GIS based generation of dynamic hydrological and land patch simulation models for rural watershed areas

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ABSTRACT

This paper introduces a GIS based methodology to generate dynamic process model for the simulation based analysis of a sensitive rural watershed. The Direct Computer Mapping (DCM) based solution starts from GIS layers and, via the graph interpretation and graphical edition of the process network, the expert interface is able to integrate the field experts' knowledge in the computer aided generation of the simulation model. The methodology was applied and tested for the Southern catchment basin of Lake Balaton, Hungary. In the simplified hydrological model the GIS description of nine watercourses, 121 water sections, 57 small lakes and 20 Lake Balaton compartments were mapped through the expert interface to the dynamic databases of the DCM model. The hydrological model involved precipitation, evaporation, transpiration, runoff, infiltration. The COoRdination of INformation on the Environment (CORINE) land cover based simplified "land patch" model considered the effect of meteorological and hydrological scenarios on freshwater resources in the land patches, rivers and lakes. The first results show that the applied model generation methodology helps to build complex models, which, after validation can support the analysis of various land use, with the consideration of environmental aspects.

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1. Introduction

The integrated multidisciplinary research of complex environmental processes and their interactions in sensitive geographical (e.g. watershed) areas requires new methodologies and solutions [1]. An early overview about previous developments of complex environmental modelling methods, involving hydrological modules, was provided by Melli and Zannetti [2]. Another comprehensive overview introduced the attempt to connect geographic information systems with agent-based dynamic modelling methodologies to simulate ecological and even social processes [3]. From amongst problem oriented approaches, the various land use change models have to be mentioned. Several overviews (e.g. [4,5]) and research papers (e.g. [6,7]) dealt with this topic. A frequently and still used, freely available tool is Conversion of Land Use and its Effects (CLUE), which is a spatially explicit and dynamic land use and land cover change model [8]. Many frameworks are reviewed in the paper of Borah and Bera in detail [9], mainly from mathematical point of views.

Having recognized the need of multi-scale problem solving, the case-specific models were followed and replaced by the generally applicable modelling frameworks. These

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Notations

Variables

A1i	the surface of a given water section, at the average operating level, ha
A1	surface of the land patch, m^2
DEvap	total amount of evaporation, considering the given surface, m^3
DOut	amount of water that flows out from the given land patch, m^3
DH1	decrease of water content in the given land patch, m
DT	time step of the simulation, e.g. day
DV1	decrease of water volume in the land patch, m^3
DV2	increase of water volume in the connected water section, m^3
EP	evaporation, calculated according to Eq. (A1), mm/day
ET	evapotranspiration, calculated according to Eq. (A3), mm/day
ETP	evapotranspiration, mm/day
H	initial water content of the land patch, mm
Hmin	water level limit of the land patch for sink flow, mm
Hsink	water level limit of the land patch for return flow, mm
Hsurf	water level limit of the land patch for surface flow (runoff), mm
Hunder	water level limit of the land patch for lateral flow, mm
Klat	lateral flow coefficient, l/day

Kret	return flow coefficient, l/day
Ksink	sink flow coefficient, l/day
Ksurf	surface flow coefficient, l/day
Precip	daily precipitation from the meteorological database, mm/day
Humid	relative humidity of the air from the meteorological database, %
P	atmospheric pressure from the meteorological database; hPa
PC	plant coefficient (Posza and Stollár, [60]), dimensionless
Rate	calculated flow rate from the patch to the respective water section, m^3/day
TAir	air temperature from the meteorological database, °C
TWater	water temperature from the meteorological database, °C

Predicates

g()	a predefined global predicate that refers to the global data (e.g. time step)
met()	a predefined predicate that calls for meteorological information from the database

Constants

dt	time step of the model, e.g. day
patch_311	name of the prototype, referenced by the actual elements

general frameworks, such as MIKE/Système Hydrologique Européen (MIKE SHE, e.g. [10]), Soil & Water Assessment Tool (SWAT, e.g. [11]), GISHydro [12] or Watershed Analysis Risk Management Framework [13] have the ability for the combined consideration of various hydrological processes in watershed scale. Most of these frameworks were applied for the investigation of different watershed scale processes. According to several papers ([14–16]), SWAT seems to be the best known and most widely used tool.

Implementation and combination of System Dynamics (SD) is a frequently used method in hydrological modelling. SD method was originally created in the last century by Forrester [17] to understand the behaviour of complex systems. In the past decade, many SD based applications were developed and combined with GIS tools for hydrological and environmental modelling. For example, the most commonly used SD implementations are STELLA (e.g. [18–24]) and Vensim DSS (e.g. [25–29]).

Object Modeling System [30] is another modelling framework for building agro-environmental models, developed by Agricultural Research Service of United States Department of Agriculture. Within this framework field experts are able to create components for the model development, next can parameterize and modify, as well as re-use the model according to the requirements [31].

Special characteristics and particular sensitivity of shallow lakes multiply the problems to be solved in watershed management. In a 1982 paper Somlyódy investigated the Lake Balaton ecosystem and its modelling aspects [32]. He highlighted on that time that complex modelling requires to take into account the processes and interactions both in the watershed and in the waterbody. A comprehensive overview from that time was an edited volume on the modelling aspects of shallow lake eutrophication [33]. One of the most comprehensive works about Lake Balaton from the past decades was the edited book of Virág that contains the accumulated knowledge both from hydrological and ecological points of view [34].

Deep and detailed investigations on hydro-botany and hydrozoology have been carrying out for many years by the Balaton Limnological Institute of Hungarian Academy of Sciences (e.g. [35–38]). Their measurements, in line with the related experiences justified that phosphorous and phosphorous related biological, chemical and physical processes determine the water quality.

Turning to the methodological background of the suggested methodology, the functional and structural approaches in process modelling can be distinguished. The functional models can usually be described by sets of algebraic, differential and/or integral equations (IPDAE, e.g. [39]). The 'a priori' (white box) models can be derived from simple

first principle elements, and then they are transformed into various sophisticated mathematical constructs. The 'a posteriori' (black box) control models are based on various flexible mathematical expressions with free parameters to be identified from the available data. Summarizing the way from the cognitive model to the computerized solution, first a theoretically well established mathematical construct is composed that cannot usually be solved analytically. Therefore, next it is decomposed into the discrete elements of a numerical algorithm, executed by the computer. Nevertheless there is not a viable, plausible relation between the elements of the cognitive model and the computational algorithm. Considering the structural approaches, the essential features of process models are usually represented by network structures. Originally, networks were designed for the illustration of static structures, as well as for the steady state or dynamically changing fluxes along the network routes. However, starting with the very innovative Petri Net [40], many dynamic net structures appeared within the framework of the later appeared General Net Theory [41]. Net models inspired other avenues for the representation of dynamic processes. In the past decades, extensive efforts have been made towards the implementation of the quantitative, time- and event driven functionalities in the structural models, e.g. in the form of higher order Quantitative Petri Nets [42,43], Timed Petri Nets [44], etc.

2. Objective and approach

The objective of this work is to develop a methodology for the computer aided generation of GIS based dynamic environmental process models, as well as to test it for the simulation based analysis of a sensitive rural watershed.

In the suggested approach the model building procedure starts from the GIS layers and through a graph transformation, generates a process model in sense of Direct Computer Mapping (DCM). The major components (and the actually used tools) of the methodology are the followings:

- *GIS tool*: The structural information about water network and land patches can be derived from the GIS (actually QGIS, http://qgis.osgeo.org) maps, consisting of several polygon and polyline layers, extended by an appended attribute that describes the network connections. It means that all of the elements contain a reference to the subsequent element of the water network. This provides the topological information to graphical model, consequently it is not necessary to apply any other network analyst tool.
- *GraphML manipulating tool*: Importing of the GIS network into GraphML format can be solved by the structured spreadsheet import capability of yEd Graph tool [45]. In the expert interface these large process networks can be visualized as graph structures, so the GraphML file format can be used for the description of the model. This XML-based format supports the graph structure data exchange, effectively. In this work the yEd Graph editor is used for the graphical edition of GraphML, while the functional data and expressions were added to the structure as the extensions in this GraphML file. Actually, having edited the graphical process model, the prototype elements are added,

containing the local programs of the state and transition elements, which are parameterized, according to the language of Direct Computer Mapping. Next the connections between the elements are specified. Finally the structural elements can be filled with the initial data, and parameters.

