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FLOW PATTERNS FOR DRYING AND WETTING OF A RETENTION RESERVOIR BED – NUMERICAL MODELING

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Summary

This paper deals with one of the aspects important from the point of view of water quality maintenance in storage reservoirs, namely the dynamics of water currents that accompany changes of the water surface elevation in such reservoirs. Numerical simulations were conducted to back observations that high discharges are in the long term beneficial to water quality in the reservoir. Calculations made using the AdH finite elements model confirmed that the water current pattern in shallow regions varies greatly with the total discharge value. The sample analysis shown in this article concerns a mid-size storage reservoir of Tresna located in southern Poland.

It appears that for small discharges the currents that wet some areas of the previously dry reservoir bed are similar to reversed currents that occur when the area is dried. Thus some amounts of water may move from one stagnant area to another forth and back and then the water exchange is limited. It means that it is not enough to lower the water level within the reservoir steering rules and then raise it again to be assured that the water quality improves in the reservoir, especially in the lull parts. But for higher discharges the current pattern is different and the exchange of the reservoir water really does happen. In most cases in order to "flush" a reservoir that way one could just wait for high water to come, but if reservoirs form a cascade creating an artificial controlled freshet that propagates down the cascade may be a considerable means of altering water quality in lower reservoirs.

Key words: retention reservoirs, water quality, water dynamics, numerical simulation, finite element method

INTRODUCTION

Retention reservoirs are water bodies that are difficult to model – either conceptually, physically or numerically. Complex bathymetry of their beds, ever-changing water surface elevation, inflows and outflows variable by several orders of magnitude, very small water velocities in "standard" condition – they all make the understanding of the processes in dam reservoirs hard to improve. For many purposes it was – and it still is – enough to treat a reservoir as a zero-dimensional object along the river: a point of storage. Some other problems require to treat the reservoir like a one-dimensional structure along the river it is located on. But for such issues like water quality or transport phenomena in retention reservoirs at least a planar 2D approach is necessary.

This paper deals with one of the problems that arise when one wants to analyze the factors influencing the quality of water reservoir. It is flow dynamics considered in a pretty common situation when the water surface level changes over time. In such a case not only depths are consecutively changing but also some regions of the reservoir bed are dried or flooded according to the nature of the changes. Thus the total area of the reservoir changes and specific currents appear, i.e. currents that are responsible for either taking from or delivering water to the shallow regions.

Common observations (unofficial and unpublished) made by people directly involved in the work with storage reservoirs are as follows: 1) Water is generally somewhat more clear (so its quality is probably better) after lowering the reservoir water level and rising it again. 2) No matter how muddy flood water is, a high discharge period improves the overall condition of the reservoir waters afterwards, when the mud finally falls down. It is noteworthy that the second sentence is often spoken with a touch of astonishment and disbelief.

The aim of this research is to verify whether it is possible to simulate such a "flushing" effect of higher discharges combined with an increase of the reservoir water level using a numerical model. There are several models that are capable of simulating water dynamics in retention reservoirs. But most of them have very limited capabilities of dealing with water surface level changing by several meters. Other models that are targeted towards drying and wetting of the land are weaker in proper re-creating the actual dynamics of the currents.

Among the modeling tools familiar to the authors the only one capable to perform the desired calculations is the AdH (**Ad**aptative **H**ydraulics model) (Berger 2010) created by The US Corps of Engineers (USACE 2014) and available in the SMS (Surface Water Solution) package (Winters 2008) distributed by the AQUAVEO company (AQUAVEO 2014). This is why this model, checked before for a free surface water dynamics in a few different retention reservoirs (see e.g. Witek (2013)) and also for ice-covered flow in such reservoirs (Hachaj, Szlapa, Tutro 2014) has been chosen for this study.

The reservoir model selected for this research has been made for the Tresna reservoir. The Tresna reservoir is a mid-size retention reservoir located in southern Poland on the Soła river as the first of three reservoirs forming the Soła cascade. It has one main inflow – the river – and one outflow located by the dam. Table 1 shows a comprehensive summary of the reservoir parameters while figure1 presents the geographical location of the reservoir (Trzewik 2011).

