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A System Dynamics Model for Basin Level Forecasting on the Basis of a Digital Elevation Model

Jelena Pecherska, *Riga Technical University*

Abstract **– Geographic Information System (GIS) is an information technology that is readily applied as a decision aid for a variety of water resource applications. System dynamics as a method of computer simulation of dynamic systems is based on the basic concept of stock with incoming and outgoing flows. In most real-world problems the change in the level of the basin is considered to be the result of summation of incoming and outgoing flows over a certain period of time, taking into account the initial level of the basin. This makes system dynamics an appropriate tool for modelling the behaviour of water basins. A digital terrain model consists of a digital elevation model and a digital model of the situation. For the needs of system dynamics modelling in this case-study only the digital elevation model (DEM) is used. GIS product – DEM –usage in system dynamics models advances simulation-based analysis and decision making for local and regional operational forecasting.**

The task of the article is to formulate both necessary and sufficient requirements for DEM usage in effective forecasting of water basin behaviour with system dynamics model. Within the proposed approach simple system dynamics models of a basin are developed and verified. These models include incoming and outgoing flow models in form of time-series and basin level DEM-based model. The incoming flow is defined with a hydrograph. The water regime of the basin is determined by its geometrical properties. The outgoing flow is formed at the exit from the basin. The models are formalized as a set of first-order difference equations, which are solved sequentially after constant time steps. The solutions provide simulation progress over time. The concept of constant time step is associated with the periodicity of observations of the natural water objects. The basin level function of the volume makes it possible to develop the system dynamics model of the basin suitable for simulation of the level changes in the basin. The developed system dynamics models are used for experimentation with various scenarios of the behaviour of the system under investigation and for forecasting the consequences of changes in parameters or structure of the system. The requirements for DEM usage in system dynamics models are formulated.

The application of system dynamics with incorporated DEM-based basin models makes it possible to analyse the behaviour of the investigated basins and to obtain operational forecasts of the situation for various scenarios. Further research is outlined on the accuracy of simulation results depending on the complexity increase in the simulated object for closer similarity to real reservoirs.

Keywords **– Computer simulation, digital elevation model, high water forecasting, system dynamics**

I. INTRODUCTION

Recently many of GIS projects have been implemented with the use of digital elevation models (DEMs). Actual examples from different human activity areas are Afghanistan Geological Survey and U.S. Geological Survey 2010 Minerals Project, Sutton Common Project in Archaeology, US National Tsunami Hazard Mitigation Program, Okavango Delta Management Plan and other projects and research programs. The tasks that can be solved with the help of DEM are diverse and among them one can find: (a) the calculation of grades and aspects that is important in the construction of roads and pipelines and in agriculture, when the fields for crops with different requirements for lighting are selected; (b) the surface water flow analysis on a territory; (c) flood modelling and other tasks [3].

II. GIS AND DEM FOR SYSTEM SIMULATION

GIS is a tool to capture process and store spatial geographical data and information about related objects. Nowadays GIS are complex hardware and software systems. The information may be obtained from remote sensing or digitization of map information. Two main approaches to store data in GIS are raster images and vector graphics. Digital Elevation Models (DEMs) are a type of raster GIS layer [1]. The integration of a raster DEM into a simulation model will provide extra potential to system simulation in flood event simulation area.

When forecasting the flooding of a territory, the main source of information about the area is its digital model [3]. The use of digital models significantly saves time and labour in comparison with the traditional technology of the extraction of information from topographic plans or maps. Extraction of accurate DEMs is important for flood planning, map generation, three-dimensional GIS, erosion control, environmental monitoring, and other applications. The accuracy of DEMs based on space images mainly depends on the image resolution, height-to-base-relation, and image contrast [2].

A digital terrain model consists of a digital elevation model and a digital model of the situation. For the needs of system dynamics modelling in this case-study only the digital elevation model is used. DEM is digital data, in which each point represents *x*, *y*, and *z* coordinates or latitude, longitude and height describing the bare soil [5]. A grid format DEM stores elevations in a regular array, very much like a raster image comprised of pixels (Fig. 1).

