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iEMSs International Congress on Environmental Modelling and Software

9th International Congress on Environmental Modelling and Software
Fort Collins, Colorado, USA, Mazdak Arabi, Olaf David, Jack Carlson, Daniel P. Ames (Eds.)
https://scholarsarchive.byu.edu/iemssconference/2018/

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Abstract: A network-focused modeling approach is introduced to represent hydrological relations in catchments and subcatchments and to manage related modeling solutions through flexible computational bindings. The representation is built upon the mathematical concept of Extended Petri Nets (EPN). It aims to display (water) budgets processes and catchment interactions using explicative and self-contained symbolism based on circles (to represent states), squares (to represent fluxes) and arrows to represent their connection. The IT perspective hinges on an extension of the Object Modeling System (OMS) v3. The latter is a non-invasive flexible environmental modeling framework designed to support component-based model development. The implementation results in a Directed Acyclic Graph (DAG) data structure, namely NET3. It represents interacting systems as networks where: vertices match any sort of time evolving modeling solution; edges correspond to their data (fluxes) interchange. It currently hosts the GEOframe-NewAge components that can be used to simulate the elements of the terrestrial water cycle, and those implementing travel time analysis of fluxes. Further bio-physical or management oriented components can be easily added.

Keywords: Extended Petri Nets, OMS3, NET3, GEOframe-NewAge.

1 INTRODUCTION

The modeling of natural phenomena results into the description of physical processes in mathematics and its consequent translation into codes, written in some programming language. Although this procedure is necessary, it ends up with hiding important modeling concepts into mathematical terminologies and programming practices which can be quite involved. As a result, both researchers and decision makers strive to approach new physical models because these translation of concepts in mathematics and codes are very difficult to understand at first.
This paper introduces: 1) a new complex network-based multi-level schematic representation of differential equations and 2) related informatic practices that accomodate an innovative software development approach.
The end product allows for smoothing the translation of natural phenomena perceptual models into differential equations and code base accordingly.

2 RESERVOIROLOGY

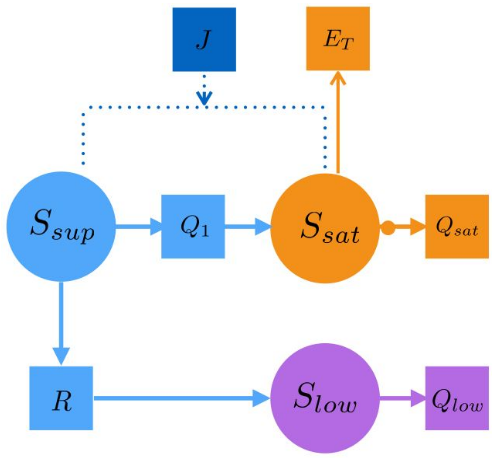
Reservoirology is the name we gave to a complex network-based representation of ordinary differential equations (ODEs) used to simulate watershed hydrology. This contribution mainly proposes hydrological applications. Nevertheless, this flexible methodology can be easily extended to different fields where there can be identified systems composed by parts described by ODEs.

As the name itself explains, *Reservoirology* (science of reservoirs) has been initially developed as an alternative to describe systems of interconnected reservoirs. The latter is indeed a standard practice in hydrology when it comes down to schematize water budgets between compartments whose name are "root zone", "groundwater storage", "runoff reservoirs" or similar. The representation of interconnected reservoirs allegedly simplifies comprehension of hypothesis and assumptions behind modeling of involved physical processes. The simplest models were actually composed by a single reservoir, and therefore the need of its visual representation was pleonastic. However, actual modelling schemes are rather complicated and need, on the contrary, accurate analysis for being understood, even if small and simple processes are involved (e.g. Birkel et al. (2011)). When several processes are involved and complex interactions need to be delineated consequently, actual schemes are hardly interpreted by expert scientists as well (Savenijie et al. (2016)).
The proposed graphical representation is an algebra of objects based on Petri nets rules (Murata (1989)). Petri nets are limited to describing dynamic systems of discrete events, while water budgets, more generally, are time continuous events. As a result, Petri nets standard rules have been extended to deal with time variable, namely Extended Petri nets (EPN) (Rigon et al., 2016b).
Basic Petri nets rules remained unchanged. They have been rather reinterpreted for hydrological purposes: **places**, round shape, become storages like water volume stored in groundwater or its equivalent energy content; **transitions**, squared shape, become fluxes like water fluxes out of control volume or evapotranspiration; arcs connect storages to fluxes and vice versa and might be linear or nonlinear; compound symbol represents source or sink terms part of the equations.
The example in Figure 1 represents a simple rainfall-runoff model where three ordinary differential equations (three reservoirs) are connected: equation (1) account for superficial runoff, equation (2) computes water flow in saturated soils and equation (3) estimates the groundwater.

$$\frac{dS_{sup}(t)}{dt} = \alpha J(t) - Q_1(t) - R(t) \qquad (1)$$

$$\frac{dS_{sat}(t)}{dt} = Q1(t) + (1-\alpha)J(t) - Q_{sat}(t) - E_T(t) \qquad (2)$$

$$\frac{dS_{low}(t)}{dt} = R(t) - Q_{low}(t) \qquad (3)$$



Flux	Expression
E_T	$f\,\frac{S_{sat}(t)R_n}{S_{max}}$
$Q_1(t)$	$a\,S_{sup}(t)$
$Q_{low}(t)$	$d\,S_{low}(t)$
$Q_{sat}(t)$	$d\,S_{sat}(t)^c$
$R(t)$	$e\,S_{sup}(t)$

Figure 1. EPN of a simple rainfall-runoff model and table of equations to describe fluxes, Rigon et al. (2016b).