Table 1. Basic parameters of the Tresna Reservoir.

Volume (million m^3)	Total	98.11
	Standard for summer	48.96
	Standard for winter	60.34
	Minimal	3.19
WSL (water surface level) (m above mean sea level)	Maximal	344.86
	Normal for summer	341
	Normal for winter	342.3
	Min WSL	328.36
Characteristic flow value at the dam profile (m^3/s)	$Q_{10\%}$	792
	$Q_{1\%}$	1469
	Minimal	1
	Yearly average	18.8

Figure 1. Geographical location of the Tresna reservoir

THE AdH MODEL

The AdH model belongs to the group of two-dimensional depth averaged finite element method modeling tools. The finite element method is widely used in various fields of numerical research of non-stationary processes including transport phenomena. The computational domain for such a calculation is divided to elements of finite size and simple shape. The calculations are there performed for specified vertices lying either at the edges of these elements or in their interior. The exact procedure depends on the model. For AdH the elements are triangular with vertices located in their corners. The solution is obtained using an iterative procedure.

The basic initial and boundary conditions for this model include: bed shape (bathymetry); bed friction parameters (may be expressed as the Manning roughness coefficient); initial water surface level; water parameters (density, viscosity – the latter may be depth dependent); inflows and outflows (constant, time dependent or surface level dependent). The above may be extended by case-specific conditions including wind conditions, atmospheric pressure changes, Coriolis effect, fixed ceilings (e.g. bridges), and parameters of the ice layer.

The main result of the model run is a two-dimensional planar field of the average horizontal velocity of water. This field may be static or time-dependent according to the conditions imposed upon the domain. Some additional obtainable features include drying and wetting of bed regions, particle tracking, and basic sediment transport.

The important feature of the AdH model is a possibility of drying and wetting of the appropriate parts of the modeled region. The surface of an element that subject to such wetting or drying is treated as a flat sloped triangle. Basing on the conservation laws the model calculates what part of such a triangle is submerged and what remains dry. The important thing here is that: the AdH model adapts the computational mesh to such conditions (this is why it is called "Adaptative Hydraulics model" after all). This is done by refining (i.e. splitting) the elements into smaller triangles. Such a procedure generates of course additional vertices that are used in the given time step. For of a partially submerged element it is split at least into its dry and wet parts. More refinement is performed if desired.

In order to obtain the solution the AdH model uses conservation equations for both mass (continuity equation) and momentum. The following subsections present the appropriate formulas. The following continuity equations are in use for determining the cross-section area and discharge in any given section:

$$A = \int_B H \quad dB \tag{1}$$

$$Q = \int_B U \cdot H \, dB \tag{2}$$

where:

A – cross-section area,

Q – discharge,

U – vertically averaged velocity of the flow,

H – local water depth,

B – section width.

The mass conservation equation on any given planar element

$$\frac{\partial H}{\partial t}+\frac{\partial(Hv_x)}{\partial x}+\frac{\partial(Hv_y)}{\partial y}=0 \qquad (3)$$

where:

v_x, v_y – velocity components in x and y directions respectively.

The AdH model uses two-dimensional momentum conservation equations. The equation for the x direction is as follows:

$$\frac{\partial v_x}{\partial t}+v_x\frac{\partial v_x}{\partial x}+v_y\frac{\partial v_x}{\partial y}-c_f\cdot v_y+g\frac{\partial \varsigma}{\partial x}+g\cdot v_x\frac{\sqrt{v_x^2+v_y^2}}{C^2\cdot H}-v_x\left(\frac{\partial^2 v_x}{\partial x^2}+\frac{\partial^2 v_x}{\partial y^2}\right)+\frac{1}{\rho}\frac{\partial p}{\partial x}=F_x \qquad (4)$$

where:

c_f – Coriolis factor,

g – gravitational acceleration,

ς – bed level,

C – Manning roughness coefficient,

p – external pressure,

ϱ – water density.

The equation for the y direction is analogous.

This basic equation may be both simplified and/or supplemented if necessary. For standard calculations of water flow in retention reservoirs the external pressure, treated as the atmospheric one, is considered to be constant, and the Coriolis effect is neglected. This allows omitting appropriate terms and simplifying the equation. Additional forces caused by ice or wind may be added to this equation if desired.