The raster model of the terrain is a subset of the broader class of raster models that can represent the distribution of any quantity (temperature, the exposition of the slopes, etc.) on the surface of the earth. For the purposes of this article, let us consider a simplified geometrical raster model of the reservoir *V* as a structure

$$V = (S, h, \Delta h), \tag{1}$$

where

S – the finite set of sections of the basin defined by lines of equal level; $S = \{s_1, s_2, \ldots, s_n\}$;

n – the number of items in the set S, $n = H / \Delta h$;

H – the maximum depth of the reservoir, relative to the selected base mark.

The level of the basin h does not exceed a certain base mark.

h – the current level of the reservoir, which is defined with a precision of up to Δh;

Δh – the increment of measurements of vertical size of the object, the size of the raster; determines the accuracy of the model (up-to-date DEMs provide planimetric resolution of 1 *m* and even finer [8]).

Within the approach, the natural object – basin – is described as a discrete mathematical structure, which can be used in the mathematical modelling of the changes of the basin level.

In most real-world problems the change in the level of the basin $V(t)$ is considered to be the result of summation of incoming and outgoing flows over a certain period of time, taking into account the initial level of the basin. Intensity of incoming F_{in} and outgoing F_{out} flows can be obtained in the form of water consumption (water volume flowing through the cross-section of the flow per time unit, usually in m^3/sec). This kind of data can be obtained for some particular points of time and can be interpreted as time-series:

$$F_{in} = f(t) \text{ and } F_{out} = g(t) \tag{2}$$

Then

$$V(t) = V_0 + \int_0^t f(t)dt - \int_0^t g(t)dt \tag{3}$$

or taking into account the discrete nature of measurements of levels and flow rates in such systems

$$V(t) = V(t - \Delta t) + (f(t) - g(t)) \cdot \Delta t \tag{4}$$

The latter equation makes it possible to assert that Forrester's system dynamics may be an appropriate tool to determine a reservoir level at particular points of time with time increment Δt, taking into account the assumptions about the nature of the input data.

III. System Dynamics for Flood Simulation

In system dynamics continuous models the time steps are constant, time advance is regular and the state variable changes are directly linked to time advance, and simulated system state variable values display the state of the system at any particular time. In system dynamics models the flows may be interpreted as flows of liquids in pipes, at any time the liquid volume could vary, but flows in general are continuous. Flow intensities are constant during a single fixed time step.

System dynamics (SD) simulation models are discrete-time models, which implement one of the basic system specification formalisms – Discrete Time System Specification (DTSS). Discrete time models belong to the most intuitive dynamic system models [6].

Discrete time model formalism provides step-by-step simulation. At any time *t* the model state is exactly and unambiguously defined, and this state determines the model state at time $t + \Delta t$.

System dynamics models are developed using a fairly small number of model element types. The main SD model elements are: (a) levels or stocks – the elements for simulating quantities of some objects or resources; (b) flows for simulating the intensities or rates of level changes; (c) decision functions and variables and (d) informative connectors simulating the information exchange between model elements.

Among model elements there are "flows", which can be used to simulate a variety of natural flow objects within system dynamics models. In system dynamics any type of "savings" are simulated as stocks, e.g., product inventory item in transit, cash in a bank, the staff of a company, requests for assistance system, means of transport on a road, liquid in a reservoir, tank or basin, etc. Stocks are simulated as variables. At any simulation time *t* the stock variable value can be derived from the stock variable value at time $t - \Delta t$. Here Δt is a constant value, which was determined before the simulation run and is appropriate for the current study of the system under investigation.

The stock values provide information about the state of the simulated system at any particular simulation time *t*. The flow rates provide changes of stock values and characterize the activity of the system. In general, the equations for decision functions determine system behaviour. Decisions are made on the basis of the values of stock variables and flow rates. Information links provide data exchange between elements of the model.

Model behaviour and simulation results are dependent on the determined time step value Δt. In practice, this means that a discrete model is developed and the model state changes after every time step Δt. When the time step Δt is large, the model can give inaccurate results. In turn, with fine time steps Δt simulation results should be reasonably accurate, but the volume of performed calculations and the volume of the saved model data will increase dramatically. The correct choice of Δt value depends on the goals of the simulation project and on the experience of the author of the model.

