation simply by taking the antilog of an estimated dependent variable results in negative bias.

(e) The multiple regressions used in regionalization are commonly univariate (having one dependent variable). Multivariate multiple regressions (having two or more dependent variables) are likely to be more appropriate: for example, where the first four L-moments are to be estimated at the ungauged basin. Although the regression coefficients will be the same, whether multivariate or univariate regressions are used, the confidence regions for estimates of the dependent variables in the ungauged basin will be quite different.

5. Where the basin of interest is not completely ungauged, but has a limited record, regionalized estimates (e.g. of model parameters) would seem to be the way to incorporate prior information. Apart from using Bayesian procedures to incorporate prior information, Bayesian procedures should also be explored for identifying which rainfall-runoff models are appropriate. There is a lot of new theory on this which could be useful for PUB, to be found in recent books on Markov Chain Monte Carlo methods.

6. A point of major concern for PUB, in my view, is that hydrological regimes are changing in some parts of the world. This is particularly true of South America, where there is now a substantial body of published work showing how river flows and climate have either changed, or exhibited long-term irregular fluctuations of the "seven fat years, seven lean years" type. These changes and long-term fluctuations may be the result either of land-use change, which has been extensive, or climate change, or both. The consequence is that past hydrological records are no longer a reliable guide to what will happen in the future, and new analytical procedures need to be developed (or existing ones modified) to take account of this. It would be very desirable for PUB to pay particular attention to this developing problem, which will become more important than ever in the future if climate changes in the future. Also, it is in developing countries that land-use changes are most in evidence, where hydrological records are scarce and diminishing, and where the problem is most acute. Standard procedures in analytical hydrology which are no longer valid where hydrological regimes are changing include the following:-
   (a) Estimation of the annual flood (annual mean runoff, annual low flow…) with T-year return period;
   (b) Generation of synthetic runoff sequences by ARMA models, to estimate frequencies of occurrence of extremes;
   (c) Intensity-Duration-Frequency curves for rainfall;
   (d) Regionalization, of any kind;
   (e) Rainfall-runoff modelling where models are calibrated using past records (although if the model is used for short-term forecasting, the problem is less serious because parameter estimates can be updated as new data comes along. But where the basin is ungauged, and parameters of a rainfall-runoff model are to be estimated from records at neighbouring basins, the problem again becomes important).

Appendix III – Some alternative answers to PUB questions

(those questions were made in a document written by Daniel Schertzer's, in 22 Jan. 2003)

What are the key gaps in our knowledge that limit our capacity to generate reliable predictions in ungauged catchments? –We need to place greater emphasis on what PUB intends to do that is different from what hydrologists have been doing in the past, and on what new problems hydrologists have to solve – problems which are extremely important for societies and economies, but which are exarcebated by the loss of sites at which hydrological observations are recorded. The scientific community under PUB needs to have originality to overcome difficulties from interpreting hydrologic variability occurring over a wide hierarchy of scales. To overcome those difficulties we should include both traditional and alternative viewpoints in the discussion and Science Plan.

What are the information requirements for reliable prediction in the future? Firstly, new problems, arising from changes in land-use and climate, have the consequence that past hydrological records may no longer be adequate to make predictions and forecasts about the future. We need to know better how resilient are basins under change. Secondly, PUB programme should motivate specific observational layouts to define the adequate framework for new modelling methods that accept that PUB is a learning process and need for a study of how could we enhance and interpret the underlying resilience, in a nested spatiotemporal continuum, to constrain the uncertainty in the prediction of ungaged scales.

What experimentation is needed to underpin the knowledge required? Experimental nested basins because the basin balance equation needs for better data collection technology and processing. For instance, streamflow is not a full-gauged hydrologic component because traditional gauging stations fail on register the flow contributions of the hyphoercic zone and in the near, depicting a clear physical uncertainty of the riverflow component.

How can we employ new observational technologies in improved predictive methods? Improving our ability to estimate, measure and interpret how hydrologic components could be integrated in either upscaling or downscaling through nested experiments.

How can we improve the hydrological process descriptions that address key knowledge elements which can reduce uncertainty?
Knowing more from experiences gained and lessons learned of field hydrologists and water practitioners who must take part of PUB programme.