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Influence of river routing methods on integrated catchment water quality modelling

A. Moreno-Rodenas[1*], V. Bellos[2,3], J. Langeveld[1] and F. Clemens[1]
[1] *Water Management Department, Technishe Universiteit Delft, The Netherlands*
[2] *CH2M, UK*
[3] *School of Rural and Surveying Engineering, National Technical University of Athens, Greece*
[*] *e-mail: a.m.morenorodenas@tudelft.nl*

Abstract: Compliance with the water framework directive (2000/60) in urbanised catchments requires effective water management strategies. Integrated catchment modelling (ICM) represents a key tool in the decision making process. ICM evaluate pollution dynamics by linking urban drainage infrastructure, wastewater treatment facilities and receiving water bodies. Within this set of linked sub-models the river model structure plays an important role. River hydraulic characteristics directly influence water quality processes (e.g. dilution of pollutant loads, pollutant residence time or reaeration dynamics). Several approaches exist in order to simulate flow routing phenomena. In general, these approaches can be categorised in hydraulic or hydrological routing methods. In this paper, we investigate the effect of river flow model structure on dissolved oxygen simulations. Specifically, three methods were compared: a simple hydrological storage method (SM), the fully mass-conservative Variable Parameter McCarthy-Muskingum Method (VPMM) and the solution of the full form of the one-dimensional Shallow Water Equations (1D-SWE). First, the comparison is performed in a simple benchmark case study in order to define the most sensitive parameters for the derived results. Second, the two hydrological methods are implemented in a real world case study for the Dommel catchment (the Netherlands), which is simulated using the software WEST for integrated urban water systems. Based on the results, it seems that the selection of river routing method can be a relevant factor, which should be carefully addressed.

Key words: Integrated Catchment Modelling, river routing, Muskingum method, water quality, WEST software

1. INTRODUCTION

Integrated Catchment Modelling (ICM) aims to simulate the links between several complex subsystems, such as urban drainage networks, rural hydrology, wastewater treatment plants (WWTP) and water bodies (Solvi, 2006). In the context of the ICM, both water quantity and quality parameters can be simulated. This paper discusses the influence of hydrological-simplified river routing methods in ICM structures for dissolved oxygen simulations. Two hydrological routing methods were tested: i) Storage Method (SM), in which the river is represented as a sequence of tanks-in-series and ii) Variable Parameter McCarthy-Muskingum Method (VPMM). The two routing schemes were implemented in a series of synthetic experiments, which represent different geometrical configurations of a river channel. Water quantity outputs (flow and water depth) were compared against the solution of the one-dimensional Shallow Water Equations (1D-SWE). This was considered as a validation process to describe the behaviour of the hydrological representation. Additionally, SM and VPMM methods were applied to a real case study: an urbanised catchment located in the river Dommel (the Netherlands). Model results were compared with observed data for both water quantity and quality.

2. RIVER ROUTING

2.1 Storage Method (SM)

The SM can be classified as a conceptual hydrological model. The river channel is discretised in a series of tanks with a given length and cross-section. The volume conservation equation is applied to every tank with specified stage-discharge relationship, which defines the outflow at any given time.

$$\frac{dV}{dt} = Q_{in} - Q_{out} \tag{1}$$

$$Q_{out} = \frac{1}{n} A R_H^{\frac{2}{3}} \sqrt{S} \tag{2}$$

where V is the i^{th} tank's volume state, Q_{in} is the incoming flow, n is the Manning's coefficient, A is the section's wet area, R_H is the hydraulic radius and S is the longitudinal slope.

2.2 Varying Parameters McCarthy Muskingum

The VPMM method is based on the Muskingum method (Cunge, 1969) and was developed by Perumal and Price (2013). The classical form of Muskingum method accepts two parameters (x and k), which are dependent on the input hydrograph conditions. Although the geometry of the channel is considered as stationary, the input hydrograph is not. Additionally, in real-world simulations, both water quantity and water quality simulations are often performed in long-time series. Therefore, they are subjected to several input hydrographs with different characteristics. In the context of the VPMM method, these two Muskingum parameters are automatically determined through an algorithm based on the geometry and the dynamics of the river. Additionally, VPMM compensates for the non-conservation of mass phenomena observed at the Muskingum scheme. A full description of the method can be found at Perumal and Price (2013).