Remarkably, there is a one-to-one correspondence between the graphical symbols and the equations. Any circle correspond to a time differential of the quantity represented. Outcoming fluxes are represented by outgoing arrows and squares. Incoming fluxes are represented by squares with arrows going into circles. A **place** is connected to **transitions** and **transitions** to **places.** Place -arrow-place sequences are not allowed, nor are transition-arrow-transition sequences. However a transition can feed multiple places. The modeling understanding is not fully understood if further specification about the fluxes are not give. How to accomplish this completion has been explained in Bancheri (2017). This new representation can really assist scientists approaching new modeling solutions or simply sharing ideas as also shown in, Tubini (2017). Reversing the approach we used, once a researcher believe that a system can be represented by, for instance, three reservoirs, he/she knows that it can represent them as three circles, and they correspond to three ODEs. Once he/she fully connects the circles, he/she establishes the causal effects existing between the state variables, and finalises implicitly the writing of the ODEs. This actually could be deployed automatically in future. The representation with EPN is compositional and, in fact, usually a catchment modeling ia an assembly of graph as those represented in Figure 1. More importantly, the same topology of Figure 1, and similar, supports more than one semantics (i.e. the writing of differential equations). In fact the same representation can be used to reveal how to parallelise the computational processes involved.

3 NET3

NET3 matches the representation of subcatchment interactions with Petri Nets into an IT infrastructure. It implements a directed acyclic graph (DAG) data structure in OMS3 (David et al. (2013)). In turn, OMS3 is a non-invasive flexible environmental modeling framework which eases scientific model development by enabling component-based model implementation (Lloyd et al. (2011)). Because of its high level abstraction, every hydrological process can be easily implemented into a single OMS-compliant component. Processes interactions and temporal steppings are managed by the framework capabilities and modeling the hydrology of a single subcatchment is straightforward in OMS. Eventually, the framework provides intrinsic parallel computation of independent components avoiding the burden of managing multi-threading implementation from the user-side. NET3 increases the OMS capabilities to add management of interacting modeling solutions. Every vertex in NET3 can support a different modeling solution for the water budget in a subcatchment. This means that every vertex can run a different computation, allowing, for instance, a different modeling for water budgets in mountain and plain subcatchments. Edges correspond to data (fluxes) interchange (output and input of connected modeling solutions must match), transitions in ePN language. Therefore the budget of the catchment in Figure 2 can be schematically draw as in Figure 2b.

Then, NET3 adds TO OMS3 a further layer of implicit parallelization by executing first the model present in the external leaves of the tree and subsequently the more internal, to the outlet.

As a proof of concept, all the GEOframe-NewAge components produced so far (Formetta et al. (2011), Formetta et al. (2013), Formetta et al. (2014), Formetta (2016), Abera et al. (2017a), Abera et al. (2017b)) and travel time analysis of fluxes (Rigon et al., 2016a) have been implemented leveraging NET3 functionalities with great computational and operational advantages. Operational advantages are of two types. Net3 in fact allows for processing a catchment ``per parts” which can be implemented separately and joined when all the system is ready, and facilitating in this way the multisites calibration which can be performed for each sub-catchment where gauges are available.

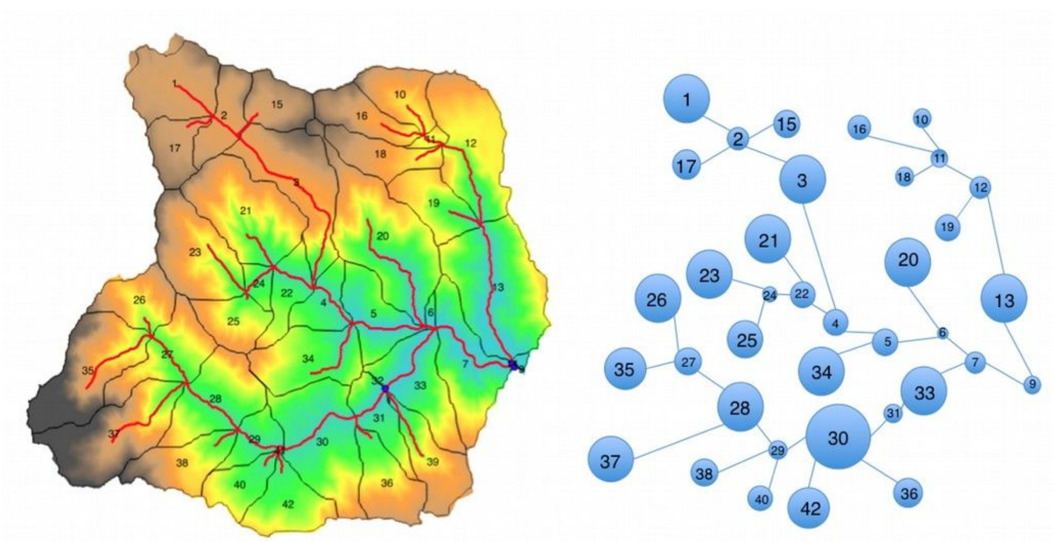


Figure 2. Representation of subcatchment connections into NET3 (Bancheri (2017)).

4 CONCLUSIONS

This contribution introduces a new graphical representation and a related innovative IT infrastructure called Net3. They facilitate the understanding of modeling concepts and their implementation in a distributed fashion. Since the system is compositional, arbitrarily large systems can be obtained by composing subsystems after having calibrated and refined separately each part. The network structure, finally drives the distribution of processes among processors.

The actual implementation is shown simulating the water budget of catchments but the network structure can be expanded to include any other type of process, like, for instance, economic evaluations and models for supporting decisions.

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