On the other hand when wetting and drying should be taken into account the above equations are not enough as the very borders of the domain may change. AdH solves for the water edge by allowing both positive and negative depths. The equations shown above are only solved in the wet (positive depth) regions. But now the algorithm is responsible for finding water surface elevation that not only satisfies the differential equations but also what is the wet region of the domain. The conservation of mass equation is much more nonlinear in such a case. The Newton method will have more trouble converging. Therefore, for problems with wetting and drying regions the elemental conservation of mass is more directly related to the tolerance used to determine that the equations are satisfied.

To deal with this problem for a shallow regions, i.e. where the depth is less than a given value (a parameter dependent on the model, several centimeters usually) the flow is treated like it was a groundwater layer. That allows flow within a partially wet element to be determined solely by the pressure differential created by water surface slope and friction. The fluxes within this drying-wetting thickness are then included into the mass conservation so that elemental mass conservation equation is preserved.

SIMULATIONS AND RESULTS

The model calculations were performed for the surface level of the Tresna reservoir changing between 337.8 and 342 m a.s.l. Figure 2 (a), (b) presents the shape and bathymetry of the reservoir in both of these states. It can be easily seen that for the lower water surface value some southern regions of the bed are dry.

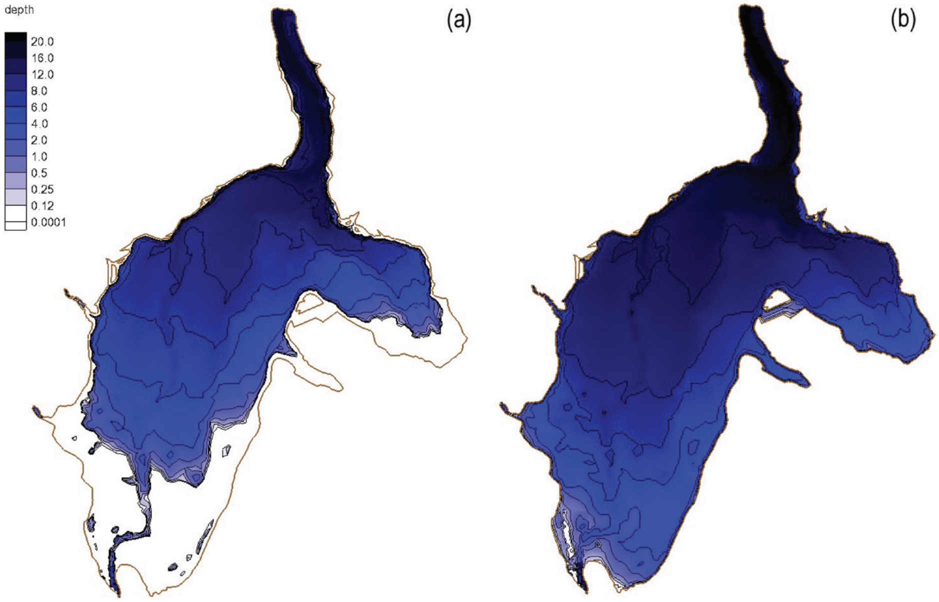

Figure 2. Water depth in the Tresna lake for the surface level 337.8 m a.s.l (a) and 342 m a.s.l (b)

The boundary conditions imposed on the model were that there was only one outflow from the reservoir located at the dam and only one inflow to the reservoir – the Soła river. While the first assumption is true, the second one is a simplification. There are additional inflows mainly at the eastern bank of the reservoir, yet they are much smaller than the Soła. Taking them into account may somewhat change the pattern of water currents especially in the eastern bay of the reservoir. But the analysis shown below focuses on the southern regions of the reservoir, ones close the Soła inlet, that cannot be affected by additional inflows located further to north and east.

All the remaining figures in this paper are flow maps. The vectors show the direction of the current at given points of the reservoir while the colors and lines indicate the flow intensity U measured in m^2/s as unitary discharge: water velocity multiplied by water depth:

$$U = vd \tag{5}$$

The scale on the *z* axis is always logarithmic with two contours per order of magnitude.