System dynamics software makes it possible to describe the simulated system behaviour with first-order difference equations. The "current" model state is derived from the previous state using these equations. The basis of system dynamics theory was formulated in the 1960s and is widely applied to a global problem theoretical analysis. Jay Forrester, the founder of system dynamics, defined the system dynamics approach emphasizing the role of feedbacks: an approach to continuous dynamic systems analysis by treating such systems as informative systems with systemic feedbacks. Feedbacks as specific system elements are mostly associated with the philosophy of system dynamics, whereas computer model development is based on DTSS formalism. The models are formalized as a set of first-order difference equations, which are solved sequentially after time steps Δt. The solutions provide simulation progress over time.

Taking into account the above-mentioned considerations, one can suggest that system dynamics may be applied as a method of investigation of some types of dynamic hydraulic systems. Such characteristic elements of system dynamics models as levels and flows directly encourage modelling the main objects of hydraulic systems. The concept of constant time step Δt is associated with the periodicity of observations of the natural water objects. The principle of information feedback can be used for realistic modelling and simulation of reservoirs with input and output flows. The main challenge in this area is to formulate the basic principles of arbitrary shape reservoir simulation.

IV. The Conceptual Model of Basin Level Estimation

Let us consider an object that represents a basin of irregular shape, described as a simple raster model and formulated on the basis of lines of equal level (Fig. 1).

Basin surface elevation contour makes it possible to generate a DEM from contour lines and scattered data. The altitude difference between the lines of equal level Δh allows for the estimation of the volume of the basin along the lines of equal level. Data on the basin volume in relative units are presented in Table I.

The basin level function of the volume is shown in Fig. 2.

The available information about the basin makes it possible to develop the system dynamics model of the basin suitable for simulation of the level changes in the basin under various scenarios.

The water regime of the basin is determined by its geometrical properties and incoming flow Q, which is defined with a hydrograph, as shown in Fig. 3. The outgoing flow is formed at the exit from the basin.

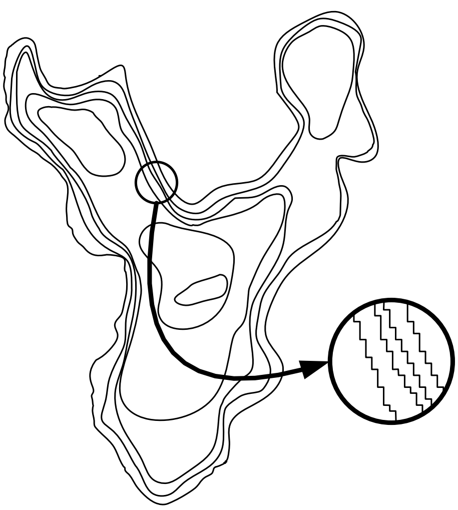

Fig. 1. The basin equal level lines and a detail of the coastal line

TABLE I

The Level Function of the Volume

Basin layers from bottom to top	The share of the volume of the basin
0	0%
1	17%
2	38%
3	60%
4	87%
5	99%
6	100%

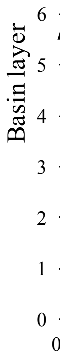

Fig. 2. The level function of the basin

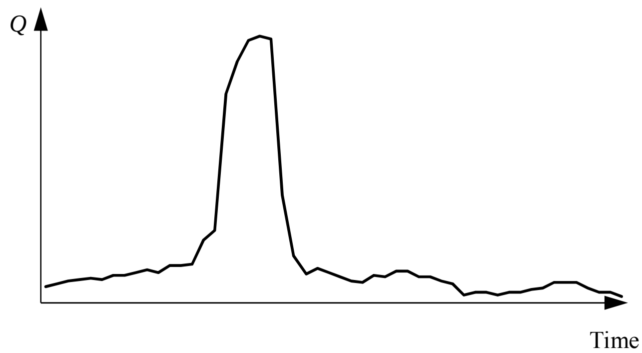

Fig. 3. A hydrograph showing the rate of incoming flow of the basin Q

V. Simulation Software and System Dynamics Model

System dynamics software, e.g., Analytica, AnyLogic, DYNAMO, Stella, iThink and others provide very similar tools for model creation, even the conceptual models in various software environments look similar. Vensim PLE software is a tool that allows conceptualizing, developing and simulating dynamic systems of various natures using system dynamics method and has outstanding features for analysing and optimizing models of these systems. The model of the basin is developed using Vensim PLE software.