3. SYNTHETIC EXPERIMENTS

Two synthetic experiments were generated in order to evaluate each model structure. Figure 1 shows the set-up of the hypothetical case study. The first experiment implemented the routing of an input hydrograph along a trapezoidal channel of 40 km with a steady slope (corresponding to sections S_1.1, S_1.2 and S_3 from Figure's 1 scheme). The solutions rendered by SM and VPMM were compared against the 1D-SWE results, derived from the well-known HEC-RAS hydraulic software (HEC, 2016).

The river section geometry was tested in 9 configurations (E1-E9 shown at Table 2). This served to test the behaviour of the hydrological model implementations against values of four parameters: the width of the channel (W), the embankment's slope (z), the Manning coefficient (n) and the channel slope (S). The second experiment was implemented in order to investigate the effect of rapidly varying lateral inflows (often seen in urban drainage discharges). In this experiment, the full set-up was used.

Input hydrographs were defined according to the Equation (3) (NERC, 1975). Table 1 summarises the parameters used in both of the experiments. The solution scheme was obtained at three space discretisation levels (500 m, 1000 m and 2000 m). Table 2 presents a quantitative assessment for the flow routing comparison with the 1D-SWE, whereas a graphical comparison is provided at Figure 2. It should be mentioned that the space step for the numerical solution through the HEC-RAS software was 100 m. Figure 3 depicts the results from Experiment 2. It is also noted that both methods (VPMM and SM) showed a mass conservative behaviour.

$$Q(t) = Q_{base} + \left(Q_{peak} - Q_{base}\right)\left[\frac{t}{t_{peak}} exp\left(1 - \frac{t}{t_{peak}}\right)\right]^{\beta} \tag{3}$$

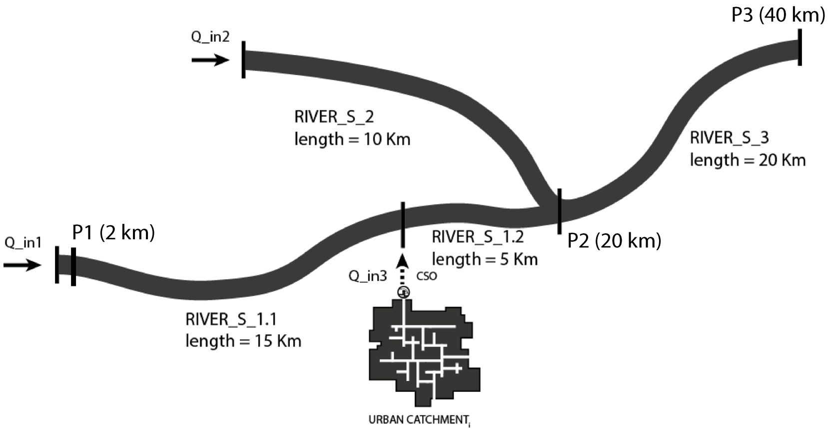

Figure 1. Synthetic set-up of the hypothetical case-study: Experiment 1 attends only to the main river section (S_1.1, S_1.2, S_3) and Experiment 2 is composed by the full set-up.

Table 1. Hydrograph shape parameters

	Q_{base}	Q_{peak}	t_{peak}	beta	dt(s)	Duration
Q_in1_**Experiment1**	5	15	48	10	3600	10 days
Q_in1_**Experiment2**	5	15	48	10	3600	10 days
Q_in2_**Experiment2**	2	8	35	10	3600	10 days
Q_in3_**Experiment2**	1	8	40	200	3600	10 days

Table 2. Nash-Sutcliffe efficiency (%) (NSE) and Root Mean Square Error (RMSE) for the selected parameter combinations and spatial discretisation (L).