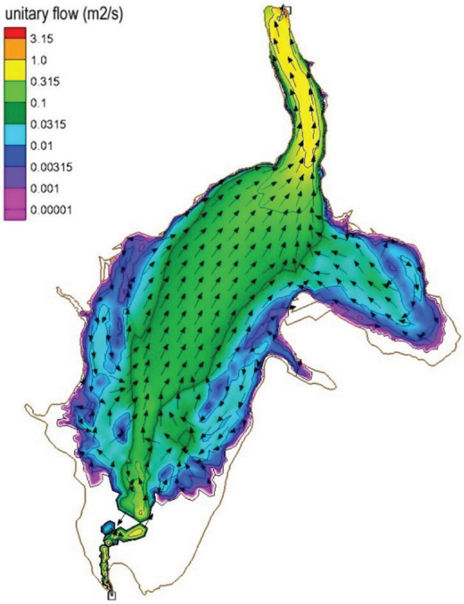

Figure 3. Flow map for 10 m^3/s inflow, 110 m^3/s outflow at 339 m a.s.l. water level

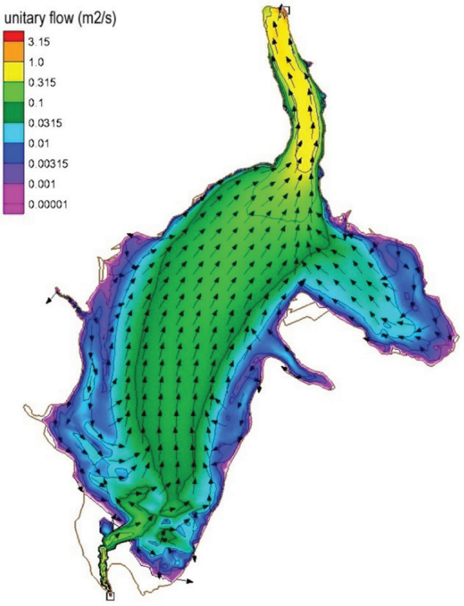

Figure 4. Flow map for 10 m^3/s inflow, 110 m^3/s outflow at 341 m a.s.l. water level

Figures 3 and 4 are made for drying the reservoir at the rate of 100 m^3/s (10 m^3/s inflow, 110m^3/s outflow) for two different transient water surface levels: 339 and 341 m a.s.l. Figures 5 and 6 are close-ups of the southern part of the reservoir for the above. The flow pattern observed is just a gravitational flow down the reservoir. It is noteworthy that for other drying rates only quantitative changes do appear, not any qualitative ones, i.e., the dry-up currents are faster or slower but they appear in the same places and they follow the same paths. Thus the appropriate pictures are very similar to the ones shown here. One should be aware here that all numerical models usually underestimate the flow rate in the current regions and overestimate it out of the current (Hachaj 2013). It is possible that in stagnant areas the real velocities are even smaller that the calculated ones.

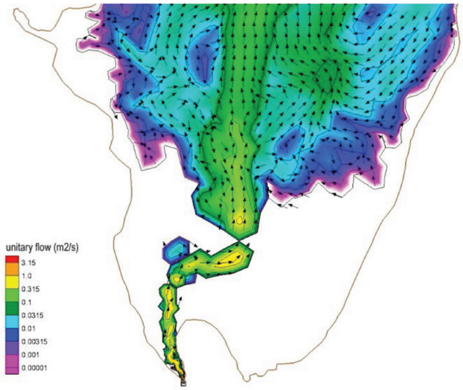

Figure 5. Flow map for 10 m^3/s inflow, 110 m^3/s outflow at 339 m a.s.l. (close-up of shallow regions)

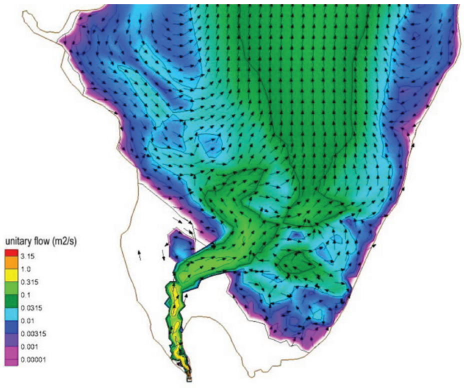

Figure 6. Flow map for 10 m^3/s inflow, 110 m^3/s outflow at 341 m a.s.l. (close-up of shallow regions)

