JETIR.ORG ISSN: 2349-5162 | ESTD Year : 2014 | Monthly Issue
JOURNAL OF EMERGING TECHNOLOGIES AND INNOVATIVE RESEARCH (JETIR)
An International Scholarly Open Access, Peer-reviewed, Refereed Journal

HYDROLOGICAL MODELLING AS TOOL FOR SUSTAINABLE WATER RESOURCE MANAGEMENT

[1]Vikas Kumbhar*, [2]Dr. V. A. Swami*, [3]Mrunalini P. Jagtap, [4]Kishori A. Sutar
[1,3,4] Research Scholar, Dept. of Technology, Shivaji University, Kolhapur
[2]Professor, KIT's Institute of Technology (Autonomous) Kolhapur

Abstract:
Large-scale hydrologic models are being used more and more in watershed management and decision making. Sometimes rapid modelling and analysis is needed to deal with emergency environmental disasters. However, time is often a major impediment in the calibration and application of these models. To overcome this, most projects are run with fewer simulations, resulting in less-than-optimum solutions. In this paper we explain a methodology where a parallel processing scheme is constructed to work in the Windows platform. Parallel processing is implemented in SWAT-CUP (SWAT Calibration and Uncertainty Procedures) using the optimization program SUFI2 (Sequential Uncertainty FItting ver. 2). The problem of scales and particularly the modelling of macro or continental scale catchments in hydrology is addressed. It is concluded that the magnitude of the scale problem is related to the specific hydrologic problem to be solved and to the scientific approach and perspective of the modeller. In this paper, we discuss validation of hydrological models, namely the process of evaluating performance of a simulation and/or prediction model. The performance of two popular watershed scale simulation models – HSPF and SWAT – were evaluated for simulating the hydrology of the 5,568 km2 Iroquois River watershed in Illinois and Indiana. Interactions between humans and the environment are occurring on a scale that has never previously been seen; the scale of human interaction with the water cycle, along with the coupling present between social and hydrological systems, means that decisions that impact water also impact people.

Index Terms **– Hydrological Modelling, Parallel Process, SWAT-CUP, SUFI2, Macroscale hydrological modelling, Scale problem, Baltic basin, Validation, HSPF, SWAT, Socio hydrological modelling.**

I. Introduction

All hydrological models are simplified representations of the real world. In Section 2 a consistent, general terminology and methodology applicable within the whole range of hydrological modelling is presented. The parallel processing scheme developed here utilizes the existing capabilities of the available systems and is ideal for performing hydrologic model calibration and uncertainty analysis. Hydrological modellers have different views on the scale problem depending on their perspective and scientific outlook. Scaling and macroscale modelling are problems which are addressed by the Continental Scale Experiments (CSEs) carried out under the Global Energy and Water Cycle Experiment (GEWEX) research umbrella, such as the GCIP (Mississippi Basin), the LBA (Amazon Basin), the MAGS (Mackenzie Basin) and the BALTEX (Baltic Sea Basin) programs. The need for agreed and standardized validation protocols in hydrological modelling has become progressively more urgent. And also, there is study is to compare and assess the suitability of the Hydrological Simulation Program – FORTRAN (HSPF) and the Soil and Water Assessment Tool (SWAT) models for simulating the hydrology of one major tributary of the Upper Illinois River Basin, which is representative of the land use and soils throughout much of the Illinois River Basin. This paper also seeks to draw together relevant information and concepts pertaining to the modelling of socio-hydrological systems; it is structured as dealing with the questions of "why?", "what?" and "how?"

II. Terminology and Methodology

2.1 Definition of basic terms –

The *natural system* that is considered here is the hydrological cycle or parts of it as we currently conceive it. A *hydrological model* is a simplified representation of the natural system. From a hydro informatics point of view, a model is a collection of signs that serves as a sign, so that the hydrological model is the set of signs (symbols and other tokens) that serve as a representation of the natural system or some aspects of it. A *mathematical model* is a set of mathematical expressions and logical statements combined in order to simulate the natural system. *Simulation* is the time-varying description of the natural system computed by the hydrological model. A *routine*, a *component*, or a *sub model* is part of a more comprehensive model, e.g., the snowmelt simulation part of a model for the complete land phase of the hydrological cycle. When an object encapsulates knowledge that acts upon information so that it both acts upon and is itself acted upon by other objects, it is called an *agent.* A *parameter* is a constant in the mathematical expressions or logical statements of the mathematical model. It remains constant in virtual time. A variable is a

quantity which varies in space and time. A *deterministic model* is a model where two equal sets of input (i.e., collections of signs) always yield the same output sign if run through the model under identical conditions. A *stochastic model* has at least one component of random character which is not explicit in the model input, but only implicit or 'hidden'.

