Hydrologic Modeling Methodology

Frank Wissinger, Dr. Ravi Shankar, Dr. Jorge Restrepo
Florida Atlantic University
777 Glades Road
Boca Raton, FL 33431
fwissing@fau.edu
shankar@fau.edu
restrepo@fau.edu

***Abstract*— Complex hydrological models are employed to mimic real world behavior and, if integrated with other hydrological complex models from different domains, may lead to a new powerful hydrological model that will provide answers to ever more sophisticated queries. However, integration will be a slow process since each hydrological model may be self-contained, with different timescales and simulation speeds. Electronic Design Automation (EDA) methodologies have evolved for chip design for precisely such situations, but in a different domain. Integration of hydrological models can benefit with such EDA techniques; there, however, is also an added advantage. A complete detailed model can take days to simulate and yield useful information to the end user. However, trading off precision in some sub models with overall system response time may be acceptable, thus returning useful information much sooner. We will present methodology, model, and simulation results for a hydrologic model that is based on concepts, languages, and tools used in EDA. This results in multiple models that can trade-off precision with response time. We hope this helps open many new lines of inquiries and potential practical uses.**

Keywords—Hydrological Modeling, SystemC-AMS , Electronic Design Automation (EDA) methodologies

I. INTRODUCTION

Complex hydrological models are employed to mimic real world behavior and, if integrated with other hydrological complex models from different domains, may lead to a new powerful hydrological model that will provide answers to ever more sophisticated queries. However, integration will be a slow process since each hydrological model may be self-contained, with different timescales and simulation speeds.

Electronic Design Automation (EDA) methodologies have evolved for chip design for precisely such situations, but in a different domain. One uses hierarchical mixed mode design to translate an abstract specification of a subsystem to a detailed implementation, while the remainder of the system is held at a higher abstraction level. This leads to several engineering advantages:

- Model and design that are correct by construction
- Faster translation from specification to implementation
- Easier Plug-and-play with alternative subsystems
- Need for fewer detailed simulations, increasing engineering design productivity.

Integration of hydrological models can benefit with such EDA techniques; there, however, is also an added advantage. A complete detailed model can take days to simulate and yield useful information to the end user. However, trading off precision in some sub models with overall system response time may be acceptable, thus returning useful information much sooner. A side benefit of EDA may thus be the main reason to adapt to hydrologic modeling.

II. BACKGROUND

Hydrological models are classified according to their conceptualizations and assumptions of three key parameters: randomness, space and time. Depending on how randomness, space, and time are conceptualized, different kinds of models may be derived as follows:

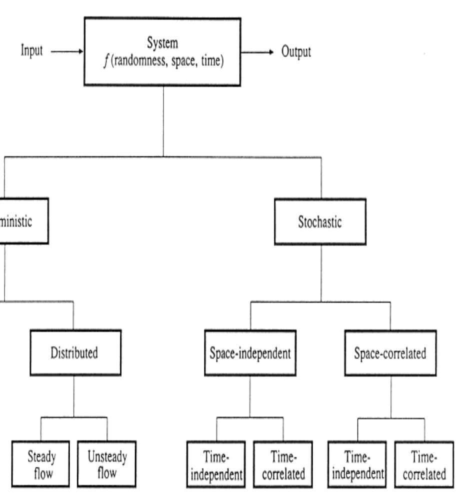

Fig 1. Hydrological classification

The two hydrological model subdivisions illustrated in Figure 1 are distinguished as follows:

Hydrological models may be subdivided as follows:

- Stochastic Models: These models are black box systems, based on data using mathematical and statistical concepts to link a certain input, e.g., for instance rainfall to the model output, e.g., for instance runoff. Certain Stochastic models may be space and/or time dependent or not.
- Deterministic Models: These models try to represent the physical processes observed in the real world. Typically such models contain representations of surface runoff, subsurface flow, evaporation and transpiration flow, and channel flow. These models may be further subdivided as follows: (1) Lumped: A lumped model is equivalent to a discrete function, where the model dependent on variables of interest is a function of time; and (2) Distributed: A distributed model is equivalent to a continuous function, where the model dependents on all the variables of time and space. Either a lumped or distributed model may be steady or unsteady. Steady and unsteady flow describes how depth (space) and velocity change over time. A flow is considered steady if depth and velocity are constant over time while they are not so for unsteady flow.

From an EDA perspective, all these models may be considered to be continuous time models, but with widely different time scales, thus paving the way to adapt analog and digital subsystem modeling techniques of EDA.