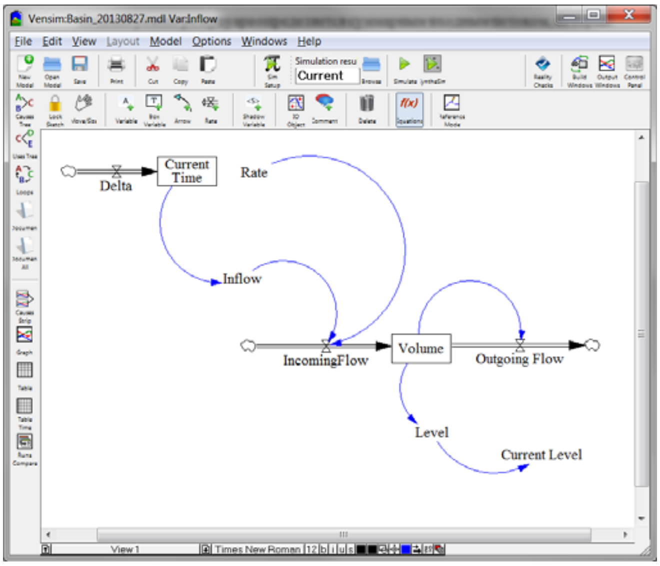

Fig. 3. A fragment of a system dynamics model of a simple basin

The fragment of the model overview is shown in Fig. 4. The share of the volume of the basin, determining the level of the reservoir, is represented in the model with VENSIM object of type *Level*. The total input flow in the form of a hydrograph is specified using the VENSIM *Graph Lookup* function, see Fig. 4.

The total outgoing flow is determined by the set of constraints on the volume of the basin, the total incoming flow and initial level. The basin level is determined by the *Graph Lookup* function, based on the graphic dependencies shown in the figures above. The period of one year is used as the length of simulation experiments. The simple simulations provided the results of the simulation as time-series of the share volume of the basin and its level changes over the year. Simulation results are associated with a particular set of initial conditions and a particular total incoming flow.

VI. Simulation Results

Simulation results are available in the form of graphs and tables, fragments of which are depicted in Figures 5, 6 and 7.

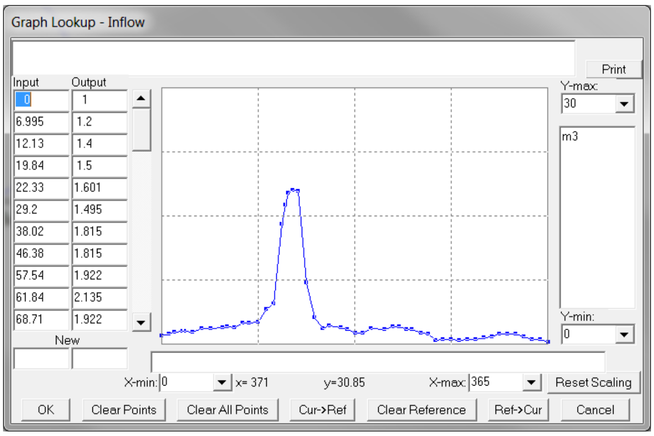

Fig. 4. The *Graph Lookup* function of the total incoming flow

Automatic sensitivity analysis is not available in Vensim PLE; nevertheless, the comparison of alternative scenarios can be performed. An example of comparison of the simulation results – basin level time-series – is shown in Fig. 7.

The verification of the system dynamics model of a simple basin is performed analytically.

The results shown in Fig. 7 are obtained by simulating the hydrographs with different rates and allow making conclusions regarding the magnitude and duration of changes of the basin level.

VII. Conclusion

This paper is the first study to use the DEM in a particular area – system dynamics. It is obvious that the object and scenarios considered in this case study are simplified. It should be mentioned that the feedback principle, which is typical of system dynamics models and reinforces effective forecasting, is not fully used in this case study. Nevertheless, it is possible to formulate the main principles of construction of system dynamics model of the basin and the main data requirements for model development of this type. More research is needed on the accuracy of simulation results depending on the complexity increase in the simulated object for closer similarity to real reservoirs.