We conceive a *catchment* as a region of physical space over which flows occur that are collectively of concern to us. A catchment is thus an object towards which the universe of discourse of hydrology becomes directed. A *lumped model* is a model where the catchment is regarded as one unit. The variables and parameters are thus representing average values for the entire catchment. A *distributed model* takes account of spatial variations in all variables and parameters. By a *physical process* we understand a representation in our own minds of an event occurring in our outer world of sense experience. A *black box* or an *empirical model* is a model developed without any consideration of the physical processes that we otherwise associate with the catchment. A *conceptual model* is one that is constructed on the basis of the physical processes that we 'read' into our observations of the catchment. A *physically-based model* describes the natural system using the basic mathematical representations of the flows of mass, momentum and various forms of energy. This type of model, also called a *white box model*.

A *model* is defined as a particular hydrological model established for a particular catchment. A *modelling system*, on the other hand, is defined as a generalized software package, which, without program changes, can be used to establish a model with the same basic types of equations (but allowing different parameter values) for different catchments. The term *model code* is often used synonymously with the term modelling system.

2.2 General Terminology for Model Credibility

Many different definitions of model validation are presently used. A consistent terminology with a set of definitions for terms such as conceptual model, computerized model, verification, validation, domain of applicability and range of accuracy, using a philosophical framework, states that verification and validation of numerical models of natural systems is theoretically impossible, because natural systems are never closed and because model results are always non-unique. Instead, in this view models can only be confirmed. The following terminology is based on the general terminology. The elements in the terminology and their interrelationship are as follows:

The different terms in a manner that appears the most suited to current hydrological thinking, while hydro informatics is obliged to define them more generally, as follows: *Reality:* The natural system, understood here as the hydrological cycle or parts of it. For hydro informatics reality and truth must be defined together. Thus [3] *"Reality* is the name that we give to the interface between our outer and our inner worlds and a *truth* is an intimation of the oneness of these two worlds". *Conceptual model:* Verbal descriptions, equations, governing relationships, or 'Natural laws' that purport to describe reality. This is then the sign representation of that place where our outer and inner worlds intersect. *Domain of intended application (of a conceptual model):* Prescribed conditions for which the conceptual model is intended to match reality. *Level of agreement (of the conceptual model):* Expected agreement between the conceptual model and reality, consistent with the domain of intended application and the purpose for which the model was built. This then becomes the observed agreement that can be expressed between the virtual world that the mathematical model is capable of reproducing when translated into code and the world of nature as we perceive it. *Model qualification:* An estimation of the adequacy of the conceptual model to provide an acceptable level of agreement for the domain of intended application. *Computerised model:* Anyone of an infinite number of operational computer programs which implements a given conceptual model. *Model verification:* Substantiation that a computerized model is in some sense a true representation of a conceptual model within certain specified limits or ranges of application and corresponding accuracy. *Domain of applicability (of a computerised model):* Prescribed conditions for which the computerised model has been tested, i.e., compared with reality to the extent that is practically possible and judged suitable for use (through the process of model validation, described below). *Range of accuracy (of computerised model):* Demonstrated agreement between the computerised model and reality within a stipulated domain of applicability. Since the introduction of Computational Hydraulics [1] this has also been called the 'performance envelope' of the computerised model.

Model validation: Substantiation that a computerised model within its domain of applicability possesses a satisfactory range of accuracy consistent with the intended application of the model. The first is the relation established by our own sense experiences of the world of nature and the second is the relation expressed through the virtual world that the model presents to us. The process of validation then corresponds to a working out of the relation between these two relations so as to bring them as closely as possible into harmony [2] as schematised in Fig. 1

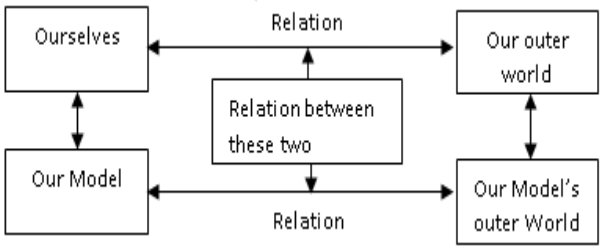

fig. No. 1 Schematic illustration of the term validation in traditional hydro-informatics sense as working out the relation between two relations.

Models generally can only be more or less validated, but never 'absolutely validated'. This is to say that 'reality' and 'truth' can never coincide in any human construction. *Certification documentation:* Documentation intended to communicate knowledge and information concerning a model's credibility and applicability, containing, as a minimum, the following basic elements: (1) Statements of the purposes for which the model has been built. (2) Verbal and analytical descriptions of the conceptual model and the corresponding computerised model. (3) Specification of the domain of applicability and range of accuracy related to the purpose for which the model is intended. (4) Description of tests used for model verification and model validation and a discussion of their adequacy.

Model certification: Acceptance by the model user of the certification documentation as adequate evidence that the computerised model can be effectively used for a specific application. *Computer simulation:* Exercise of a tested and certified computerized model to 'gain insight into' reality or rather, in the general terms of computer semiotics [4] to modify the user's perception of reality. It is therefore important to distinguish between the terms modelling system and model, as defined in Subsection 2.1 and Section 3.