Figures 7 and 8 are prepared for slow wetting of the bed at the same water levels as before (339 and 341 m a.s.l.) at the rate of 20 m^3/s (30 m^3/s inflow and 10 m^3/s outflow). Comparing these maps with figures 3 and 4 one can see that in the deeper parts of the reservoir the flow pattern is similar in both cases; these parts are deep enough not to be susceptible to the water level changes. The differences appear, of course, in the shallow regions that are being flooded now instead of dried. These areas deserve our further attention.

For better readability figures 9 and 10 show only the regions of the Soła inflow, and they should be compared with the corresponding figures 5 and 6. Figure 9 is prepared for water surface level of 339 m a.s.l. for four different flooding rates. They are accordingly:

(a) 20 m^3/s (30 m^3/s inflow and 10 m^3/s outflow), the same that figure 7 is made for;

(b) 40 m^3/s (50 m^3/s inflow and 10 m^3/s outflow);
(c) 100 m^3/s (110 m^3/s inflow and 10 m^3/s outflow);
(d) 200 m^3/s (210 m^3/s inflow and 10 m^3/s outflow).

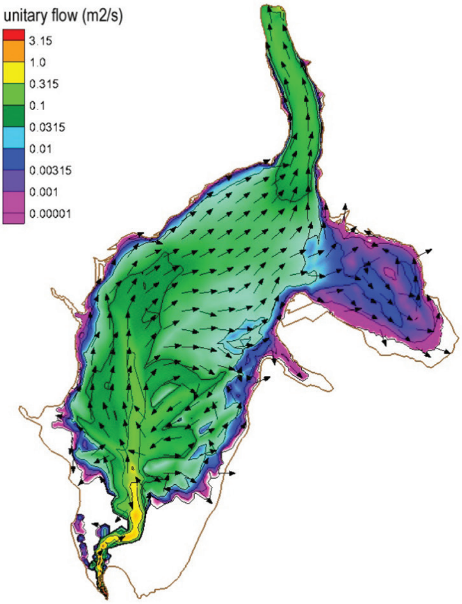

Figure 7. Flow map for 30 m^3/s inflow, 10 m^3/s outflow at 339 m a.s.l. water level

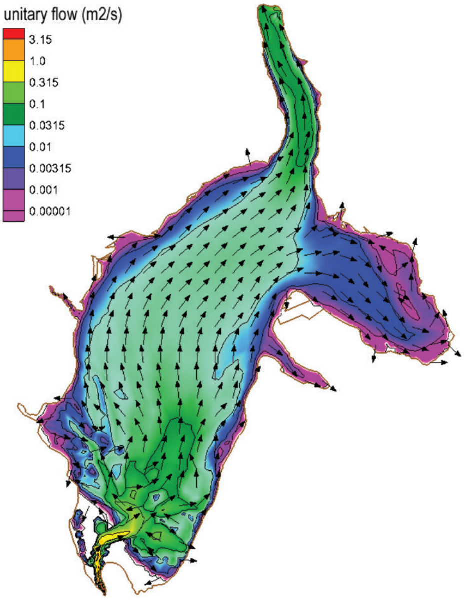

Figure 8. Flow map for 30 m^3/s inflow, 10 m^3/s outflow at 341 m a.s.l. water level

Figure 10 is made for the same discharge rates as above but for a higher water surface level of 341m a.s.l., thus Figure 10(a) is a close-up of the southern part of figure 8.

The vectors that indicate the local flow direction show that for small flooding discharge rates the shallow regions got wetted mostly in the opposite direction that they were dried when the water level was going down: they are being submerged from the deeper parts upwards. As the flooding discharge grows, the incoming water seeks new ways to get into the reservoir making new shallow streams on a previously dry bed. As the results with the growing flooding discharge rate more and more shallow regions get wetted from their upper parts downwards.

