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The Model Parameter Estimation Experiment (MOPEX): its structure, connection to other international initiatives and future directions

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Abstract The Model Parameter Estimation Experiment (MOPEX) is an international project aimed at developing enhanced techniques for the *a priori* estimation of parameters in hydrological models and in land surface parameterization schemes connected to atmospheric models. The MOPEX science strategy involves: database creation, *a priori* parameter estimation methodology development, parameter refinement or calibration, and the demonstration of parameter transferability. A comprehensive MOPEX database has been developed that contains historical hydrometeorological data and land surface characteristics data for many hydrological basins in the United States (US) and in other countries. This database is being continuously expanded to include basins from various hydroclimatic regimes throughout the world. MOPEX research has largely been driven by a series of international workshops that have brought interested hydrologists and land surface modellers together to exchange knowledge and experience in developing and applying parameter estimation techniques. With its focus on parameter estimation, MOPEX plays an important role in the international context of other initiatives such as GEWEX, HEPEX, PUB and PILPS. This paper outlines the MOPEX initiative, discusses its role in the scientific community, and briefly states future directions.

Key words *a priori*; calibration; hydrological models; parameters; regionalization; transferability; uncertainty

INTRODUCTION

Hydrological and land surface models are tools of increasing importance for water resources management worldwide: they support decision making and strategic

planning in a context of possible climate and land use change in basins. They are important to assess the impact of these changes on water resources. Requirements to successfully perform these modelling tasks are that we can reliably model a wide range of hydroclimatic regimes and understand how changes in the basin are reflected as changes in the model parameters or in its structure. Current model structure requires that at least some key parameters are adjusted according to the fit of the model predictions to observations of the response variable of interest (usually streamflow), a process called calibration. However, these measurements are not always available and where available, they may be very sparse. Thus, other approaches are needed to derive *a priori* (before calibration) parameter estimates. Current procedures for *a priori* parameter estimation are often based on relationships between model parameters and basin characteristics—that is, soils, vegetation, topography, climate, geology, etc. These developed relationships have not been fully validated through rigorous testing using retrospective hydrometeorological data and corresponding land surface characteristics. This is partly because the necessary database needed for such testing has not been available. Moreover, there still exists a gap in our understanding of the links between model parameters and land surface characteristics. Generally, available information about soils and vegetation typically only indirectly relates to model parameters that conceptualize aspects such as the hydraulic properties of soils and rooting depths of vegetation. It is also not clear how heterogeneity associated with spatial land surface properties affects those characteristics at the scale of a basin or a grid cell. Consequently, there is a considerable degree of uncertainty associated with the parameters derived using current procedures, which is propagated into the model predictions and into the subsequent decision making process.

The Model Parameter Estimation Experiment (MOPEX) is an ongoing international project to help develop techniques for the *a priori* estimation of parameters used in land surface parameterization schemes of atmospheric and hydrological models. MOPEX is affiliated with both the Predictions in Ungauged Basins (PUB) and the Global Energy and Water Cycle Experiment (GEWEX), and is supported by the GEWEX Americas Prediction Project (GAPP) as well as by individual participants. MOPEX evolved to address the parameter estimation problem and to promote and guide the development of improved *a priori* parameter techniques applicable to both gauged and ungauged basins. The MOPEX project has been an international collaborative effort since 1996, with the involvement of international scientists and data sets assembled from different countries.

The scope of this paper includes an outline of the MOPEX initiative, a discussion of its role in the scientific community and closes with a statement of future directions.

MOPEX SCIENCE STRATEGY

The MOPEX science strategy involves three major steps (Fig. 1):

- To develop the necessary data sets from a range of hydroclimatic regimes.
- To use these data to develop *a priori* and calibrated parameters and then develop and test new *a priori* techniques.
- To demonstrate transferability to other basins.