In this context it should be observed that a modelling system or a code can itself be verified. A code verification involves comparison of the numerical solution generated by the code with one or more analytical solutions or with other numerical solutions. Verification ensures that the computer program solves the equations that constitute the mathematical model with an accuracy that is deemed adequate for the proposed application. Similarly, a model is said to be validated if its accuracy and predictive capability throughout the process of validation has proven to lie within acceptable limits or errors. It is important to notice that the term 'model validation' refers to a site-specific validation of a model.

2.3 Modelling Protocol

In this context it is essential that the user both has a thorough knowledge of the hydrological processes being modelled and has a solid experience in modelling. A third crucial factor is a good and rigorous procedure for applying models. Such a procedure, which comprises a sequence of steps in a hydrological model application, is often referred to as a modelling protocol. The protocol is described step by step in the following.

(1) The first step in a modelling protocol is to *define the purpose* of the model application. An important element in this step is to give a first assessment of the desired accuracies of the model outputs. Once the purpose has been sufficiently clearly defined, it may be obvious which type of modelling system is required in order to solve the specific problem.

(2) Based on the purpose of the specific problem and an analysis of the available field data, the user must establish a conceptual model. In other words, a conceptual model comprises the user's perception of the key hydrological processes in the catchment and the corresponding simplifications and numerical accuracy limits which are assumed acceptable in the mathematical model in order to achieve the purpose of the modelling.

(3) After that, a suitable computer program has to be selected. In this case it is important to ensure that the selected code has been successfully verified for the particular type of application in question.

(4) In case no existing code is ·considered suitable for the given conceptual model a code development has to take place. The computer code is a computer program that contain algorithm capable of solving the mathematical model numerically. The term computer code is here used synonymously with the term generalised modelling system. In order to substantiate that the code solves the equations in the conceptual model within acceptable limits of accuracy a code verification is required.

(5) After having selected the code and collected the necessary field data, a model construction has to be made. This involves designing the model with regard to the spatial discretisation of the catchment, setting boundary and initial conditions and making a preliminary selection of parameter values from the field data.

(6) The next step is to define performance criteria that should be achieved during the subsequent calibration and validation steps. If the performance criteria are specified unrealistically high, it will either be necessary to modify the criteria or to collect more and possibly quite other field data.

(7) Model calibration in general involves manipulation of a specific model to reproduce the response of the catchment under study within the range of accuracy specified in the performance criteria. In practice this is most often done by trial-and-error adjustment of parameters, but automatic parameter estimation methods may also sometimes be used.

(8) Model validation is the process of demonstrating that a given site specific model is capable of making sufficiently accurate predictions. The model is said to be validated if its accuracy and predictive capability in the validation period have been proven to lie within acceptable limits or to provide acceptable errors.

(9) *Model simulation* for prediction purposes is often the explicit aim of the model application. In view of the uncertainties in parameter values and, possibly, in future catchment conditions, it is advisable to carry out a predictive sensitivity analysis to test the effects of these uncertainties on the predicted results.

(10) *Results* are usually *presented* in reports. However, with the newest information technology that is now emerging it is also possible to display modelling results as (colour) animations. Furthermore, in certain cases, the final model is transferred to the end user for subsequent day-to-day operational use.

(11) An extra possibility of validation of a site-specific model is a so-called *post audit.* A post audit is carried out several years after the modelling study is completed and the model's predictions can be evaluated.

III. Classification according to Hydrological Process Description

3.1 Classification

The present classification is applicable to hydrological simulation models. The classification is in principle applicable both to catchment models and to single component models such as groundwater models. The two classical types of hydrological models are the deterministic and the stochastic. However, over the last decade, increasingly more interplay has occurred and a joint stochastic deterministic methodology today provides a very useful framework for addressing some of the fundamental problems in hydrology such as taking spatial variability account and assessing uncertainties in modelling.

3.2 Deterministic Models

Deterministic models can be classified according to whether, the main groups as follows:

3.2.1 Empirical models (black box).

Black box models are empirical, involving mathematical equations that have been assessed, not from the physical processes in the catchment, but from analyses of concurrent input and output time series. Black box models may be divided into three main groups according to their origin -

Empirically hydrological methods- empirical hydrological methods are often used in some components of more comprehensive models, e.g., the unit hydrograph is often used for streamflow routing and a linear reservoir is often used to represent the groundwater system in conceptual rainfall-runoff models.

Statistically based methods- These methods are often mathematically more advanced than the above empirical hydrological methods. Linear regression and correlation techniques are standard statistical methods used to determine functional relationships between different data sets.

Hydro informatics-based methods. A new group of 'transfer function models' based on methods introduced more generally in hydro informatics is now emerging.