- *General interpreter of DCM kernel*: Having prepared the expert's input, our general interpreter generates the files containing the dynamic model from the GraphML description. The underlying process models can be generated from the same, predefined types of state and transition elements, connected with standardized connections, following the general feedback architecture of process systems in sense of Direct Computer Mapping. The state and transition elements are associated with the field specific local programs, declared in the respective prototype elements, contained in the so-called expert file. The case specific knowledge is determined by the actual state, transition and connection elements, which are described in the so-called user file. The dynamic partitions of expert and user files can be executed by the general purpose, invariant simulation kernel.
- *Web based user interface with mapserver*: The user can parameterize the model through a web-based map interface. The layers come from GIS description to the mapserver, while the parameters can be edited according to the model generated data templates, prepared together with the model.

3. The investigated problem and the applied method

3.1. *GIS elements of the investigated area*

Lake Balaton (Fig. 1) is one of the largest shallow freshwater lakes in Europe with a size of 596 km^2 and an average depth of 3.2 m [46]. Its whole catchment basin is 5774 km^2, while the direct watershed planning sub-area is 3183.3 km^2 [47]. There are 20 permanent and 31 periodic watercourses, including the most important water supply, River Zala (∼45–50% of the whole yield). The single outflow, Sió Canal has been operated since 1863.

Description of the water network in the studied area (blue polylines in Fig. 1) was started from the corresponding shape files of watercourses, water bodies and sub-watersheds, developed by the Environmental Protection and Water Management Research Institute. In this work Quantum GIS (QGIS) software (http://qgis.osgeo.org) was used for the refinement and editing of the original shape files. The sections of water network, transformed into model elements, were the followings:

- waterbody of Lake Balaton, compartmentalized into 20 sub-compartment with the detailed characterization of flows and mixing;
- 121 water sections of the South catchment basin, segmented by the intermediate small fishponds and lakes as well as by the boarders of sub-watersheds (signed with black lines in Fig. 1);
- 57 lakes, fishponds, reservoirs and marshes in the South catchment basin.
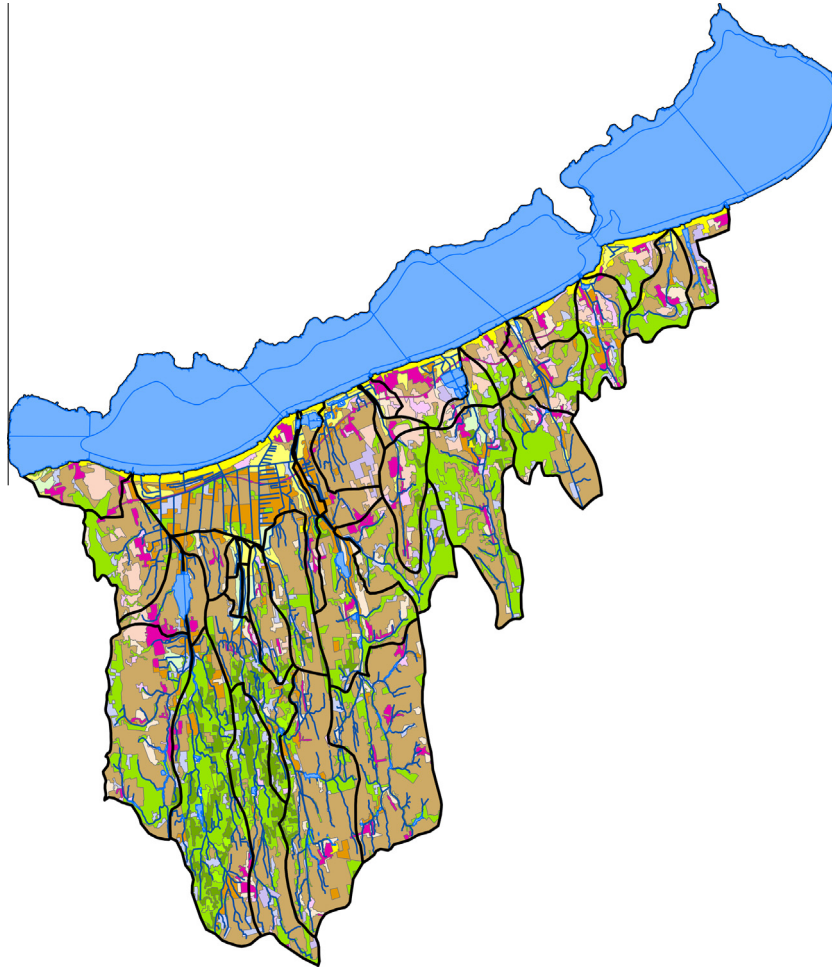
Fig. 1 – GIS layers of the investigated area (with sub-watersheds, water network, and land patches).

To take into consideration the land use in computational models, the CORINE Land Cover (CLC) database [48] is generally used. For the complete and disjoint covering of the whole investigated area, the freely available vector data of the national data set in 1:100.000 scale (CORINE Land Cover 2006 Hungary, coloured patches in Fig. 1) were applied. This data set was created by the Institute of Geodesy, Cartography and Remote Sensing, and it was refined in terms of the changes from 2000 to 2006. It is to be noted, that the 1:50.000 scale data set [49] is also available for Hungary, however, the granularity of our model does not require this detailedness. Polygons were identified with the general three-level CLC nomenclature.

In the composition of the flow structure, built from the above described water flow segments and lake compartments of the watershed, the Digital Elevation Model (DEM) was applied for description of the water network. Regarding the Lake Balaton compartments, flows with superimposed mixing were modelled between the 20 lake compartments. In both cases a directed network structure, was described, indicating the outlet water section for each element in the attribute tables of the various layers.

Considering the medium complexity of the model, for the land patches the following simplification principles were applied:

- all of the various land patches were represented by a single land patch in the sub-watersheds, summarizing the spatially fragmented areas of the identical patches in each subwatershed;
- the hydrological effect of these summarized patches are distributed and assigned to all elements of the water network in the given sub-watershed (because the description of the exact spatial distribution of patch originated water sources is almost impossible, an approximate proportional distribution was applied, according to the ratio of the lake perimeter or the double length of the water sections, related to their sum in the given subwatershed).

3.2. Direct Computer Mapping (DCM) based interpretation and simulation of process models

Nowadays complex, multidisciplinary and multiscale models claim for clear and sophisticated coupling of structures and functions. Multiscale, hybrid processes in biosystems and in human-built process networks contain more complex elements and structures, than the theoretically established mathematical constructs. Moreover, the execution of the hybrid, discrete/continuous and optionally multiscale models

is a difficult question, because the usual integrators do not tolerate the discrete events, while the usual representation of the continuous processes cannot be embedded into the discrete models conveniently [50]. Another challenge is the effective combination of quantitative models with rule-based qualitative knowledge.

Having recognized these difficulties, in our approach, called Direct Computer Mapping (DCM) of process models ([51,52]) the elements and their connections are mapped onto an executable process model without using any single specific mathematical construct. In the recent development of DCM the experiences coming from the sophisticated analysis of a broad range of processes are synthesized from cellular biosystems [53] through technological process units [54], to sector spanning agri-food process networks [55]. The continuous development of the method is motivated by the studied actual problems. For example, the recent implementation of agrifood processes has also been motivated by the ongoing applications for Recirculating Aquaculture Systems. Based on these different examples a general set of building and connecting elements was recognized, which have the capability to implement all of the investigated process models. Accordingly, the complex structures and functionalities of the various continuous and discrete, as well as quantitative and qualitative process models can be mapped onto the quite uniform state, transition and connection elements (see various nodes and edges in Fig. 2), while the elements are associated with locally executable programs.

Explanation of Fig. 2 is the following:

- State elements (ellipses, S), characterize the actual state of the process;
- Transition elements (rectangles, T), describe the transportations, transformations and rules of the time-driven or event-driven changes of the process;
- Increasing (solid) and decreasing (dashed) connections, transport additive measures from the transitions to the state elements;
- Signalling connections (dotted), carry signs from state to transition elements and *vice versa*.

The state and transition elements contain slots (small circles and rectangles) for the lists of parameters (Sp or Tp), inputs (Si or Ti) and outputs (So or To), as well as references for the respective programs (bold names). The local functionalities of the state and transition elements are described by the local program codes, defined in the prototype elements. Many elements may use identical programs, declared by the prototype for the given subset of elements. The connections carry data from an output slot to an input slot. The slots, the connection elements and the executing kernel are prepared for lists of optional data triplets d(DataName, DataList, Dimension) where DataList contains the numerical or symbolic data called DataName with the respective Dimension. The declarative description of the general structure and execution of DCM model is written in Prolog.