III. METHOD

Application of EDA methodology to the hydrological cycle results in a decomposed structure with a myriad of integrated hydrological models as illustrated below [1]:

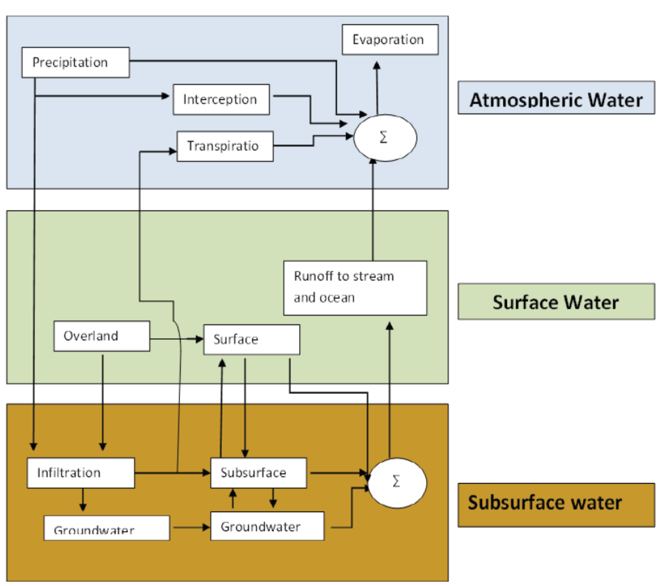

Fig 3. Hydrological cycle system

Each process in the hydrological cycle illustrated represents a hydrological model that approximates the actual behavior of the process, whereby inputs and outputs are expressed as functions of time. These inputs and outputs are linked through a transformation functions that are analogous to EDA's Models of Computation (MoC) as depicted in the following diagram:

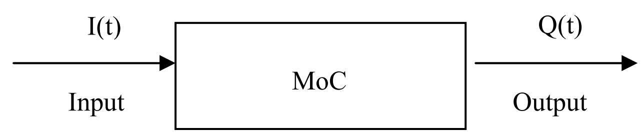

Fig 2. (Moc) Model of Computation

The SystemC-AMS language, a C++ based standard modeling language for mixed signal circuits, is used in EDA methodology [3]. Designers of analog and mixed signal systems and integrated circuits employ this modeling language to create and use modules that encapsulate high-level behavioral descriptions, as well as structural descriptions of systems and components. The SystemC-AMS modeling language may also be used to model complex systems such as hydrological models, since the laws of water movement (Darcy's Law and Manning's equation) and electrical processes (Ohm's and Kirchhoff's laws) are analogous [2]. The following table illustrates mapping between Darcy's Law and Ohms law [2]:

TABLE I

Darcy's Law	Ohm's Law
$Q = k * A * \frac{dh}{dl}$	$i = k * A * \frac{d\Phi}{dl}$
$v = \frac{Q}{A} = k * \frac{dh}{dl}$	$j = \frac{I}{A} = k * \frac{d\Phi}{dl}$
Q-Flow rate	i-Electrical current rate
k – Hydraulic conductivity (groundwater) or friction slope (open channel flow, Manning equation)	k –Electrical conductivity
A- Flow area(of wetted cross- section)	A-Conductor cross -section
h-hydraulic potential(head)	Φ Electrical potential(voltage)
v-Flow rate per unit cross sectional area	j-Current density

The continuity equation applies to hydrological systems (law of conservation of mass) as well as electrical systems, as illustrated in the following table [2]:

TABLE III

Hydrological Continuity Equation	Electric Charge Continuity Equation
$\oiint v da = 0$	$\oiint j da = 0$
v-Flow rate per unit cross sectional area The amount of flow entering a closed area is equal to the amount of flow leaving the area	j-Current density The amount of electricity entering the closed area in a stationary field is equal to the amount of electricity leaving this area

Since the hydrological continuity equation is analogous to the electric charge continuity equation, the first Kirchhoff law applies to electrical networks as well as hydraulic networks as illustrated in the following figure [2]:

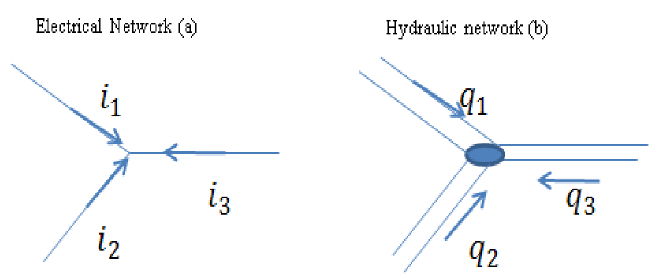

Fig 4. Electrical and Hydraulic networks

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The algebraic sum of currents in Fig 4(a) or flow rates in Fig 4(b) at a node equals zero as illustrated in the following table [2]:

TABLE IIIII.

First Kirchhoff law on electrical networks	First Kirchhoff law on hydraulic networks
$i_1 + i_2 + i_3 = 0$	$q_1 + q_2 + q_3 = 0$

The second Kirchhoff law may be applied to describe a steady and uniform open channel with a regular prismatic channel (the free water surface is parallel the bottom) as illustrated in the following table [2]:

TABLE IVV

Water surface and hannel elevation Difference Equation	Electric Potential Difference (Voltage) Equation
$\Delta Y_{AB} = \int_A^B S_w dl = \int_A^B S_o dl = YB - YA$	$U_{AB} = \int_A^B E dl = \Phi B - \Phi A$
ΔY-Difference in water elevations	U-Differencein Electrical potential
S_w Slope of free water S_o Slope of channel bottom	E-Electrical Field