Setup	Geometry				VPMM						SM					
	W	S	z	n	L=500 m		L=1000 m		L=2000 m		L=500 m		L=1000 m		L=2000 m	
	(m)	(%)	(-)	($s/m^{1/3}$)	NSE	RMSE	NSE	RMSE	NSE	RMSE	NSE	RMSE	NSE	RMSE	NSE	RMSE
E1	5	0.20	1	0.035	99.99	0.03	99.99	0.03	99.99	0.03	99.87	0.08	99.85	0.08	99.76	0.01
E2	10	0.20	1	0.035	99.99	0.06	99.99	0.06	99.98	0.06	99.52	0.15	99.50	0.15	99.35	0.17
E3	5	0.050	1	0.035	99.70	0.08	99.71	0.07	99.75	0.07	98.40	0.18	99.03	0.13	99.63	0.07
E4	10	0.050	1	0.035	99.76	0.08	99.79	0.07	99.85	0.06	98.90	0.17	99.34	0.13	99.52	0.12
E5	10	0.025	1	0.035	98.18	0.19	98.25	0.19	98.41	0.18	90.74	0.41	93.63	0.32	96.98	0.19
E6	10	0.050	5	0.035	99.79	0.08	99.82	0.08	99.88	0.07	98.91	0.16	99.55	0.11	99.41	0.16
E7	10	0.050	1	0.040	99.63	0.09	99.67	0.08	99.75	0.07	98.53	0.19	99.19	0.14	99.51	0.11
E8	10	0.050	1	0.060	99.00	0.15	99.08	0.14	99.25	0.12	94.69	0.32	97.27	0.21	99.13	0.10
E9	10	0.050	1	0.080	98.27	0.18	98.38	0.17	98.63	0.16	88.62	0.43	94.11	0.29	98.39	0.11

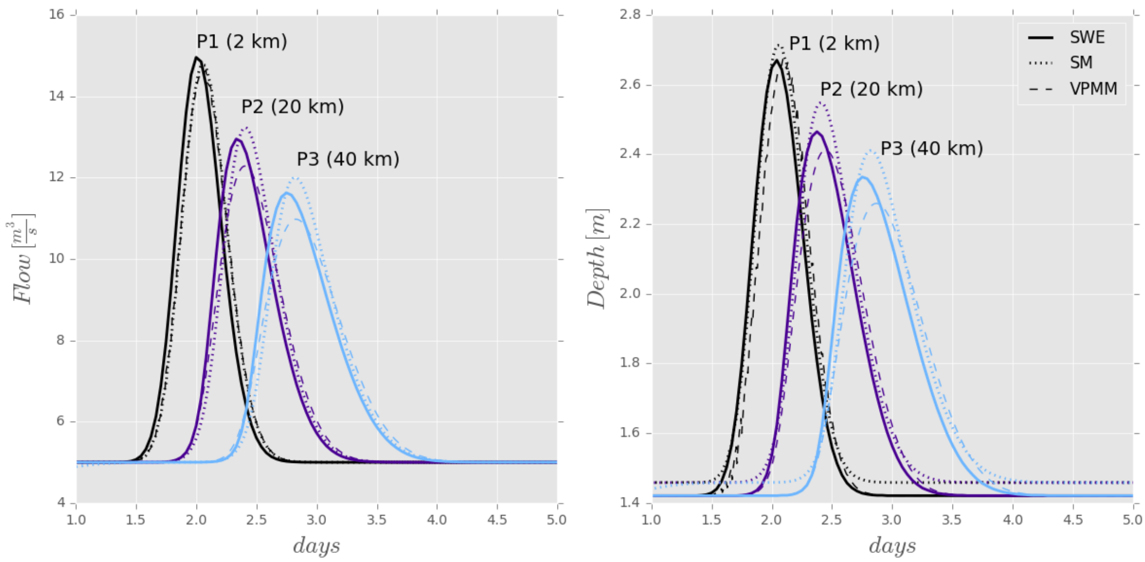

Figure 2. Comparison of flow and depth simulated at several locations along the channel (distances from channel's upstream boundary). Parameter combination E9 with 1000 m spatial discretization.

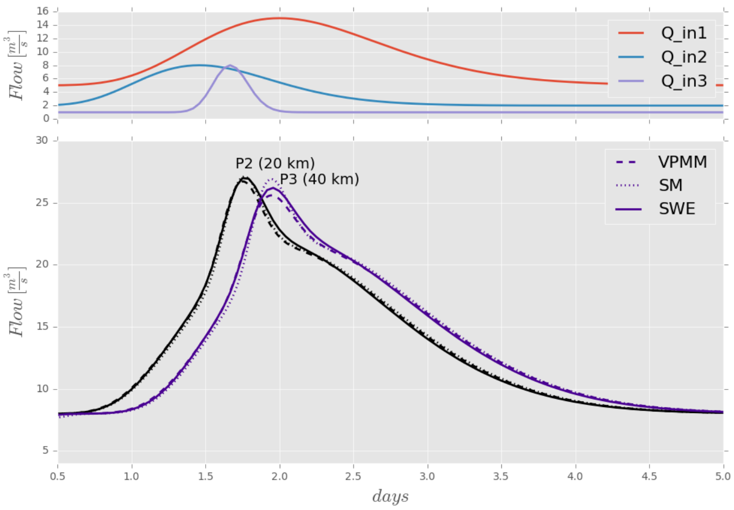

Figure 3. Routing in Experiment 2. Above is shown the 3 input hydrographs. Bellow the flow propagated at 2 sections of the river (corresponding to P2 and P3).