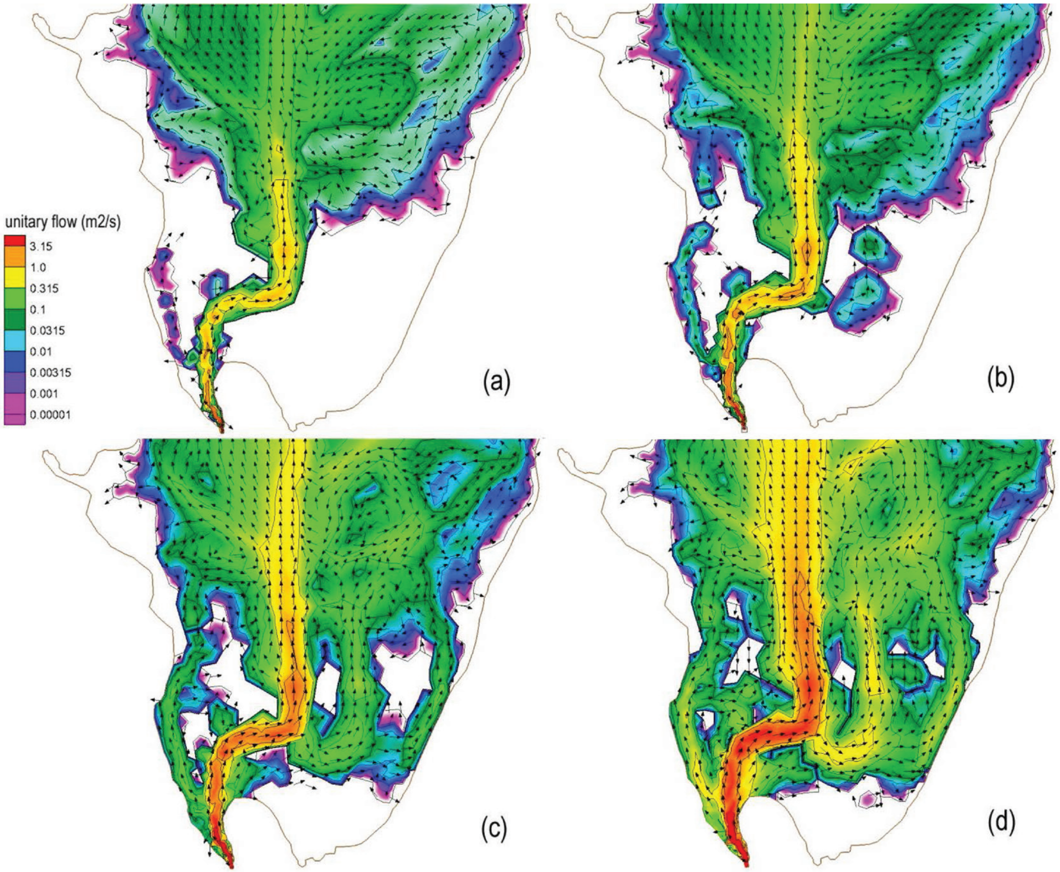

Figure 9. Unitary flow maps for transient water level 339 m a.s.l. and: 30 m^3/s inflow and 10 m^3/s outflow (a); 50 m^3/s inflow and 10 m^3/s outflow (b); 110 m^3/s inflow and 10 m^3/s outflow (c); 210 m^3/s inflow and 10 m^3/s outflow (d).