3.2.2 Lumped conceptual models (grey box).

The lumped, conceptual models are especially well suited for the simulation of the rainfall-runoff process when hydrological time series exist that are sufficiently long for a model calibration. Thus, typical fields of application include the extension of short streamflow records based on long rainfall records and real-time rainfall-runoff simulations for flow forecasting.

3.2.3 Distributed physically-based models (white box).

The principal mode of operation of a distributed physically-based model is illustrated in Fig. 2. Instead, the flows of water and energy are directly calculated from the governing continuum (partial differential) equations, such as for instance the Saint Venant equations for overland and channel flow, Richards' equation for unsaturated zone flow and Boussinesq's equation for groundwater flow.

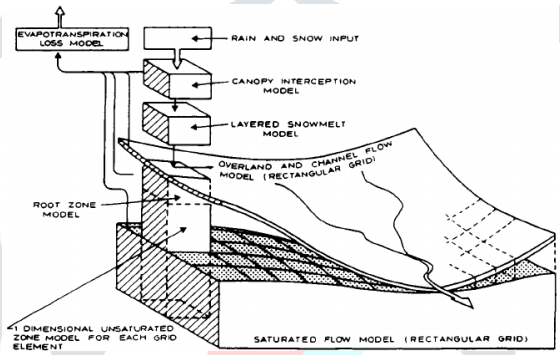

fig. No. 2 Schematic diagram of a catchment and the MIKE SHE quasi three-dimensional distributed physically-based model

Distributed physically-based models give a detailed and potentially more correct description of the hydrological processes in the catchment than do the other model types.

3.3 Stochastic Time Series Models

A stochastic model is derived from a time series analysis of the historical record. The stochastic model can then be used for the generation of long hypothetical sequences of events with the same statistical properties as the historical record. The classical stochastic simulation models are comparable to the empirical, black box models. Hence the stochastic time series models are in reality composed of a simple deterministic core (the black box model) contained within a comprehensive stochastic methodology.

3.4 Joint Stochastic-Deterministic Models

Several model types based on a joint stochastic deterministic approach have been developed. These models are composed of two, in principle equally important parts, namely a deterministic core within a stochastic frame. the governing equations become what are often described as stochastic partial differential equations (PDEs), which are of course usually much more difficult to solve than are traditional deterministic PDEs. Two possible approaches to the stochastic PDE's are: 1) The Monte Carlo technique, whereby the deterministic model is run several times using different (equally probable) realizations of the parameter field. 2) The stochastic PDE is simplified and solved analytically. The joint stochastic-deterministic models, on the other hand, produce uncertainty bands (such as are described by mean values and standard deviations) for each of the predicted time series. Thus, the Joint stochastic-deterministic models are able to transfer the inherent uncertainty on the input variables or effects of non-described variability of spatial parameter values to probabilistic descriptions of the output variables.

IV. Modelling of Spatial Variability of Hydrological Parameters

Hydrological parameter values exhibit very large spatial variations in nature. Consider for illustrational purposes how the Stanford and the MIKE SHE, as typical representatives for the lumped conceptual and the distributed physically-based model types, describe the infiltration process in the unsaturated zone over a catchment. the spatial variability of the key soil parameter is implicitly taken into account. As a result, the mechanism for generation of overland flow functions as a contributing area approach. Being a distributed model, the catchment is divided into a number of grids, and the infiltration equation is thus used on a number of unsaturated zone columns, each of which is characterised by soil hydraulic parameters. In principle, the model parameters are different in the different soil columns. The overland flow generation in the catchment theoretically becomes too much of an 'on/off' process. In practice, this effect is often overshadowed by other dominating processes or it can be compensated through calibration. Hence, even in fully physically-based models the spatial variability of hydrological parameters will most often not be at all fully described. Another approach is adopted in TOPMODEL where the spatial variability of soil properties is built into the process equations. The advantages of TOPMODEL as compared to traditional lumped conceptual systems are the explicit accounting of the spatial variability and the direct use of spatial data such as topography and channel system together with semi-distributed calculations of hydrological variables.

V. Classification according to Technological Level

A practice of modelling can be categorized according to its technological level in different generations of modelling systems:

First Generation - Computerised Formulae Making the methods of numerical calculations that had been developed for human computation easier and quicker in through the application of the very simplest numerical methods

Second Generation - One-Off Numerical Models. Second generation models generally required comprehensive user experience within the fields of computers (hardware and software) and the related numerical techniques.

Third Generation - Generalised Numerical Modelling Systems. Traditionally, third generation systems have been based on main frame computers, but most of them can run on PC's today. However, this approach is now largely super ceded by fourth generation modelling.

Fourth Generation - The Industrial User-friendly Software Product. These are user friendly software products that can be applied by engineering and scientific professionals.