4. DOMMEL CATCHMENT

The performance of SM and VPMM methods was further tested in a real-world case study: the river Dommel (the Netherlands). This river stretch receives the discharge of about 200 combined sewer overflow (CSO) structures and of a wastewater treatment plant (WWTP) of 750,000 p.e, detailed information can be found at Langeveld et al. (2013). The simulator was composed by ~130 km of river tributaries represented by VPMM and SM routing schemes. Each section was conceptualised as tank of 800 m to 2000 m of length, with averaged section geometry from field measurements. Lateral inflows were characterised by monitoring data from CSOs and from the effluent of the WWTP. River base-flow from rural connected catchments was estimated from hydrological modelling.

The biochemical processes included in the model involved: degradation of biodegradable organic matter, nitrification, respiration from macrophytes, sedimentation of particulate organic matter and sediment oxygen consumption. The two methods (VPMM and SM) were implemented in the modelling software WEST (MIKE-DHI). The numerical solver used was a stiff scheme CVODE on a Tornado kernel (Hindmarsh and Petzold, 1995; Claeys et al., 2007) this allowed to perform efficient long-term simulations in which the dynamic state is continuously varying.

A first qualitative manual fitting was performed followed by a global optimization of Nash-Sutcliffe efficiency for flow simulated-monitored data. The parameters used were Manning's coefficient (n=0.078 s/m$^{1/3}$ for the SM method, and n=0.081 s/m$^{1/3}$ for the VPMM method) along with a re-scaling factor for the rural input hydrographs (which SM k_f=0.92 for the SM method and k_f=0.68 for the VPMM method). The later was necessary for fitting the base flow level at the river.

Literature parameter values where used to describe the dissolved oxygen processes. Followed by a global optimization of calibration parameters to fit in dissolved oxygen dynamics in detail. Figure 4 provides a graphic description of the simulated-measured comparison.

5. DISCUSSION

The river Dommel is characterised by low slopes and flow velocities. As far as the magnitude of the flow is concerned, the Dommel can be characterised as a medium river (4-20 m^3/s). The river flow is highly influenced by the connected urban areas and the WWTP effluent. This generates rapidly varying flows for a low-sloped river channel, which is characterized by highly diffusive flow patterns. Muskingum routing methods are known for their ability to simulate the diffusive term of wave propagation. In this study we compared the performance of a simplistic routing process (SM) with a more complex hydrological model structure (VPMM). The comparison was performed through a series of synthetic experiments, and showed low discrepancies in a range of geometries. However, as it can be seen at Table 2, SM's performance rapidly decreased with the defined tank length for highly rough sections (E8 and E9). This should be taken into account during the process of model design.