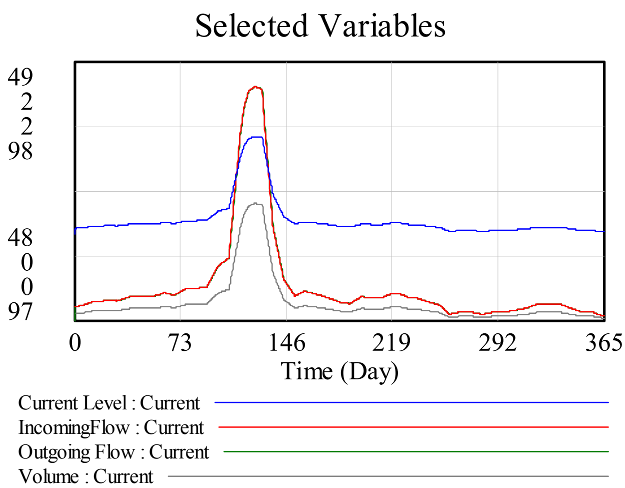

Fig. 5. The simulation results as time-series of Level and Flow variables

Table Time Down

Time (Day)	Selected Variables	Current Level	IncomingFlow	Outgoing Flow	Volume
0	Variables	48.3333	0.1	0	97
0.25	Runs:	48.3542	0.100715	0.100006	97.025
0.5	Current	48.3543	0.10143	0.100708	97.0252
0.75		48.3545	0.102144	0.10144	97.0254
1		48.3546	0.102859	0.102142	97.0255
1.25		48.3548	0.103574	0.102844	97.0257
1.5		48.3549	0.104289	0.103577	97.0259
1.75		48.3551	0.105003	0.104279	97.0261
2		48.3552	0.105718	0.105011	97.0263
2.25		48.3554	0.106433	0.105713	97.0264
2.5		48.3555	0.107148	0.106445	97.0266

Fig. 6. The simulation results in a *Table Time Down* for Level and Flow variables

The accuracy with which basin topography has been mapped directly affects the reliability and usefulness of elevation-based level rise vulnerability assessments [4]. Further research in this area should be conducted to evaluate the effects of vertical uncertainty on the accuracy of simulation results and to consider ground water flows for higher model reliability.

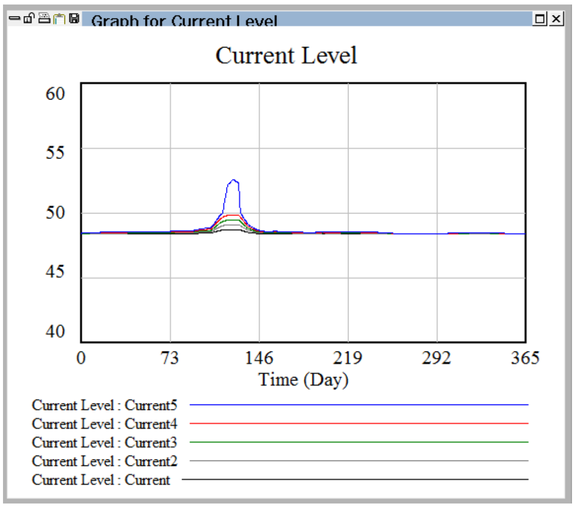

Fig. 7. The simulation results as time-series of basin level for five scenarios with the same initial conditions and various hydrograph rates

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Jelena Pecherska is a Doctor of Information Technology (2012) in the field of system analysis, modelling and development.
She has been working for Riga Technical University since 1979. At the moment, she is a Researcher at the Department of Modelling and Simulation of Riga Technical University. Professional interests include methodology of discrete-event simulation, combined simulation, supply chain modelling, practical applications of discrete-event simulation and discrete-event simulation in education. Jelena Pecherska is a member of the Latvian Simulation Society (LSS).
E-mail: jelena.pecerska@rtu.lv