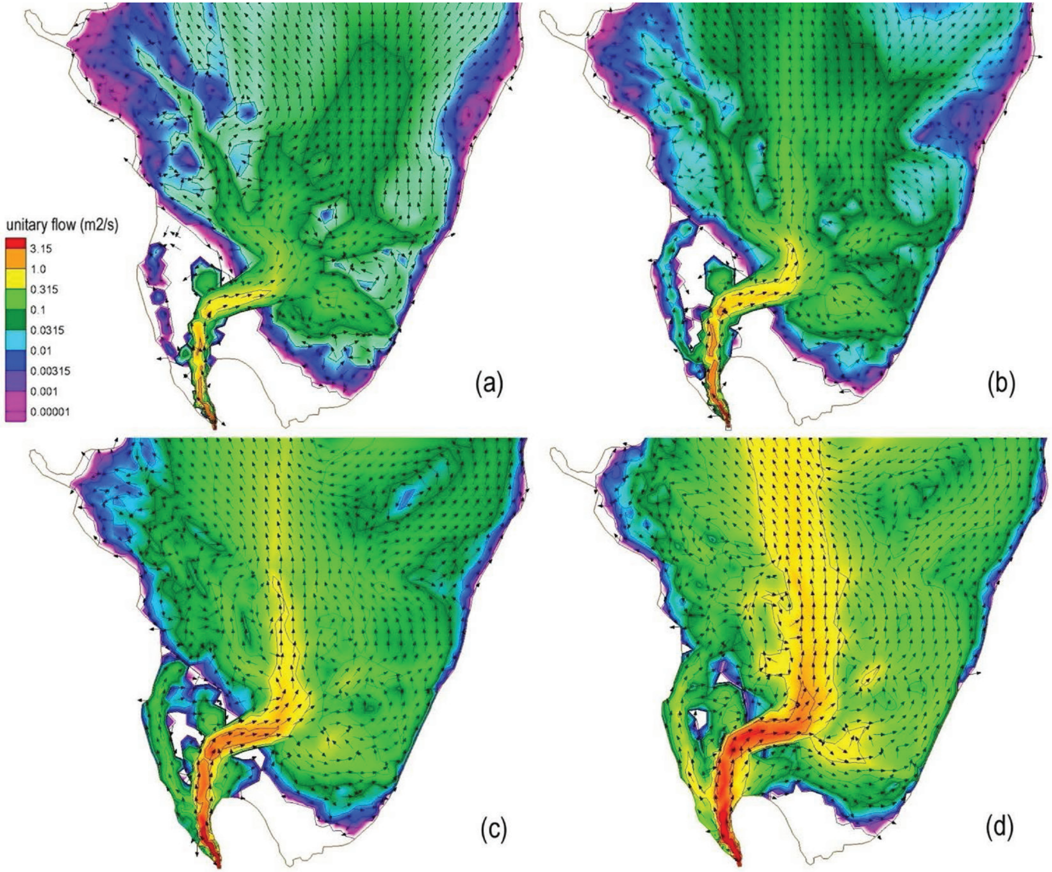

Figure 10. Unitary flow maps for transient water level 341 m a.s.l. and: 30 m^3/s inflow and 10 m^3/s outflow (a); 50 m^3/s inflow and 10 m^3/s outflow (b); 110 m^3/s inflow and 10 m^3/s outflow (c); 210 m^3/s inflow and 10 m^3/s outflow (d).

CONCLUSIONS

The simulations performed using the AdH model show that the pattern of the currents that flood dry areas of the reservoir bed indeed changes with the flooding discharge rate. These changes are not only quantitative (i.e., the currents are more intense) but also qualitative – entirely new currents appear for bigger discharge rates. On the other hand the flow pattern for drying the reservoir at different rates exhibit only quantitative changes.

For small flooding discharges the currents that wet the previously dry reservoir bed are similar to reversed currents that occur when the area is dried. As the result some amounts of water may move down the reservoir when the water level decreases and then up again when it increases – from one stagnant area to another. It means that it is not enough to lower the water level within the reservoir steering rules and then raise it again to be fully assured that actual water exchange happens in all the shallow stagnant areas. But for higher flooding discharges the currents are significantly different and the exchange of the reservoir water can be assured. This explains the paradox that the water quality in reservoirs some time after a flood can be better than before despite the fact that the flood water quality itself is poor.

In most cases to take a water quality advantage from a freshet one could only wait for high water to come. When it does it will flush the stagnant areas in the reservoir. But if reservoirs form a cascade, creating an artificial controlled freshet may be a considerable means of managing the water quality in the lower reservoirs. Unfortunately this method cannot be applied directly to the Tresna reservoir considered in this article, because it is the first reservoir within the Soła cascade. Yet controlled high discharges originating from Tresna could possibly be used to flush the two lower reservoirs down the Soła cascade.

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