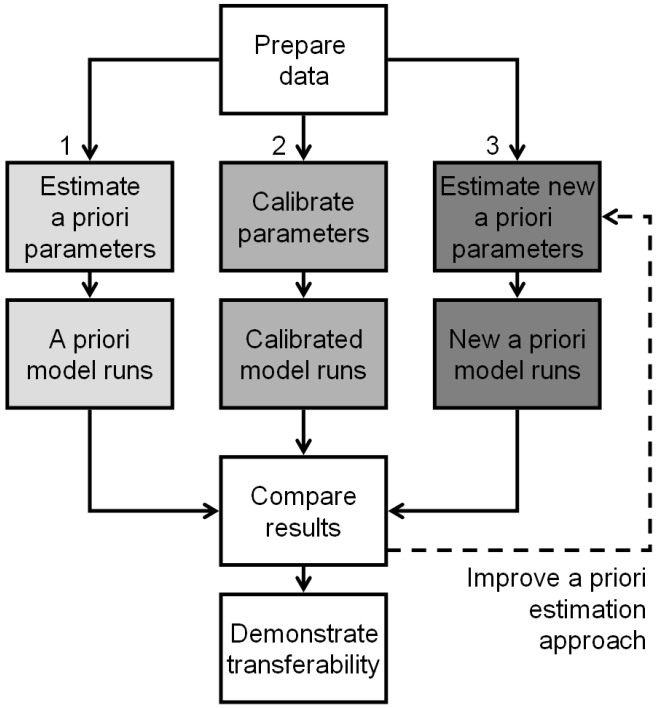

Fig. 1 MOPEX implementation strategy.

Figure 1 outlines the three-path strategy for the second step in the MOPEX science strategy. The benchmark for any development is *a priori* parameter estimation made with the currently available techniques (path 1). Any newly developed technique has to improve on this benchmark. The second path includes the calibration of the model parameters against observations of the variable of interest. These parameter estimates therefore provide the optimal (at least from an optimization point of view, not necessarily from a hydrological point of view) parameter estimates for the basin under investigation. So, while path 1 provides the lower bound of performance that any *a priori* parameter estimation method has to achieve, path 2 provides the upper bound since it is (or at least should be) not feasible that any *a priori* estimates perform better than optimized parameters. Within the path 2, the calibrated parameters are analysed to improve our understanding of relationships between model parameters and basin characteristics (i.e. climate, soils, vegetation and topographic features). This improved understanding can then be used to derive new methods and to make new model runs in path 3. The success of step two is measured by how much improvement in model performance is achieved in path 3 compared with results from the benchmark runs in path 1.

A range of objectives or focus areas has been defined by the MOPEX participants over the years in order to foster the research and activities required to achieve improved *a priori* estimates. These can be listed as follows:

– Objective 1: To evaluate the transferability of *a priori* model parameters between watersheds;
– Objective 2: To develop and test improved *a priori* model parameter estimation techniques for ungauged basins;

- Objective 3: To develop improved strategies to classify basins and to measure hydrological similarity;
- Objective 4: To develop diagnostic tools to foster improved understanding of natural hydrological processes at basin scales and of the related behaviour of hydrological models;
- Objective 5: To promote the standard assessment of uncertainty, including assessing the uncertainty in *a priori* parameter estimates;
- Objective 6: To improve calibration strategies, including the use of *a priori* parameter estimates within these strategies;
- Objective 7: To develop objective measures to evaluate the parameter estimate techniques and to understand parameter uncertainty.

The research will be facilitated through the development and use of an international database of retrospective hydrometeorological data and basin characteristics data for a wide range of climate and geophysical conditions. This database should include data for a wide range of Intermediate Scale Area (ISA) river basins (500–10 000 km^2) throughout the world. MOPEX has already assembled retrospective hydrometeorological data and basin characteristics data for many US basins. Data for select basins from other countries such as Australia, France, UK, Germany, and China have also been collected. Details about this database effort can be found in Schaake *et al.* (this issue). The MOPEX initiative will continue to promote and facilitate the exchange of ideas and experiences on approaches to model parameter estimation for different climatic regimes.

MOPEX WORKSHOPS

MOPEX participants have organized a series of workshops (Table 1) as one of the main instruments in advancing MOPEX science. Workshops, which started in 1999, have been held in each of the past three years to investigate various issues related to parameter estimation and regional model applications. Prior to the workshops, model participants are asked to apply their model and parameter estimation procedures to (preferably) a nominated set of MOPEX basins for prior analysis. The main goal of these workshops has been to investigate some of the MOPEX science strategies using various hydrological and land surface models on long-term hydrometeorological data. Details of past and currently planned workshops are given in Table 1. Past workshops centred particularly around the following questions:

- How do we define the relationships between model parameters and basin characteristics?
- How can model calibration be used to refine the *a priori* parameters?
- How do we evaluate the uncertainty due to model structure, calibration data and model parameters?