The model-driven execution of the process simulation consists of six cyclically repeated, consecutive steps, as follows: calculation of the state programs; upgrading of state → transition connections; upgrading of transitions' input; calculation of transition programs; upgrading of transition → state connections; upgrading of state's input. During the model-driven simulation, the prescribed spatial and temporal scales are taken into consideration, automatically.

3.3. State and transition prototypes

Model building starts with the determination of the field specific prototypes for the state and transition elements, which contain also the local programs of the given (e.g. hydrological) model. In present study the state prototypes are the followings:

- Flow sections: describe segments of the various watercourses;
- Lake compartments: determine the compartmentalized parts of Lake Balaton;
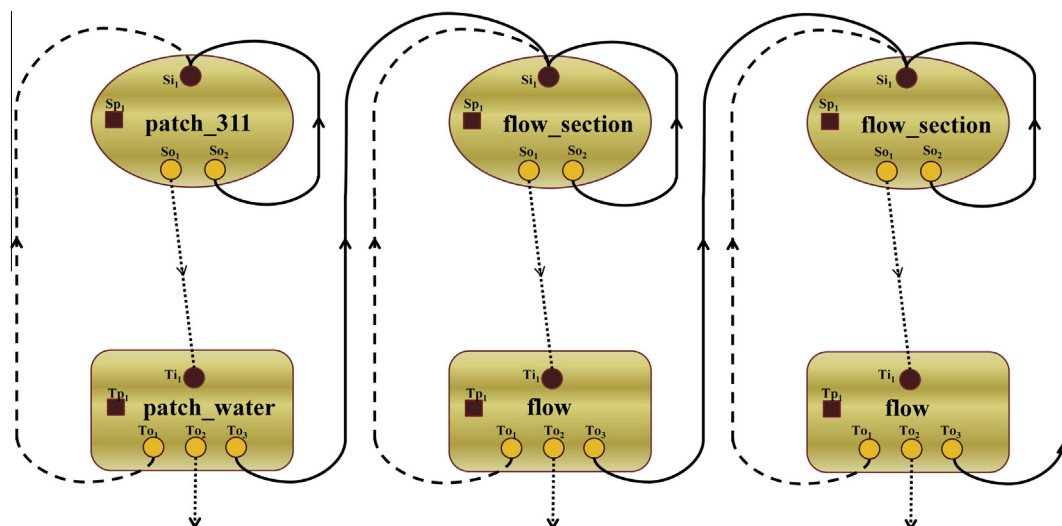- Marsh compartments: define the given parts of a marshland;

Fig. 2 – Part of a process net structure in DCM.

- Fishponds: declare lakes on the catchment that is used mainly for fishery or fishing;
- 17 kinds of land patches: according to CORINE land cover.

The transition prototypes are responsible for the description of the water transport between the various water sections and from the various land patches to the connected water sections, as follows:

- inflow: describes water flow to a lake (compartment);
- outflow: describes the outlet from a lake (compartment);
- flow: passes the water from one element to the subsequent one;
- pump: describes the operation of loading or draining into or from a lake (compartment);
- mixing: describes the flow with a superposed mixing between two compartments of a lake;
- patch to water: describes the water supply from a given type of area to the connected elements of the water network. Functionally, there are 17 kinds of patch_water prototypes, according to the CORINE nomenclature, that are divided into 7 groups, according to their permeability and evaporation capacity, determined by soil type and plant covering.

All of the introduced state and transition elements are associated with their own executable programs, described in the respective prototypes. The actual elements contain the necessary initial conditions of the inputs and parameters to calculate the water balance for the investigated area. The coherence of the model is given from the discretized dynamic network of water flows and storages, as well as from the complete and disjunct covering of the whole area by modelled patches besides the water network. It is to be noted, that these two parts of the model (coming from the respective GIS layers) are described with structurally identical model elements in sense of DCM.

The formulation of water balance for land patches connected with the water network is based on the SWAT land phase description. Accordingly, the initial water content of the land patches at H1 elevation level (signed with H in Fig. 3), can be compared with the limit levels (Hmin, Hsink, Hunder, Hsurf in Fig. 3) and with the elevation level of the connected flow section level (H2 in Fig. 3). The various water movements are associated with specific flow coefficients (Ksink, Kret, Klat, Ksurf in Fig. 3) for the calculation of changes during a simulation time step.

In the simplified model instead of the sophisticated expressions of SWAT (considering many unknown parameters as soil structure, slope, etc.) a simple kinetic relationships were used, containing the additive parts, as follows:

if H > Hsurf then Surface flow = Ksurf*(Hsurf-H);
if H ⩽ Hsurf and H > Hunder then Lateral flow = Klat*(H-Hunder);
if H ⩽ Hunder and H > Hsink then Return flow = Kret*(H-Hret);
if H ⩽ H > Hmin then Sink_flow = Ksink*(Hsink-Hmin).

For the detailed parameterization of water sections, lakes and lake compartments, the necessary data (average depth, length, average width, area, perimeter, elevation) come from the GIS layers.
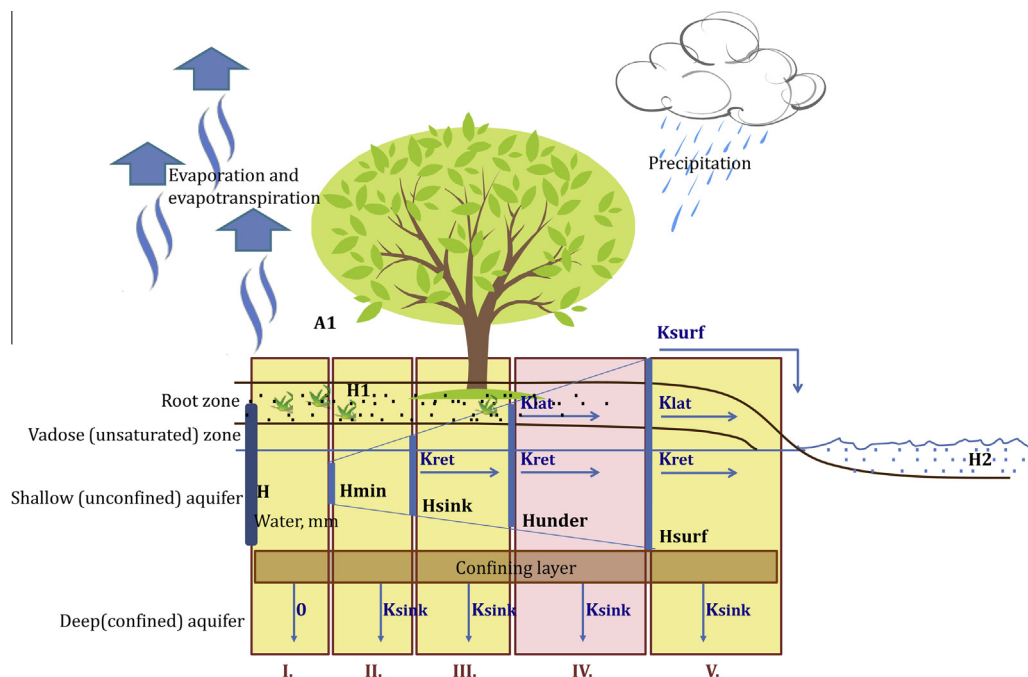

Fig. 3 – Simplified model of a land patch and its connection with a water section. Derived on the basis of Fig. 0.3 of SWAT2009 Theoretical Documentation [56].

4. Results and discussion

4.1. GIS based generation of the dynamic net model

The state and transition prototype elements give a basis to generate the water network of lake compartments, watercourses, lakes, fishponds, reservoirs and marshes, as well as the various kinds of land patches with their impact on the water network. Actually, after the graphical edition of prototype elements through the yEd graph editor, the prepared water network and land patch elements can be exported from the GIS application. Next all of the imported elements can be initialised and edited, according to their appropriate prototypes, and filled with the actual data.