Jeļena Pečerska. Digitālā reljefa modelī bāzēta rezervuāra līmeņa izmaiņu prognozēšana
Terminu „ģeogrāfiskās informācijas sistēmas" (ĢIS), bieži lieto, lai atsauktos uz dažādām tehnoloģijām, procesiem un metodēm, tai skaitā informācijas tehnoloģiju, kas tiek veiksmīgi izmantota, lai risinātu dažādas problēmas, kas saistītas ar ūdens resursiem. Sistēmu dinamika (SD) ir dinamisku sistēmu datormodelēšanas un imitācijas metode, kas balstās uz krājuma un plūsmas pamatjēdzieniem. Šā iemesla dēļ SD metode ir piemērota ūdens baseinu ar ienākošām un izejošām plūsmām stāvokļa dinamikas modelēšanai. Viena no ĢIS tehnoloģijas produktiem – digitālā reljefa modeļa – pielietošana sistēmu dinamikas modeļos ļauj sasniegt jaunu līmeni, risinot baseinu dinamikas analīzes uzdevumus ar imitācijas modelēšanas metodi, un ļauj nodrošināt lēmumu informatīvo atbalstu vietējā un reģionālajā operatīvajā prognozēšanā. Raksta pamatuzdevums ir nepieciešamo un pietiekamo prasību formulēšana DRM attēlošanai un turpmākai pielietošanai baseina stāvokļa dinamikas prognozēšanai uz sistēmu dinamikas modeļu bāzes. Saskaņā ar piedāvāto pieeju izstrādāti un verificēti vienkārši baseina sistēmu dinamikas modeļi. Šie modeļi ietver ienākošo un izejošo plūsmu laikrindu modeļus un DRM-bāzētu baseina līmeņa modeli. Izstrādātie baseina sistēmu dinamikas modeļi tiek pielietoti eksperimentēšanai ar sistēmas stāvokļa dinamikas scenārijiem un sistēmas parametru vai struktūras izmaiņu seku prognozēšanai. Formulētas DRM izmantošanas prasības sistēmu dinamikas modeļos. DRM-bāzētu modeļu pielietošana ļauj analizēt pētāmā baseina stāvokļa dinamiku un prognozēt situācijas attīstību dažādos scenārijos ar sistēmu dinamikas metodi. Atslēgas vārdi – datormodelēšana un imitācija, (Forestera) sistēmu dinamika, digitālie reljefa modeļi, plūdu prognozēšana.

Елена Печерская. Прогнозирование изменения уровня водоема методом системной динамики на базе цифровой модели рельефа
Термин «географическая информационная система» (ГИС) часто применяется для обозначения различных технологий, процессов и методов, в том числе информационной технологии, которая успешно используется в решении некоторых задач, связанных с водными ресурсами. Системная динамика как метод компьютерного моделирования динамических систем основана на базовых понятиях запаса и потока. Это делает метод инструментом, пригодным для моделирования поведения водоемов с входящими и исходящими потоками. Применение одного из продуктов ГИС технологии – цифровой модели рельефа (ЦМР) – в моделях системной динамики позволяет выйти на новый уровень в решении задач анализа динамики состояния водоемов методом имитационного моделирования, а также обеспечить информационную поддержку решений в локальном и региональном оперативном прогнозировании. Основная задача данной статьи заключается в разработке необходимых и достаточных требований к представлению ЦМР для использования в эффективном прогнозировании динамики состояния водоемов на базе системно-динамических моделей. В рамках предлагаемого подхода разработаны и верифицированы простые системно-динамические модели водоема. Эти модели включают в себя модели входящих и исходящих потоков в виде временных рядов и модель уровня водоема на основе ЦМР. Разработанные системно-динамические модели водоема используются для экспериментов с различными сценариями поведения системы и для прогнозирования последствий изменения параметров или структуры системы. Сформулированы требования к использованию ЦМР в системно-динамических моделях. Применение моделей на основе ЦМР делает возможным анализ динамики состояния исследуемого водоема и получение оперативных прогнозов развития ситуации для различных сценариев методом системной динамики. Ключевые слова – компьютерное моделирование, системная динамика (Форрестера), цифровая модель рельефа, прогнозирование паводков.