While the preceding workshops have been very successful, it was felt that a more concentrated effort is required to increase the science output derived from the cooperative efforts of the workshop participants. Starting with the 2004 workshop in France, workshops will be based on a new format with the following underlying principles:

Table 1 MOPEX workshops and symposia.

Date	Location	Sponsor	Focus
Past			
1999	Birmingham, UK	IUGG[1]/IAHS[2]	Initiating workshop
2001	Maastricht, The Netherlands	IAHS	SVAT symposium with examples of parameter estimation techniques, IAHS Publ. 270
2002	Tucson, USA	NSF STC SAHRA[3]	US Data
2003	Sapporo, Japan	IUGG/IAHS	US Data and review of techniques
2004	Paris, France	CEMAGREF	French Data
2005	Foz do Iguassu, Brazil	IAHS	Use of large data sets
Future			
2007	Perugia, Italy	IUGG/IAHS	Link to atmospheric science

[1] International Union of Geodesy and Geophysics. [2] International Association of Hydrological Sciences. [3] National Science Foundation Science and Technology Center for Sustainability of Semi-Arid Hydrology and Riparian Areas.

- Each workshop will have a specific focus, either in terms of hydro-climatic region (for example, humid or semiarid) or in terms of a specific application (for example, flood forecasting).
- Each workshop will allow different levels of participation; that is, different numbers of basins that have to be simulated, to enable every participant to contribute to the collaborative science investigation. A minimum number of basins will be specified that each participant has to simulate in order to take part in the workshop. A larger number of basins is available for those who want to contribute more.
- The data sets of 12 basins from each workshop will be archived to create a database of benchmark basins that will be taken forward in time and used for comparison studies.
- This benchmark database is in addition to the general MOPEX database, which is aimed at creating a high-quality, historical hydrometeorological and river basin characteristic data sets for a wide range of ISA river basins throughout the world. High-quality data sets have been obtained for Australia from the University of Melbourne and for the United Kingdom from the Institute of Hydrology, in addition to a large number of US data sets.
- A small, but well-defined set of science objectives will be listed for each workshop to allow for a coordinated and meaningful analysis of workshop results.

INTERNATIONAL INITIATIVES AND THEIR RELATION TO MOPEX

The MOPEX initiative has its place in the international arena of initiatives, with its clear focus on improving parameters for hydrological and land surface models. Here we discuss briefly how MOPEX relates to some of the main international initiatives that are currently ongoing.

The Project for Intercomparison of Land-surface Parameterization Schemes (PILPS) has shown that different land–surface schemes can provide widely different simulation results, although driven by the same meteorological forcing data and required to use the same values for commonly named parameters (such as soil

hydraulic properties and vegetation phenology parameters). The large scattering of model results can be partially explained by the uncertainty in the values of the parameters used in each scheme. Development of enhanced *a priori* parameter estimation methodologies is therefore necessary to improve the performance of hydrological models and land surface schemes.

MOPEX has the endorsement of several international organizations and projects including: the World Meteorological Organization (WMO) Commission on Hydrology, International Association of Hydrological Sciences (IAHS) Predictions in Ungauged Basins (PUB) Initiative (Sivapalan, 2003; Wagener *et al.*, 2004) and the Global Energy and Water Cycle Experiment (GEWEX). The Office of Global Programs in the National Oceanic and Atmospheric Administration (NOAA) and funding agencies in different countries have all provided financial support for scientists to participate in MOPEX activities.

The Hydrologic Ensemble Prediction Experiment (HEPEX) focuses on bringing meteorological and hydrological scientists from research, operational and user communities together to work on advancing probabilistic hydrological forecasting (Franz *et al*., 2005). The HEPEX initiative was launched in the spring of 2004. With its focus on connecting the hydrological and meteorological communities, and with a strong emphasis on prediction, this initiative looks to MOPEX to develop improved parameterizations of the terrestrial components of the overall modelling system and to represent uncertainty in these parameterizations.

Within the PUB initiative of IAHS, MOPEX has an important position as the working group that focuses on the problems of parameter estimation in gauged and ungauged basins. Therefore it has a central role and the MOPEX database is likely to be of great value within PUB where comparison studies are a major component. Two other working groups with which we anticipate particularly strong interaction are the Top-Down Modelling Working Group (http://www.stars.net.au/tdwg/; Littlewood *et al*., 2003)—focusing on the development of parsimonious data-based modelling approaches—and the Working Group on Uncertainty Estimation for Hydrological Modelling (Wagener *et al*., 2006)—focusing on the development of an uncertainty framework for hydrological predictions.