For the graphical representation of the model elements, as well as for editing of the model structure according to the DCM principles, the freely available desktop application of yEd graph editor [45] was used. First, the various water sections and land patches of the GIS layers are transformed into a simple yEd network (see the middle example graph in Fig. 4). In this step the feature of yEd graph editor tool is used, which allows importing files from spreadsheets. Accordingly, based on the "From-To" description in the attribute tables of water network and land patch layers a simple graph is generated. In the next step, this simple graph is transformed further to a DCM process net. It is made by replacing of simple nodes

for state elements (i.e. flow sections, lake compartments, marsh compartments, fishponds and 17 kinds of land patches, represented by ellipses in sense of Fig. 2), as well as by adding transition elements (i.e. inflows, outflow, flows, mixing, pumps and the "from patch to water" elements, represented by rectangles in sense of Fig. 2) to the structure. The net structure was completed by drawing connections between these state and transition elements. Fig. 4 illustrates the transformation of a small part of a water section, from the map to the DCM model format.

4.2. Implementation of the elementary models in the local programs of DCM prototypes

Construction and utilization of a state prototype and a state element are illustrated by the example of the forest land patch, where "patch_311" refers to the forest patch, in the sense of the CORINE nomenclature. Prototype element of patch_311 (upper left) and an actually parameterized forest patch, generated from the prototype (lower right) can be seen in Fig. 5.

Prototype elements (and also the actual elements, generated from the prototype) contain an optional number of input (Si), output (So) and parameter (Sp) slots. Program slots (Spr) appear only in prototype elements. The program code(s) declared in the program slots must be formulated with the
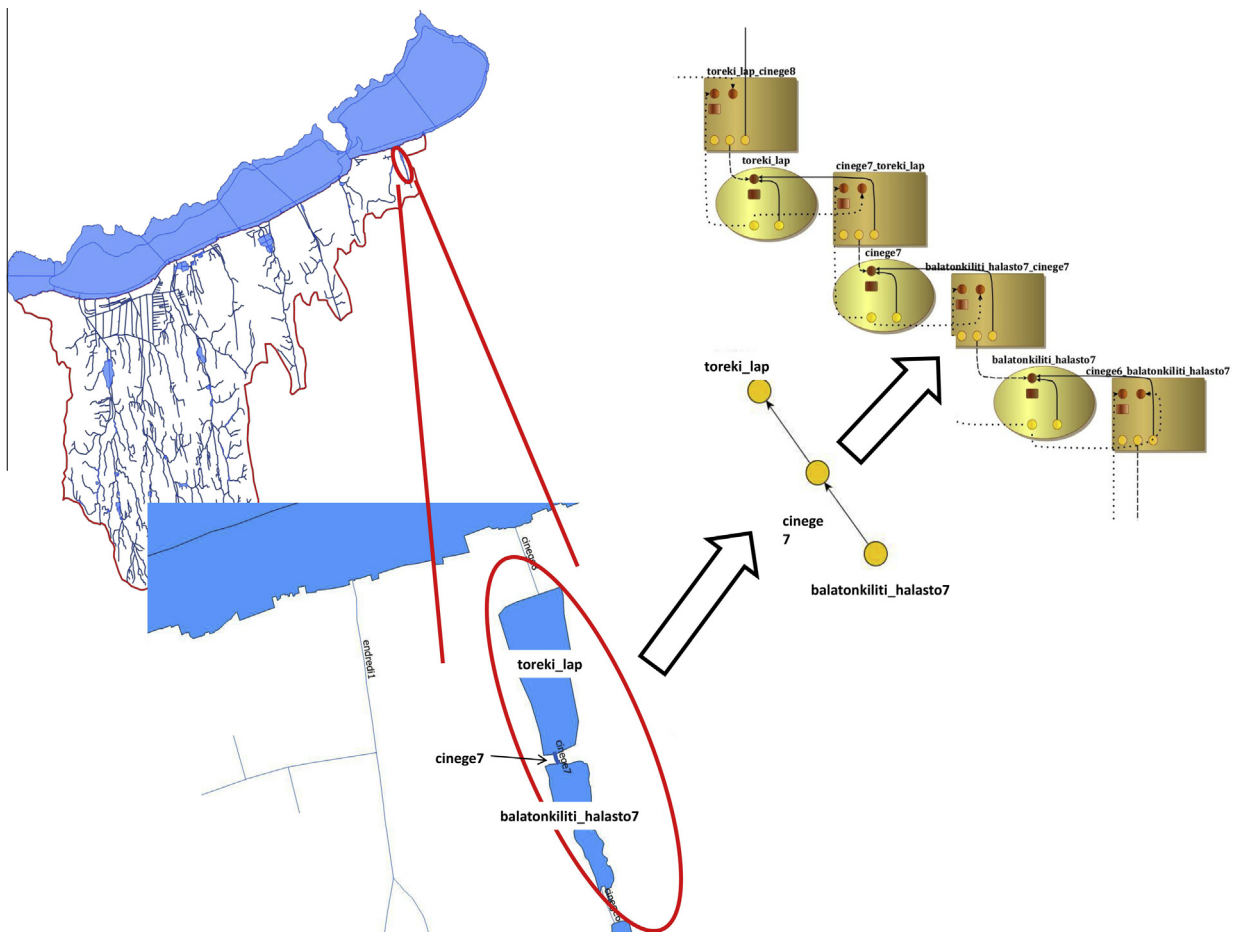

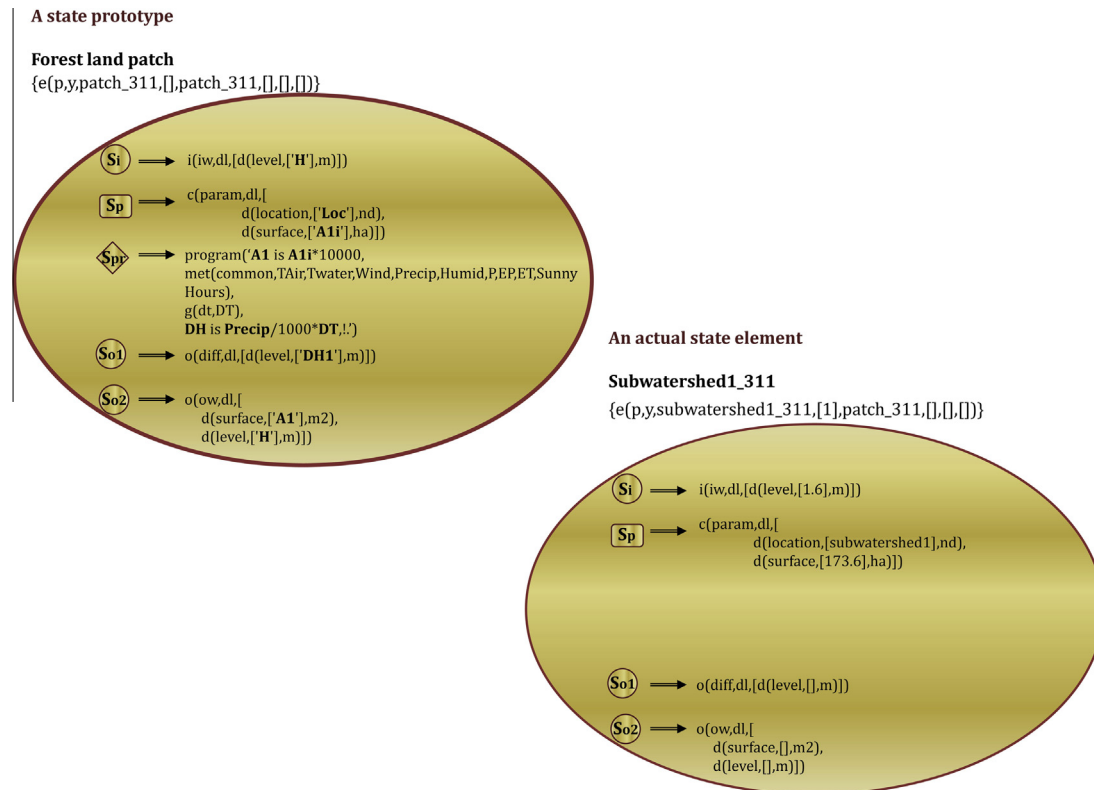Fig. 4 – Transformation of GIS elements into DCM model elements.