Fifth Generation - 'Intelligent' Modelling System. These begin with modelling systems designed for technically-skilled but non-expert users. At present only a few fourth-generation systems are operational and fifth generation systems are still mainly at an experimental stage outside of real-time control applications for urban drainage systems. Furthermore, it is believed that fifth generation systems extending to hydro informatics systems are required in order for the modelling technologies to achieve their full potential in terms of practical application.

VI. A parallelization framework for calibration of hydrological models

Parallel processing or parallel computing is the ability to carry out multiple operations or tasks simultaneously. This study is designed to investigate parallel processing issues not to perform a meaningful calibration task.

6.1 Materials and methods

6.1.1 The hydrologic simulator (SWAT)

SWAT is a process-based, river basin-scale, semi-distributed hydrologic model. SWAT is an integrated model including components such as weather, hydrology, soil, nutrients, pesticides, land management, bacteria and pathogens. SWAT is a continuous simulation model which operates on a daily time step. In SWAT the spatial heterogeneity of the watershed is taken into account. A high-resolution project could easily result in thousands of input files, which would make it challenging to reconfigure or update model parameters. All SWAT's text input and output files reside in the TxtInOut directory. Initially, SWAT-CUP copies these files to a BACKUP directory, which remain unchanged throughout the calibration process.

6.1.2 SUFI2 optimization program

This is the pre-processing stage executed by a batch file SUFI2_pre.bat, which runs the program SUFI2_LH_sample.exe. Theoretically, all samples could be run at once, hence an entire iteration would require only the time that it takes to make one model run. After pre-processing, another batch file, SUFI2_run.bat, executes the SWAT_Edit. exe program, which copies a set of sampled parameters from par_val.txt in their appropriate locations in the SWAT input files. The encoding scheme allows the parameters to be kept regionally constant to modify a prior spatial pattern, or be changed globally. By using this flexibility, a calibration process can be started with a small number of parameters that only modify a given spatial pattern, with more complexity and regional resolution added in a stepwise learning process. Next, the SWAT model is executed, and the outputs of interest are extracted from SWAT output files (output.rch, output.hru, output.sub). In the last step, postprocessing begins, where SUFI2_post.bat executes a number of programs.

6.2 Discussion

The parallel SUFI2 is designed to be used on any system, larger time savings can be achieved with multiple CPUs and larger RAM memory. Note that the emphasis of this research was not on achieving the highest possible speedup and that our current implementation is an early proof-of-concept prototype that does not contain optimization or refinement. Computations based on GPU technology hold the promise of achieving greater speedups in execution of hydrologic models [7]. However, we show that parallel SUFI2 is able to achieve reasonable speedup on real-world computation-intensive calibration applications, while significantly exceeding the performance of non-parallelized packages**.**

VII. The scale problem in hydrological modelling

Recently the problems of scale, sub-grid variability and macroscale modelling have come much more into focus as the water cycle has been identified as a key issue in climate modelling. In the following, the issue of transition between scales up to the continental scale will be discussed from a conceptual hydrological modeller's point of view.

7.1 Choice of modelling strategy.

As we have seen the classification of hydrological modelling in section 3. In addition to those classifications, a more statistically distributed approach based on variability parameters has grown in popularity. The variability approach is of particular interest in connection with hydrological modelling at different scales. As this approach assumes a statistical distribution of properties rather than a complete description, it is more likely to be valid for variable scales than other methods. Physically-based models are often said to be superior to the simpler conceptual ones as they are theoretically more exact and thus, in principle, require less tuning of parameters. On the other hand, conceptual models are often the only reasonable compromise when the model's demands for data meet the reality of operational applications. we have to choose a strategy that is proper for the problem we want to solve.

7.2 How sensitive are conceptual hydrological models to scale transition?

When shifting scales, a shift in parameter values might be necessary, in particular if these parameters are clearly related to local conditions such as climate and physiography. This is the case for parameters of snow modelling and recession in particular. The question thus arises whether our hydrological models are general, or flexible, enough to allow expansion from the traditional range of catchment size to the continental scale. The shift between scales thus means that we have to change these more specific parameters accordingly, but the overall model structure can remain unchanged.

7.3 Macroscale application to the Baltic Sea Drainage Basin

The HBV model was used on the macroscale to model the water balance of total runoff to the Baltic Sea (HBV-Baltic). Whether or not scale is a problem in macroscale hydrological modelling is a matter of formulation of the problem, scientific approach and perspective. The HBV model—originally developed for small and medium-sized basins—was successfully applied without modification to the entire catchment of the Baltic Sea with a size of some 1.6 Mkm2. For a catchment as large as the Baltic Drainage Basin it is impossible to capture all details. Therefore, it is necessary to limit the demands on input data and to make the model parameterisation as scale independent as possible.