LESSONS LEARNED SO FAR

Ultimately, models are (by definition) simplified representations of the real world and are therefore imperfect. This means that their parameters are also simplified representations of the real world characteristics they represent, and we will therefore never find a 1:1 correlation between model parameters and basin characteristics. It is likely that there will remain some dependency on fitting the model to our intended real-world application considering the model purpose, data availability, hydro-climatic region, etc. This also means that there will always be some degree of uncertainty that has to be considered in this process and that has to be communicated to any decision maker. How to estimate and represent this uncertainty in the context of imperfect models is still unclear.

Results to-date of the MOPEX initiative have recently been summarized by Duan *et al*. (2006). Here we restate the results in the form of testable hypotheses that can be corroborated or refuted through our future workshop activities:

- Result: Study results confirm earlier statements that the existing *a priori* parameter estimation procedures are problematic and are in need of improvement. This means that there is still large uncertainty regarding how parameter values would change under altered conditions, e.g. climate and land use.
- Hypothesis 1: *Current a priori estimates of hydrologic model parameters are very uncertain.*
- Hypothesis 2: *Our lack of understanding regarding how model parameters relate to physical basin characteristics precludes reliable predictions of how watershed response would change with altered conditions (e.g. land-use change).*
- Result: Calibration results clearly demonstrate the potential for improvement in *a priori* parameter estimation. The difference between the benchmark and optimized modelling results shows that there is still a clear need for calibration to be included in modelling studies and that it should be possible to improve currently available *a priori* approaches. In addition, different models seem to represent hydrological processes differently and all of them are imperfect. This means that parameters will in most cases be model dependent, even if they have the same name and units. Understanding this model dependence should help in understanding what level of correlation between model parameters and basin characteristics can be expected.
- Hypothesis 3: *We are currently not able to achieve reliable hydrological predictions without relying on the calibration of at least some key parameters*.
- Hypothesis 4: *Model parameters are model structure dependent and any regionalization or transfer approach will necessarily be model specific.*

Corroborating or refuting these hypotheses requires repeatable tests on a sufficiently large number of basins to allow for statistically results. However, possible sample sizes will—at least for the near future—be limited for some more physically-based model approaches that cannot be applied easily to new basins.

MOPEX thrives on the contributions of a heterogeneous group of scientists. Its experiments/tests have to be sufficiently flexible to allow for the participation of everybody who wants to contribute. Our intention is to provide a platform to perform tests on the above mentioned and other hypotheses utilising as wide a range of model structures, methods and expertise as possible.

FUTURE OUTLOOK

The work of MOPEX will continue contributing to the improved understanding of *a priori* and *a posteriori* (calibrated) model parameters for hydrological and land surface models. This will be implemented through workshops with different foci, and an increased interaction with other initiatives such as HEPEX, and other working groups, such as the PUB Top-down modelling and Uncertainty working groups.

A particular strength of MOPEX is the continuing growth and use of an international database of basin data for the comparison of techniques and models. This enables us to create an increasing knowledge base of methods applied to the same data. Connecting this database to others created within the context of the PUB initiative will provide international benchmark data sets.

We invite discussion and input from interested researchers on the following aspects:

- *MOPEX initiative*: We invite anybody interested in the above subjects to participate in the MOPEX initiative. Additional information about the MOPEX initiative can be found at http://www.seas.ucla.edu/~thogue/MOPEX/ and in the article by Hogue *et al*. (2004).
- *MOPEX workshops*: We invite suggestions for geographical or topical foci of future workshops. Of particular interest would be a group willing to host a MOPEX workshop. The most effective workshops so far have lasted around 2½–3 days.
- *MOPEX database*: We are continuously expanding the MOPEX database and are always looking for new data sets of different hydroclimatic and geographical regions (or additions to data sets of regions already covered). Please contact any of the authors if you have a data set that fulfils the MOPEX quality and content requirements, and could be added to our database.

The next MOPEX workshop will be held during the IUGG/IAHS Perugia General Assembly in 2007. The workshop will focus on the connection to the atmospheric science community and their need for parameter estimation. As always, any constructive criticism on any aspect of this paper is very welcome.

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