A state prototype

Forest land patch
{e(p,y,patch_311,[],patch_311,[],[],[])}

An actual state element

Subwatershed1_311
{e(p,y,subwatershed1_311,[1],patch_311,[],[],[])}

Fig. 5 – A state prototype and an actual element derived from it.

variables of input and parameter slots, and they are responsible to calculate the variables of output slots, with the consideration of some added-on predicates, coming e.g. from the meteorology database.

The explanation of variables, predicates and constants of input (Si), output (So), parameter (Sp) and program (Spr) slots, as well as the (simplified) brief program of the "patch_311" prototype, defined by the input, parameter, program and output slots of the given element, written in a declarative Prolog syntax, can be studied in the Appendix, in detail.

Accordingly, the change in water level of the forest patch (DH1, content of So1 output slot in Fig. 5), caused by the precipitation is calculated in every time step of the simulation, considering the actual meteorological data (TAir, TWater, Wind, Precip, Humid, P, EP, ET, see Notations). The calculated change via a connection from the diff slot will increase the level in the iw slot of the same element in the next time step. The ow slot replies the area of the patch (transformed from ha to m^2). The content of ow slot is transferred also to the respective output stream.

To illustrate a transition prototype, the patch_water prototype (upper left) and the parameterization for one of its actual elements (lower right) are shown in Fig. 6.

Similarly to state elements, input, parameter, program, and output slots are applied in transition elements, signed with Ti, Tp, Tpr1 … Tpr5 and To in Fig. 6. Calculation is described by the programs, contained in the optional number of program slots. The program code declared in the program slots must be formulated with the variables of input and parameter slots, and they are responsible to calculate the

output variables with the consideration of some added-on predicates, coming e.g. the meteorology database. As it was shown in Fig. 3, considering the initial water content of the land patch (H), and compared it with the respective limit values determined by the various zones (Hmin, Hsink, Hunder$_r$, Hsurf), there are five different cases. In the Appendix, the brief local program, corresponding to the signed case IV in Fig. 3 is described.

Accordingly, the change in water level of the forest patch (DH1), caused by the evapotranspiration, by the water transport from the patch to the connected water section and by the outflow from the shallow aquifer is calculated in every time step of the simulation, considering the actual meteorological data (TAir, TWater, Wind, Precip, Humid, P, EP, ET, see Notations). Also the volume DV2 of the water source from the patch to the connected water section is calculated by the program. The calculated changes are given for the connections in the "from" and "to" slots, respectively, while the report slot transfers the Rate to the output stream (see Fig. 6 output slot).

Direct Computer Mapping (DCM) of process models supports the GIS based generation of dynamic simulation models for hydrological and land patch related processes. In the developed methodology, structural information about water network and land patches can be derived from the GIS (actually QGIS) maps. Having edited the graphical process model, the prototype elements can be added, containing the local programs of the state and transition elements. It can be followed by the parameterization of the actual state and transition elements according to the semantics and syntax of Direct
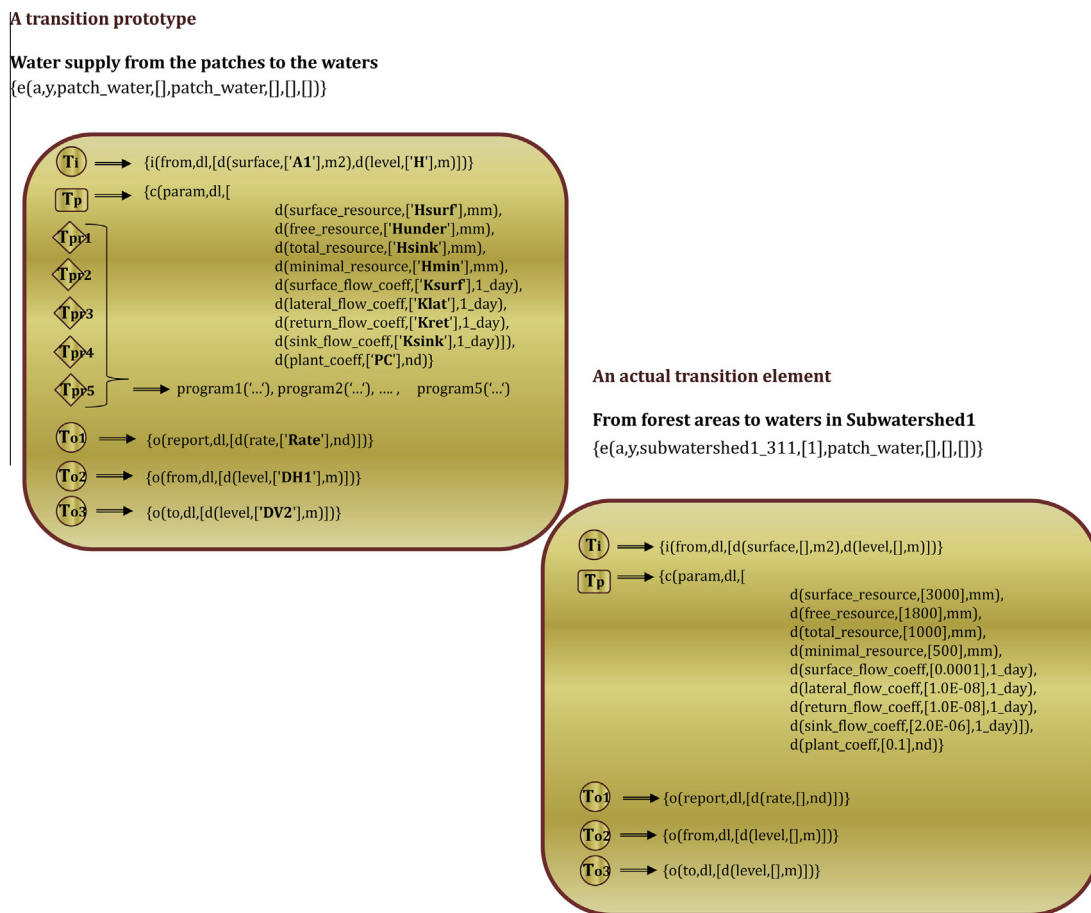
A transition prototype

Water supply from the patches to the waters
{e(a,y,patch_water,[],patch_water,[],[],[])}

Ti ⟶ {i(from,dl,[d(surface,['**A1**'],m2),d(level,['**H**'],m)])}

Tp ⟶ {c(param,dl,[

Tpp1   d(surface_resource,['**Hsurf**'],mm),
        d(free_resource,['**Hunder**'],mm),
        d(total_resource,['**Hsink**'],mm),
Tpp2   d(minimal_resource,['**Hmin**'],mm),
        d(surface_flow_coeff,['**Ksurf**'],1_day),
Tpp3   d(lateral_flow_coeff,['**Klat**'],1_day),
        d(return_flow_coeff,['**Kret**'],1_day),
Tpp4   d(sink_flow_coeff,['**Ksink**'],1_day)]),
        d(plant_coeff,['**PC**'],nd)}

Tpp5 ⟶ program1('…'), program2('…'), …. , program5('…')

To1 ⟶ {o(report,dl,[d(rate,['**Rate**'],nd)])}

To2 ⟶ {o(from,dl,[d(level,['**DH1**'],m)])}

To3 ⟶ {o(to,dl,[d(level,['**DV2**'],m)])}

An actual transition element

From forest areas to waters in Subwatershed1
{e(a,y,subwatershed1_311,[1],patch_water,[],[],[])}

Ti ⟶ {i(from,dl,[d(surface,[],m2),d(level,[],m)])}

Tp ⟶ {c(param,dl,[

        d(surface_resource,[3000],mm),
        d(free_resource,[1800],mm),
        d(total_resource,[1000],mm),
        d(minimal_resource,[500],mm),
        d(surface_flow_coeff,[0.0001],1_day),
        d(lateral_flow_coeff,[1.0E-08],1_day),
        d(return_flow_coeff,[1.0E-08],1_day),
        d(sink_flow_coeff,[2.0E-06],1_day)]),
        d(plant_coeff,[0.1],nd)}

To1 ⟶ {o(report,dl,[d(rate,[],nd)])}

To2 ⟶ {o(from,dl,[d(level,[],m)])}

To3 ⟶ {o(to,dl,[d(level,[],m)])}

Fig. 6 – A transition prototype and an actual element derived from it.

Computer Mapping. Next, the connections between the elements can be specified. Finally the structural elements can be filled with the initial data, and parameters. This methodology represents an intermediate solution between the two mainstreams of the existing approaches, which are the sophisticated field specific packages on the one hand, and the interfacing between the independently developed modules. In our case, the general core of process modelling can be utilised through the general, but configurable expert and user interfaces.