VIII. Validation of hydrological models.

The term validation is well known in hydrology and environmental modelling and is commonly used to indicate a procedure aimed at analysing performance of simulation and/or forecasting models. The definitions adopted in this work are based on the consideration that the most frequent validation procedures, used in hydrologic and environmental modelling in general, proposed to split model evaluation in three complementary phases [6]: (a) quantitative evaluation of model performance; (b) qualitative evaluation of model performance; (c) qualitative evaluation of model structure and scientific basis. In the following, we alternatively use the expressions model validation or performance validation to indicate the concepts (a and b). This would be equivalent to the definition of model validation proposed by Matott et al. [9]. We instead adopt the expression scientific validation to refer to the activities described in point (c).

8.1 Overview of techniques and methodological practice

8.1.1 Performance validation: graphical techniques and performance metrics

The typical approach adopted to evaluate model performance requires the comparison between simulated outputs on a set of observations that were not used for model calibration. The choice of the validation criteria is guided by several factors. It depends on the nature of the simulated variables and the main model purpose. A hydrological model simulating the streamflow in a river basin, thus focusing on metrics and graphical techniques primarily applied to time series. Introduce the techniques useful for validating performance of deterministic simulations and, then, we discuss the methods utilised for assessing accuracy of probabilistic hydrological predictions.

- **Graphical techniques**

Graphical techniques allow a subjective and qualitative validation. Graphical techniques allow a subjective and qualitative validation. In most cases, they are based on a graphic comparison of simulated and measured time series. This kind of plots can be difficult to read, especially when the observation period is long. Scatterplots of simulated versus observed discharge are more easily interpretable and provide an objective reference given by the 1:1 line of perfect fit. Other common graphical representations are residual plots and the comparison of streamflow duration curves as well as flood frequency distributions.

- **Performance metrics**

The performance metrics provide a quantitative and aggregate estimate of model reliability and are generally expressed as a function of the simulation errors. The review presented so far has been focused on metrics mainly applicable to deterministic simulations and is not intended to be exhaustive. When dealing with probabilistic forecasts, traditional goodness of- fit metrics (like those mentioned for deterministic simulations) do not allow a complete and fair evaluation of the forecast performance. In his essay on the nature of goodness in weather forecasting, [10], considering a distribution-based approach, distinguishes nine attributes that contribute to the fullest description of the multi-faceted nature of the probabilistic forecast quality: Bias, Association, Accuracy, Skill, Reliability, Resolution, Sharpness, Discrimination and Uncertainty. Fundamental information about the forecast performance and, only recently, some techniques have been specifically designed to quantify their weight in the process of verifying hydrologic probabilistic forecasts.

- **Scientific validation**

The concept of scientific validation has been originated from the idea that verifying the model performance by simply comparing outputs and observations does not assure that the model is correct from a scientific point of view. It is well known that every model provides a simplified representation of reality, which depends on availability of observations, knowledge of phenomena, computational capability, and final purposes of the application. Given these limitations, the scientific validation aims at evaluating the consistency, and the coherence with real world, of the model thought as an ISO (input- state-output) system. One goal of scientific validation is the assessment of model hypotheses. Besides the assessment of model hypotheses, scientific validation aims at providing the proof of model adequacy to the representation of real world beyond (or together with) the result of validation tests. Another important checkpoint of scientific validation lies in the assessment of the equilibrium between model purpose, model complexity and availability of data sources and information. In this perspective, scientific and performance validation may be merged. This happens, for example, in cases when the performance metrics combine various measures aimed at making diagnosis or providing information to correct the model at the appropriate level.

8.1.2 Proposal of a validation protocol: general guidelines

Most of the new proposals are dedicated to specific technical details, like, for example, the optimal combination of performance metrics [12] and model diagnostic issues.

- **Guidelines for performance validation**

The guidelines are summarised by the following points: Provide clear and unequivocal indications about model performance in real world applications. 2. Apply the validation procedure by using independent information with respect to what was used for model calibration. 3. Perform validation and discussion of data reliability, and possibly implement a combined validation of models and data. 4. Use graphical techniques and several numerical performance metrics to evaluate different aspects of model performance. When dealing with probabilistic simulations, use rigorous techniques that test several attributes of forecast quality. 6. When presenting results, do not focus only on a few cases (e.g., a single intense flood event), but consider a statistically significant number of cases including those where the model did not return satisfactory results. If possible, extend the validation to model input and state variables. 7. If possible, validate the model over different temporal and spatial scales.

- **Guidelines for scientific validation**

1. Clearly identify the model purpose(s) and check if the adopted model addresses it (them).
2. List and discuss all the assumptions; describe the validation procedure and the relative hypotheses.
3. Analyse the reliability of theoretical fundaments; justify the degree of complexity and the computational burden.
4. Evaluate and discuss possible alternative modelling hypotheses.
5. Use all the possible knowledge (physical processes, observations) to support model development and application.
6. Analyse the entire ISO system pointing out the uncertainty associated with input and output components.