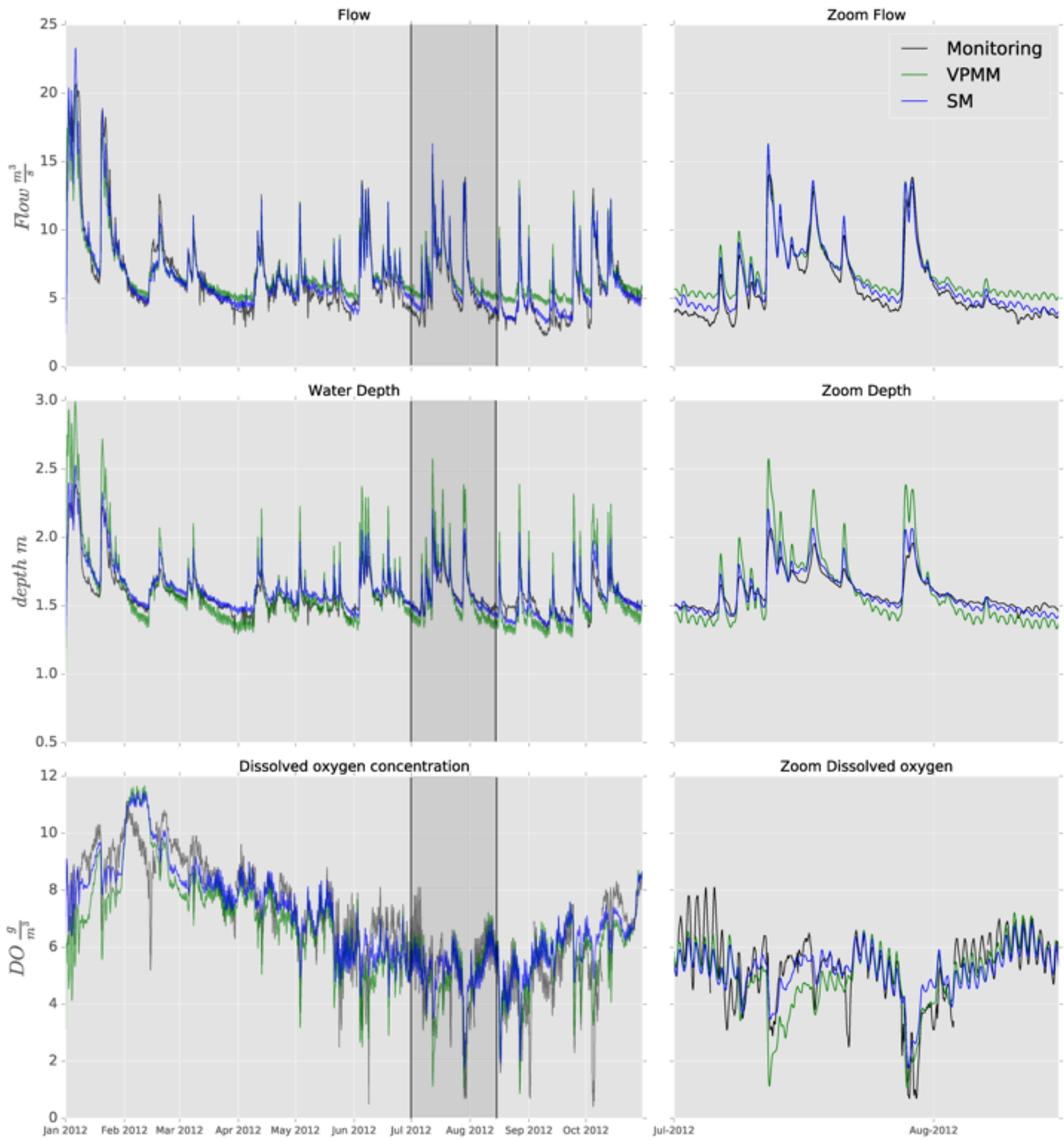

Figure 4. Comparison of monitoring data, VPMM and SM simulations for flow, water depth and dissolved oxygen at the outlet of the Dommel catchment (~17 km downstream of the WWTP). In the left side: the dynamics for January to October of 2012. In the right side: a detail for two events between the 01-Jul-2012 and the 15-Aug-2012.

The comparison of the routing methods for the real case study showed an equivalent performance when matching flow peaks. However, VPMM produced a systematic overestimation of base-flow. VPMM produced also, a higher fluctuation of averaged hydraulic depth, which in turns affects water quality processes (as reaeration potential or sedimentation). The main difference between the two model structures was apparent in the fitting of the reaeration coefficient (which relates section's depth-velocity with a reaeration potential) and of the degradation constant for fast biodegradable matter. In this case, the increase of complexity in the model structure (represented by the VPMM) didn't lead to a better performance than a simpler storage-discharge relationship.

This misfit is probably is due to the presence of structures in the river body, which are not accounted in the model structure. The VPMM implementation for the Dommel river rendered three time slower simulations that the corresponding with the SM method. Additionally, certain combination of parameter-hydrograph input generates numerical instabilities, which can hamper the use of automated calibration or parameter sampling schemes.

6. CONCLUSION

In this paper, the influence of the river routing method at the water quality parameters is examined, using both a synthetic experimental set-up and a real-world case study.

As far as the SM method is concerned, although its simplicity, the ability to reproduce diffusion is highly depended on the spatial discretisation used for the representation of the computational domain. This issue should be appropriately addressed in the model design process.

On the other hand, the VPMM method does not depend on the space step and can sufficiently reproduce the diffusive phenomena of the flow. However, in real world case studies in which flow is characterised by great complexity, human structures and low flow velocities, the VPMM method does not perform better, even though the method is more physically consistent than the SM method.

It seems that the hydrological routing method used in conceptual integrated catchment structures can have an impact in the flow routing pattern, which is transferred to dissolved oxygen patterns. Therefor the selection of model structure should be carefully assessed and tested in a case study basis.

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