4.3. *Calibration and validation of the model*

For the parameter identification of the model the factual data of the following time series were applied:

- daily measurements of meteorological data (2004–2014);
- monthly average measured flow rates for River Zala and for the major Northern inflows (West-transdanubian Environment and Water Utilities Departments, 1994–2013);
- monthly averages for Canal Sió outlet flow rates (Middle-transdanubian Environment and Water Utilities Departments, 2004–2014).

Considering the large number of the parameters to be identified, a top-down heuristic strategy with stepwise refinement was used. First, all of the land patches were assumed being alike (with identical hydrologic parameters) and the method tried to satisfy the gross water balance of the Lake with the knowledge of the available, partially measurement based water balancing data. In the vicinity of the feasible solution the various land patches were distinguished to decrease the difference between the measured and calculated flow rates. These steps were repeated cyclically. During identification H, Hsurf, Hunder, Hsink, Hmin parameters (in line with Fig 3) were changed in +-30% ranges around the initially estimated values. Ksurf, Klat, Kret, Ksink parameters were changed within 3 orders of magnitude around the initially estimated values.

With the knowledge of calibrated parameters, the levels of Lake Balaton, as well as the measured flow rates of Southern inflows were used for the validation, as follows:

- monthly averages of flow rates for the Southern inflows (West-transdanubian Environment and Water Utilities Departments, 1994–2013);
- daily measurements for Lake Balaton level (National Hydrological Service, www.hydroinfo.hu, 2004–2014).

Regarding the initial conditions of water levels, starting from rough estimations, after a longer simulation more and more realistic values were recognised. Accordingly, the case studies can be started after a previous simulated period. Nevertheless, these kinds of large models with possible new dis-
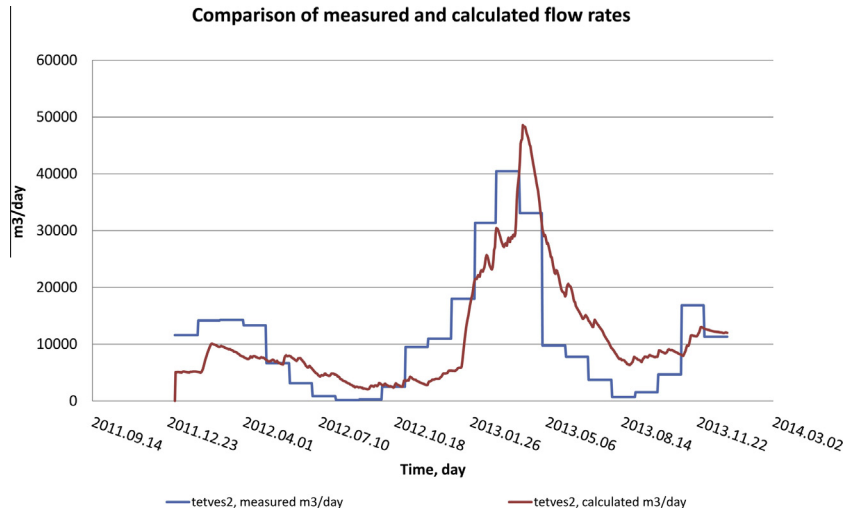
Fig. 7 – Comparison of measured and calculated data for Creek Tetves 2nd section.

turbances from climatic and other scenarios need a "never ending" continuous care of refining identification and validation. As an example, Fig. 7 illustrates the comparison of measured and calculated flow rates for a Creek section (2nd section of Creek Tetves) in the Southern watershed for years 2012–2013.

In Fig. 8 the calculated levels of the twenty Lake Balaton compartments with an average value of the measurement station (red line) for 2012–2014 are compared. Orange and green lines illustrate the largest inlet (River Zala) and the single outlet flow (Canal Sió) rates. Combined illustration of levels and flow rates indicates clearly the response of levels to the relatively large peaks of inflow and outflow. Both figures show that according to the recently experienced extreme weather events, an unusually dry year (2012) was followed by an extraordinarily wet period (2013).

For the determination of the error measure we applied the formula of mean absolute percentage deviation (MAPD):

$$\text{MAPD} = \frac{1}{n}\sum_{i}\frac{\text{abs}(x_i - x_i^m)}{x_i} * 100 \tag{1}$$

where

n is the number of data in the time series,
x_i is the measured data,
x_i^m is the calculated data.

At the present state of development the MAPD value for the average lake compartment level is 2.7%.
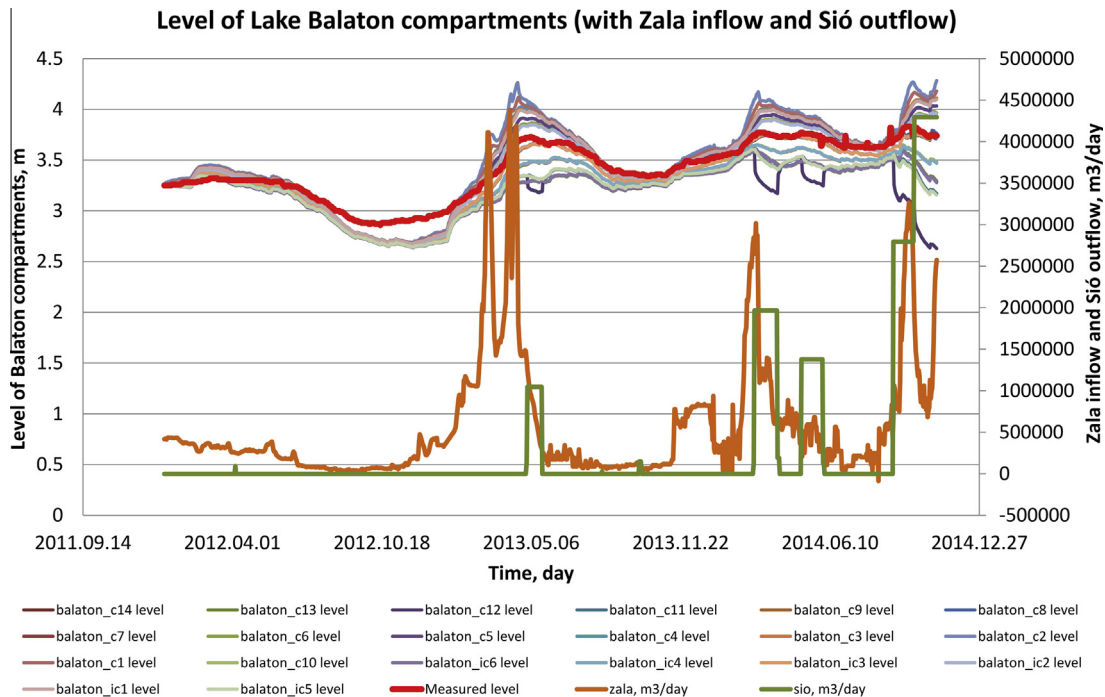

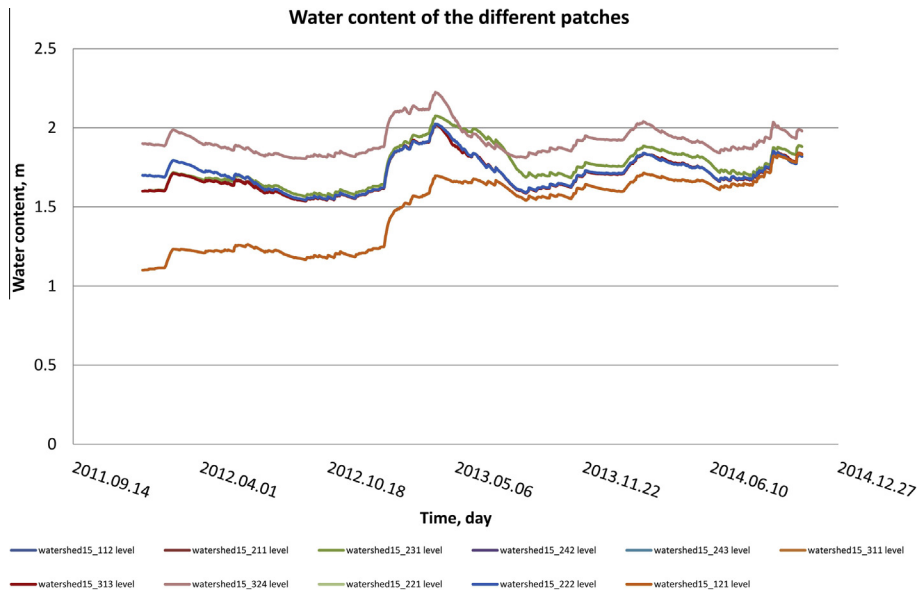Fig. 8 – Comparison of measured and calculated level of Lake Balaton.