IX. Hydrological modelling using HSPF & SWAT

HSPF is a comprehensive, conceptual, continuous simulation watershed scale model that simulates nonpoint source hydrology and water quality, combines it with point source contributions, and performs flow and water quality routing in the watershed reaches. Values of a large number of HSPF parameters cannot be obtained from field data and need to be determined through a model calibration exercise. HSPF estimates surface runoff using hourly time step as a function of infiltration computed using Philip's equation [11].

SWAT is a complex, continuous simulation conceptual model with spatially explicit parameterization [5]. SWAT can predict, over long periods, the impact of land management practices on water, sediment, and agricultural chemical loads in large, complex watersheds with varying soils, land use, and management conditions. SWAT has a simple tile flow component in which the user specifies tile depth, the amount of time required to drain the soil to field capacity, and the time lag between the water entering the tile and discharging into the main channel. Tile drainage occurs when the soil water content exceeds the field capacity.

9.1 Model preparation, performance and conclusion

The performances of the HSPF and SWAT models were evaluated for simulating the hydrology of the 5,568 km^2 Iroquois River watershed, a predominantly tile drained, agricultural watershed in Illinois and Indiana. The preparation of both model applications was performed within the BASINS 3.0 modelling system, and all data were provided by the BASINS database except additional climate data that were used by both models. Each model was calibrated for a nine-year period (1987 through 1995) and verified using an independent 15-year period (1972 through 1986) by comparing the simulated and observed daily, monthly, and annual streamflow's. Verification results were further compared for three shorter periods representing drier than average, average, and wetter than average climatic conditions. The HSPF results showed a consistent bias toward overestimating low flows, those being roughly the lowest 25 percent of the observed monthly and daily flows. This bias was particularly apparent within the model verification period. Based on the statistical and graphical comparisons, the HSPF and SWAT models performed similarly during model calibration, but SWAT predicted low flow conditions noticeably better during the model verification period. There was a significant difference between the two models in the estimation of PET. The HSPF estimate of PET provided by the BASINS database was roughly half of the estimate computed within SWAT. As noted in other studies, HSPF requires comparatively more effort to apply than SWAT. The preparation of climate data for the HSPF model required a greater effort as compared to that for SWAT, and the calibration of HSPF required many more iterations because of the larger number of parameters used in calibration.

X. Socio-hydrological modelling

The relatively new field of "Socio-hydrology" [14] however, seeks to change this by aiming to understand "the dynamics and co-evolution of coupled human water systems". In understanding socio-hydrology as a subject, it may be useful to also briefly understand the history of the terminology within hydrological thinking, and how this has led to the current understanding.

10.1 Why Socio-hydrology is necessary?

- Analysis of patterns and dynamics on various spatiotemporal scales for discernment of underlying features of biophysical and human systems, and interactions thereof.
- Explanation and interpretation of socio-hydrological system responses, such that possible future system movements may be forecast.
- Furthering the understanding of water in a cultural, social, economic and political sense, while also accounting for its biophysical characteristics and recognising its necessity for existence.

Regarding why modelling would be conducted in socio-hydrology, there could be significant demand for socio-hydrological system models in several circumstances, the three main spheres are:

- system understanding
- forecasting and prediction
- Policy and decision-making.

10.2 What is socio-hydrology?

The question of what is different and new about socio hydrology, and indeed what is not, is useful to investigate in order to then determine how knowledge of modelling in other, related subjects can or cannot be transferred and used in socio-hydrology. Here, the subject of socio-ecology (as a similar synthesis subject) is introduced, before the similarities and differences between socio-hydrology and other subjects are summarised.

Socio-ecology - The study of socio-ecological systems (SESs) and coupled human and natural systems (CHANS), involves many aspects similar to that of socio-hydrology.

In a study comparable to this, though related to socio-ecological systems, [13] give research issues in socio-ecological modelling; these issues are also likely to be pertinent in socio-hydrological modelling: - Implications of complex social and ecological structure for the management of SES's. - The need to address the uncertainty of ecological and social dynamics in decision making

-The role of co-evolutionary processes for the management of SES's. - Understanding the macroscale effects of microscale drivers of human behavior.

In a study comparable to this, though related to socio-ecological systems, [13] gives research issues in socio-ecological modelling.

- Implications of complex social and ecological structure for the management of SESs
- The need to address the uncertainty of ecological and social dynamics in decision making
- The role of co-evolutionary processes for the management of SESs
- Understanding the macroscale effects of microscale drivers of human behaviour.

10.3 How Socio-hydrology modelling?

This section gives an excellent overview of how the overall modelling process should be carried out in socio-hydrology. With the current feeling in socio-hydrological circles being that the integration of the social and economic interactions with water is a vital component of study, this integration should be seen and should be included centrally in models in such a way that demonstrates the importance of these interactions to modellers [8]. Determining how best to present and use findings from socio-hydrological studies in policy applications: the way that socio-hydrological understanding will likely be applied in the real world is via policy decisions. As such, understanding the best way to communicate findings in socio-hydrology is vital. The challenge here is to communicate the differences between the outcomes predicted by traditional analyses and socio-hydrological studies regarding the way that policy decisions may impact the system in the long term, while acknowledging the limitations in both approaches.