Where Sw is the slope of the free water surface and So is the slope of the channel bottom, YA and YB are the elevations of the free water surface above sea level at points A and B [2].
In electrical networks or hydraulic channel (open, steady and uniform) networks, the integration along a closed curve (closed loop network) is equal to zero as illustrated in the following table [2]:

TABLE V

Hydraulic Conservation of Energy	Electrical Conservation of Energy
$\oint S_o dl = 0$	$\oint E dl = 0$

The consequence of the conservation of energy is that the sum of measured voltages in an electrical network (closed loop) is zero, and the sum of measured ΔY in a hydraulic channel (open steady, uniform, and closed loop) is zero as illustrated in the following figure [2]:

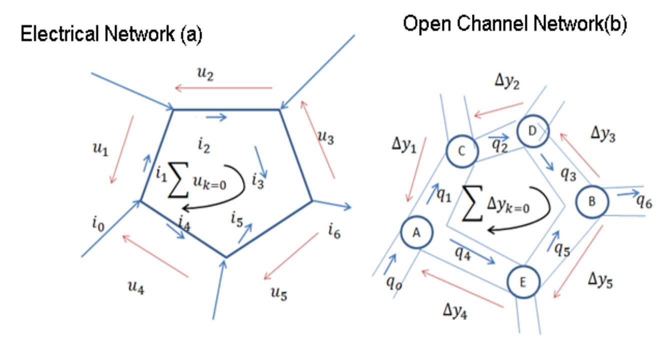

Fig 4. Electrical and Open channel networks

Electrical network may also be applied to model unsteady confined flow of water in a uniform porous medium in three dimensions (groundwater flow) as illustrated in the following table [2]:

TABLE VI

Three-dimensional unsteady confined flow of water in a uniform porous medium	Three-dimensional diffusion field in electricity
$\frac{d^2h}{dx^2} + \frac{d^2h}{dy^2} + \frac{d^2h}{dz^2} = \frac{S}{k}\frac{dh}{dt}$	$\frac{d^2u}{dx^2} + \frac{d^2u}{dy^2} + \frac{d^2u}{dz^2} = \frac{C}{k}\frac{du}{dt}$
h-hydraulic potential(head)	u – voltage
S-Storage coefficient	C-Capacitance
k – Hydraulic conductivity	k –Electrical conductivity

To easily create scripts to change parameters to SystemC-AMS hydrological models and integrate them with third party tools, we used Python to provide the following features:

- Combine remarkable power with very clear syntax.
- Provide modules, classes, exceptions, very high level dynamic data types, and dynamic typing.
- Interface to many system calls and libraries, as well as to various windowing systems.
- Write easily in C or C++ new built-in modules.

By combining the DA methodology, SystemC-AMS hydrological models, and Python scripting environment, we hypothesize that this new hydrological model will contribute to useful and JIT (just-in-time) responses to hydrological queries. Such queries may arise from a desire to evaluate future or current consequences of sea level rise and other climate change conditions. This may be compared to current models of complex hydrological systems that are slow and may not yield adequate responses quickly to be useful to home owners and local decision makers.

IV. PRELIMINARY RESULTS

We are modeling the following hydrological system for proof of concept.

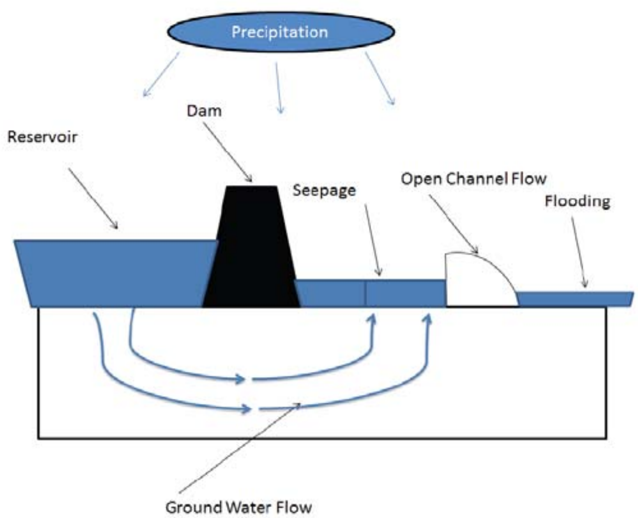

Fig 6. Modeled Hydrological system

Thus far we have developed a basic model to describe ground water flow and track seepage water level. For example, we would like to know if seepage goes above the threshold after a period of time. This will indicate flooding. Simulation results are satisfactory. They show that a large increase in reservoir water level results in a much smaller increase in flood level above the threshold. For the paper, we will develop a comprehensive model and provide simulation results. These results will be compared to those from conventional hydrologic models in terms of precision and computational efficiency.

V. CONCLUSION

We will present methodology, model, and simulation results for a hydrologic model that is based on concepts, languages, and tools used in Engineering Design Automation (EDA). This results in multiple models that can trade-off precision with response time. We hope this helps open many new lines of inquiries and potential practical uses.

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