Fig. 9 – Dynamic changes of water content of land patches in an example sub-watershed.

It is to be noted that the sub-models of evaporation and evapotranspiration were calibrated and validated in the respective, cited works. However, due to the lack of the detailed experiments, the initial and characteristic levels and kinetic parameters (H, Hsurf, Hunder, Hsink, Hmin, Ksurf, Klat, Kret, Ksink in line with Fig. 3, see Notation) of land patches could not be finally refined. Accordingly, the final calibration and validation needs complementary future work with the already available simulation model. Considering the future tendency of collecting more and more data from environmental sensor networks, the utilization of continuously learning models seems to be straightforward.

4.4. Example case studies

The hydrological model was implemented for the Southern watershed of the Lake Balaton, with the boundary consideration of the other inlets and the single outlet. The hydrological model took into consideration the meteorology determined precipitation, evaporation, transpiration, runoff, infiltration,
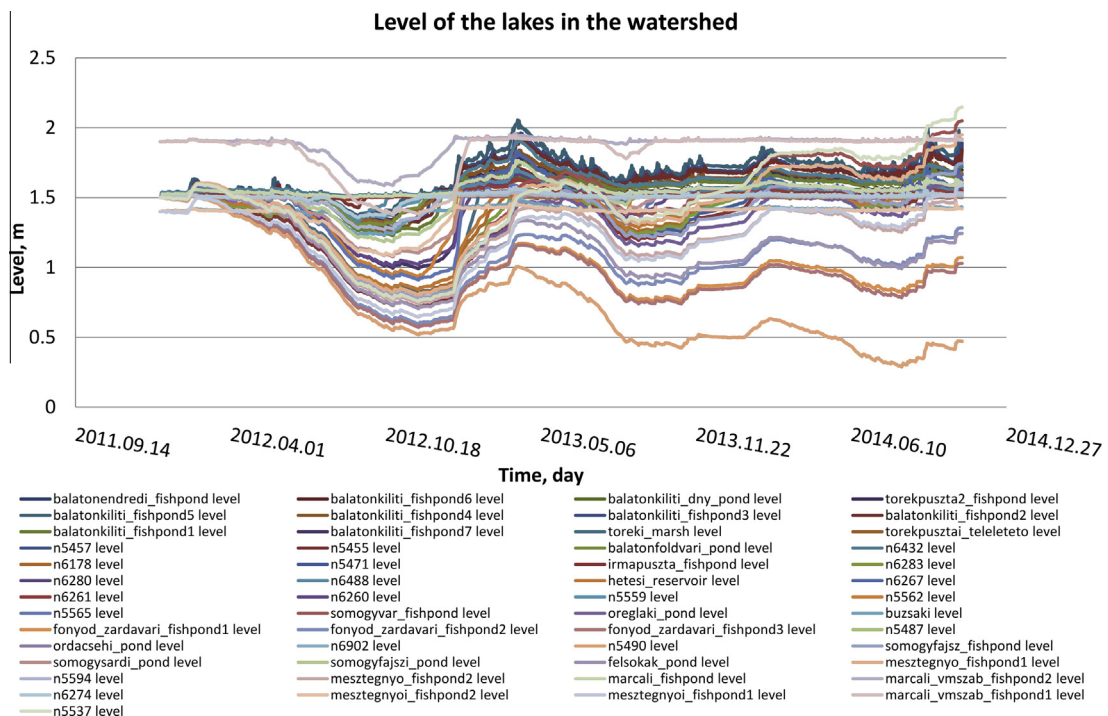

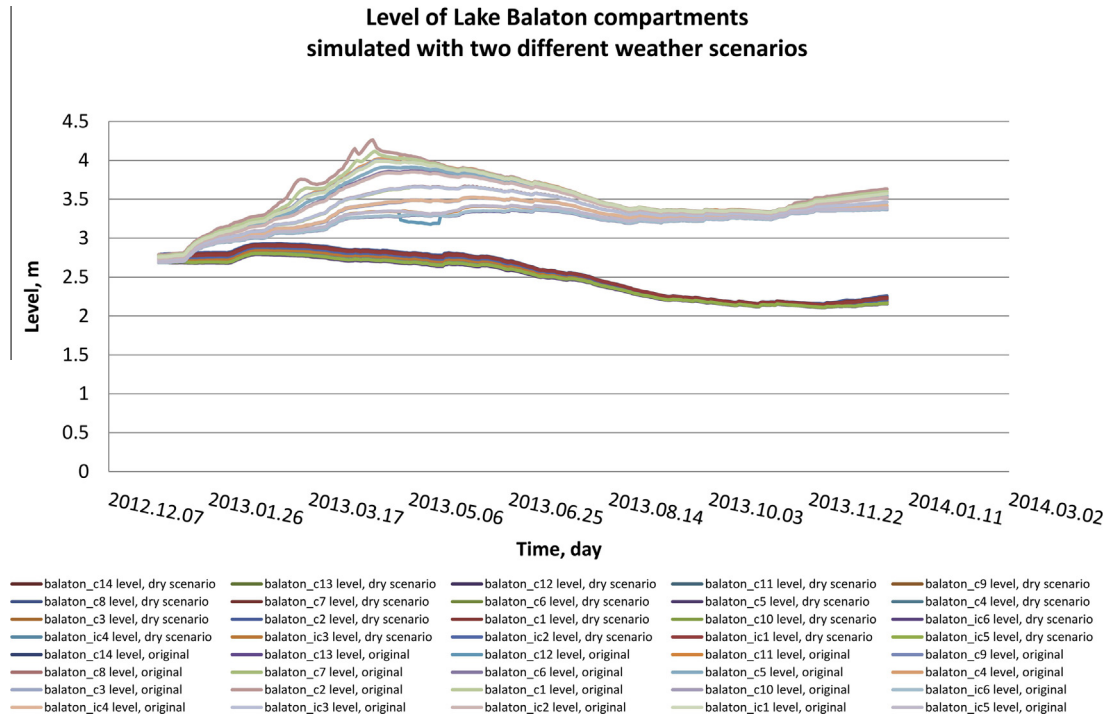**Fig. 10 – Simulated changes of lake and fishpond levels in the southern watershed.**

Fig. 11 – Comparison of Lake Balaton levels for the situations of following a dry year by a wet one (upper curves) and by a second dry one (lower curves).

etc. The CORINE land cover based simplified "land patch" model was used for the consideration of the basic natural and anthropogenic properties (e.g. land use, plant coverage), relations and empirical observations.

Using the present state of the identified model, the dynamic changes of various characteristics can be studied. Initial water content of the various land patches, as well as

the meteorological situations determine the amount of water, forwarded to the connected water sections. With the preliminarily calibrated model, the change of water content in the various land patches can be studied. Fig. 9 shows an example, how the water content of the various land patches in the example sub-watershed #15 varies during the period of 2012–2014. Fig. 10 reports about the calculated levels of the
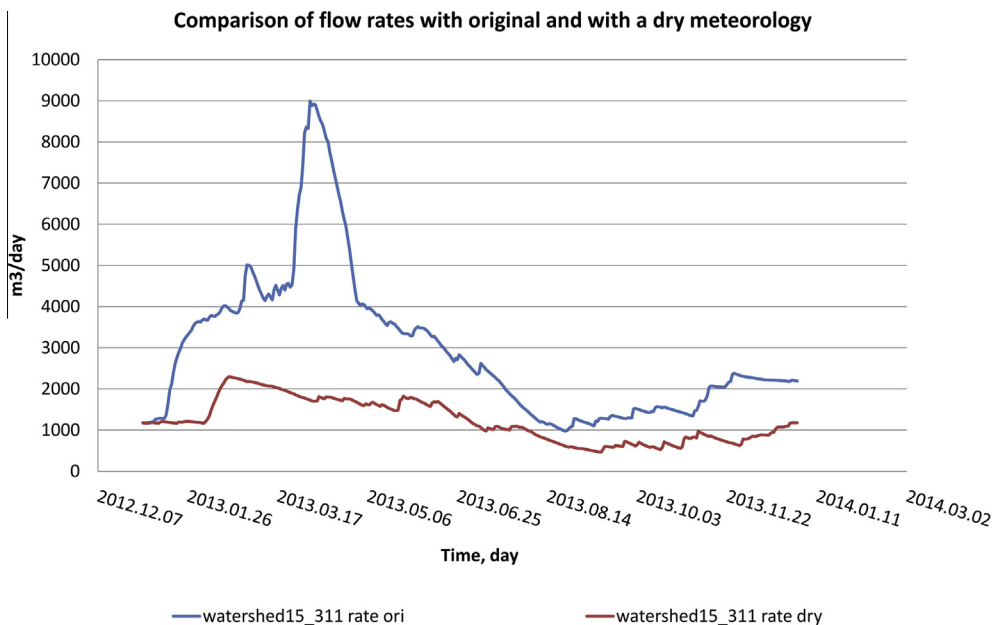