It has the following main principles

- Model classifications
- Modelling approaches
- The importance of model conceptualisation
- Agent-based modelling
- System dynamics
- Pattern-oriented modelling (POM)
- Bayesian networks (BN)
- Coupled component modelling (CCM**)**
- Scenario-based modelling
- Heuristic/knowledge-based modelling

XI. Conclusions

In this paper we presented that a hydrological model is composed of two main parts, namely a hydrological core and a technological shell. The hydrological core is based on a certain hydrological scientific basis providing the definitions of variables, the process descriptions and other aspects. We presented parallel SUFI2, a framework that automatically and transparently parallelizes the SUFI2 optimization program for higher performance calibration purposes. Performance results with both small and large size projects show that parallel SUFI2 achieves good speedup and reasonable scalability in most cases. In macroscale hydrological modelling there is a role to play for both physically based hydrological models and more empirical conceptual ones. The continental-scale conceptual HBV-Baltic model was set up within an existing modelling infrastructure with relative limited efforts. It has already now provided valuable information on the water balance of the Baltic Basin and it has been used to review some of the hydrological processes in climate models. In macroscale hydrological modelling a statistical approach with variability parameters has proved to be very useful and rather insensitive to scales. This paper also intends to provide a contribution towards the identification of agreed principles for model validation. The basic idea is that validation should provide an exhaustive evaluation of both model scientific basis and performance. Based on the statistical and graphical comparisons, the HSPF and SWAT models performed similarly during model calibration, but SWAT predicted low flow conditions noticeably better during the model verification period. The most important way in which socio-hydrology differs from other water management subjects is in understanding the system as a whole, as opposed to focusing on problem solving. As such, the research priorities at this stage are focused on different ways of improving and communicating understanding.

Author Credit Statement

V.S. Kumbhar and V.A. Swami have been planned for writing a review paper. The manuscript writing is accomplished by V.S. Kumbhar. Experimental results and data are examined by Mrunalini P. Jagtap and Kishori A. Sutar. Final revision work has been carried out by V.S. Kumbhar and V.A. Swami.

Conflict of Interest

There are no any competing interests.

References

[1] Abbott, M.B. (1979) *Elements of the theory of free surface flows.* Pitman, London. Second edition.

[2] Abbott, M.B. (1991) *Hydro-informatics: information technology and the aquatic environment.* Avebury, Aldershot.

[3] Abbott, M.B. (1994) Hydro-informatics and Copernicam revolution in hydraulics. *Extra issue on hydro informatics, Journal of Hydraulic Research*, 32, 3-14.

[4] Anderson, P.B. (1990) *A theory of computer semantics.* Cambridge Univ., Cambridge, UK.

[5] Arnold, J.G., R.S. Muttiah, R. Srinivasan, and P.M. Allen, 2000. Regional Estimation of Base Flow and Groundwater Recharge in the Upper Mississippi River Basin. J. Hydrol. 227:21-40.

[6] Gupta, H.V., Wagener, T., Liu, Y., 2008. Reconciling theory with observations: elements of a diagnostic approach to model evaluation. Hydrol. Proc. 22, 3802–3813.

[7] Kalyanapu, A.J., Shankar, S., Pardyjak, E.R., Judi, D.R., Burian, S.J., 2011. Assessment of GPU computational enhancement to a 2D flood model. Environmental Modelling and Software 26, 1009e1016.

[8] Lane, S. N.: Acting, predicting and intervening in a sociohydrological world, Hydrol. Earth Syst. Sci., 18, 927–952, doi:10.5194/hess-18-927-2014, 2014

[9] Matott, L.S., Babendreier, J.E., Purucker, S.T., 2009. Evaluating uncertainty in integrated environmental models: a review of concepts and tools. Water Resour. Res. 45. doi:10.1029/2008WR007301.

[10] Murphy, A.H., 1993. What is a good forecast? An essay on nature of goodness in weather forecasting. Weather Forecast. 8, 281–293.

[11] Philip, J.R., 1957. The Theory of Infiltration: 1. The Infiltration Equation and Its Solution. Soil Science 83:345-357.

[12] Reusser, D.E., Blume, T., Schaefli, B., Zehe, E., 2009. Analysing the temporal dynamics of model performance for hydrological models. Hydrol. Earth Syst. Sci. 13, 999–1018.

[13] Schlüter, M.: New Horizons for Managing the Environment: A Review of Coupled Social-Ecological Systems Modeling, Nat. Resour. Model., 25, 219–272, 2012.

[14] Sivapalan, M., Savenije, H. H. G., and Blöschl, G.: Sociohydrology: A new science of people and water, Hydrol. Process., 26, 1270–1276, doi:10.1002/hyp.8426, 2012.