Fig. 12 – Comparison of flow rates for the situations of following a dry year by a wet one (upper curve) and by a second dry one (lower curve) (forest patches in the 15th sub-watershed).

small lakes, fishponds and reservoirs in the Southern catchment basin during the same period. These water levels were simulated by the model, considering the water content of patches and the meteorological conditions.

In another example the model was tested for the prediction of Lake Balaton compartments' levels in case of various meteorological situations. For example, the simulation for years 2012 and 2013, the factual data of 2013, were replaced for the data of the relatively dry year of 2012. As a result, the levels of Lake Balaton compartments show considerable decrease during this hypothetically dry simulation period (see Fig. 11). Upper branch of lines in Fig. 11 shows the levels of the Lake compartments in case of simulation with the real meteorological data (with an average 3.5 m level during the two years), while the lower parts corresponds to the simulation results with two hypothetical dry years (with an average level of 2.5 m). Furthermore, decreasing difference can be seen between the various Lake compartments, too. The reason is that due to the lack of precipitation in year 2012 Canal Sio was not used for the disposal of surplus water from the Lake. Accordingly, in contrast to the case, when River Zala and other inflows feed mainly the Western compartments while Canal Sio decreases directly the level of the Eastern compartments, in this situation the levels are more or less balanced than in the original situation were.

In the case study of "hypothetical dry years", the flow rates from the land patches to the connected water sections were also monitored, individually. Fig. 12 illustrates the comparison of the effects on the water source flow from an example land patch to the water sections of the given sub-watershed. It can be seen in the example diagram that the relatively high peak, caused by the rainy period of the original meteorology in 2013 is missing and has been replaced by a hypothetical dry meteorological situation. The study on the individual water sections and lakes showed the overall consequence that water sections and small lakes are getting to dry. It is completely in line with the available observations.

5. Conclusions and outlook

The Direct Computer Mapping (DCM) based methodology provided a suitable solution for the generation of dynamic simulation models of an environmental system from GIS layers, integrating the field experts' knowledge (data, relations, empirical expressions, etc.) for the prediction of the effects of various meteorological scenarios, flexibly. The method was tested for the example of the Southern watershed of Lake Balaton.

According to our experiences the coherence of the large scale model can be given by the dynamic network of water flows and reservoirs. The completeness can be ensured by the complete and disjoint covering of the whole area by modelled land patches, corresponding to the typical parts of natural and human built environment. The complexity of the large scale and long term processes can be managed by evaluating detailed models only for one representative patch from each class, while the calculation and assessment of the similar patches can be solved by simple multiplication rules.

According to our first trials with the developed framework, the implemented medium complexity hydrological model is able to predict the effects of various climatic scenarios.

The most important challenge of the future development is the improvement of calibration and validation by systematic application of multiscale models with various granularities of the spatiotemporal decomposition. Also the automatic learning feedback between the continuous data acquisition based statistical evaluation and the continuously learning 'a priori' model ought to be applied in the further works.

Appendix A. Examples for the local programs of patch_311 and patch_water prototypes

The calculations are based on the available empirical relationships.

A generally accepted expression for the evaporation (EP) of Lake Balaton was developed by Antal and Tóth [57]. In our model, the modified version of the original formula was applied, corrected with a "seasonal" coefficient by VITUKI [58] as follows:

$$EP = a * (P0vap(Tw) - Pvap) * (0.59 + 0.013 * Wind) \quad (A1)$$

where

P0vap(Tw) is the equilibrium vapour pressure in the function of water temperature, mbar

Pvap is the actual vapour pressure calculated from the relative air humidity, mbar

'a' is a seasonal coefficient, in March: 0.7, in April: 0.8, in October: 1.3, in November: 1.4, otherwise: 1.

For the calculation of evapotranspiration (ETP), instead of the more data demanding Penman–Monteith expression, the heuristic Antal formula [59] was applied, accordingly

$$ETP = 0.74 * (P0vap(Tw) - Pvap)^{0.7} \left(1 + \frac{Tw}{273}\right)^{4.8} \quad (A2)$$

In the model, refined form (ET) was used, corrected with the k plant constant and with the ratio of disponible and maximal water content of the land patch ([60,61]), as follows:

$$ET = PC * W * ETP \quad (A3)$$

While

$$W = \frac{\text{total available water} - \text{non disponible water}}{\text{maximal disponible water}}$$
$$= \frac{H - Hunder}{Hsurf - Hunder} \quad (A4)$$

and PC is the plant constant that depends on territorial and seasonal factors.

The calculation of water balance depends on the actual case, marked with I–V in Fig. 3. For example in case IV (highlighted with pink in Fig. 3), when

$$Hunder < H < Hsurf \quad (A5)$$

the water supply from the given patch to the connected water is calculated by equation

$$DV2 = (Klat * (H - Hunder) + Kret * \frac{Hunder - Hsink}{1000}$$
$$* A1 * DT \tag{A6}$$

where

A1 is the surface of the given land patch, m^2

DT is the time step, day

DV2 is the volume of water source, transported from the patch to the water section during the time DT, m^3

The evapotranspiration is determined by expression

$$DEvap = \frac{H - Hunder}{Hsurf - Hunder} * PC * \frac{ET}{1000} * A1 * DT \tag{A7}$$

where DEvap is the volume of the evaporated water from the patch, m^3.

The respective Prolog program for the patch_311 prototype is the following:

```
m(y,patch_311,
  [c(param,dl,[d(location,[Loc],nd),d(surface,[A1i],ha)])],
  [i(iw,dl,[d(level,[H],m)])],
  [o(ow,dl,[d(surface,[A1],m2),d(level,[H],m)]),
    o(diff,dl,[d(level,[DH1],m)])]):-
      A1 is A1i*10000,
      met(Loc,_,_,_,Precip,_,_,_,_,_),
      g(dt,DT),
      DH1 is Precip/1000*DT,!.
```

The Prolog program, describing the patch_water prototype for the case of (5) is as follows:

```
v(y,patch_water,
[c(param,dl,
    [d(surface_resource,[Hsurf],mm),
      d(free_resource,[Hunder],mm),
      d(total_resource,[Hsink],mm),
      d(minimal_resource,[Hmin],mm),
      d(surface_flow_coeff,[Ksurf],1/day),
      d(lateral_flow_coeff,[Klat],1/day),
      d(return_flow_coeff,[Kret],1/day),
      d(sink_flow_coeff,[Ksink],1/day),
      d(plant_coeff,[PC],nd)])],
[i(from,dl,[d(surface,[A1],m2),d(level,[H],m)])],
[o(from,dl,[d(level,[DH1],m)]),
  o(report,dl,[d(rate,[Rate],nd)]),
  o(to,dl,[d(level,[DV2],m)])]):-
    H=<Hsurf, H > Hunder,
    g(dt,DT),
    met(_,TAir,TWater,Wind,Precip,Humid,P,EP,ET,_),
    DEvap is (H-Hunder)/(Hsurf-Hunder)*PC*ET/1000*A1*DT,
    DV2 is Klat*(H-Hunder)/1000*A1*DT + Kret*(Hunder-Hsink)/1000*A1*DT,
    DOut is Ksink*(Hsink-Hmin)/1000*A1*DT,
    DV1 is (-1)*DV2-DOut-DEvap,
    DH1 is DV1/A1,
    Rate is DV2/DT,!.
```

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