Numerical modelling of the effects of change in river channel morphology on flooding frequency in the Dijle valley, Belgium, using TELEMAC-2D modelling system

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***Abstract*— Climate and land use changes can have an important impact on the channel discharge regime and consequential river morphology. As a consequence, flood frequency and flood depth in the river valley will be impacted. This relationship remains, however, poorly understood for many rivers. Nevertheless, such information is needed to understand ecological and hydrological processes in river channels and adjoining floodplains. It requires information on the complex interlinkage between channel morphology and discharge as well as on flood frequency and flood depth at high spatio-temporal resolutions. This study uses the TELEMAC-2D model in the Dijle valley, Belgium. Due to substantial urbanization in the Dijle catchment over the last few decades, discharge peaks in the river channel have continuously been increasing. The TELEMAC-2D model shows, however, that widening and deepening of the Dijle river channel has been reducing the flood frequency, flooding water depth and area in the valley.**

I. INTRODUCTION

Flood frequency and duration can affect groundwater level and ecology in floodplains. On the other side, flood frequency and duration is influenced by climate change, hydraulic structures or changes in river and floodplain morphology. Climate change is contributing to more extreme hydrological events, which are also triggered by long lasting or heavy floods [1]. Hydraulic structures are normally used to mitigate downstream flooding by creating damming effect, however, some hydraulic structures such as ramps or bridges can also create obstacles for river flow and can cause upstream flooding by changing river morphology alone or together with climate change [2]. To deal with sediment deficiency downstream due to hydraulic structures, normally sediments are added artificially. In the absence of hydraulic structures, excessive sediments are dragged out. Poorly managed sediment addition or dredging can change riverbed morphology, which subsequently can affect flood frequency, water depth, and flood duration. This can also further affect groundwater levels and ecological processes in the floodplain.

For example under the effect of climate change, urbanization in the catchment together with artificial removal of sediments, channel morphology within the main Dijle river channel (located in central Belgium) has changed over the last decades [3]. The modified river channel may accommodate (without bank-full discharges) high flows which consequently can reduce flooding frequencies and increases hyporheic groundwater loss into the channel. This phenomenon can be more pronounced during low discharges with implications for the ecological state of the riparian zone and surrounding floodplain. Although the effect of land-cover and land-use change on river hydrology has been studied [4, 5], no study has been done to evaluate the effect of changing river morphology on the flooding frequencies and flooding areas in the valley which is also needed in groundwater and ecological modelling.

[3] made use of topographic surveys of the river channel in 1969 and compared it to LiDAR elevation data (collected from 2001 to 2003) to compute changes in river channel morphology. They found that approximately 9,000 m^3 of sediments have been eroded from a 10 km river reach upstream of Leuven (Fig. 1). Similarly, [6] applied the Pettitt test [7] to detect the qualitative and quantitative changes in discharge series collected from 1974 to 2002 at Sint-Joris-Weert and found a statistically significant increasing trends in peak discharges and their frequencies. However, there is a research gap in literature with respect to impact of the rate of increase in peak discharges and incising on the flooding frequencies: either they are balancing each other or they have dis-proportional relationship.

Therefore, to quantify the combined effect of changes in discharge and river morphology, we applied the TELEMAC-2D model as this tool not only provides high spatio-temporal resolution information about water depths, velocities and bank-full discharges, but also that its source code can be modified according to local conditions [8]. The modelling environment can also be launched on parallel processing which significantly reduces computation time. Therefore, we applied the TELEMAC 2-D hydrodynamic model to a relatively naturally maintained area between Korbeek Dijle and Sint-Joris-Weert (Fig. 1). We used simulated discharges as upstream boundary conditions which were calculated using the STREAM hydrological model [9]. The model can simulate the discharge of rivers based on input data of climate (precipitation and temperature), soil and land-use and has also previously been applied on the Dijle river [4]. The STREAM model also provides us with an opportunity to quantify the flooding frequencies on a larger time scale by providing discharges of missing periods.

II. STUDY AREA AND DATA

The Dijle river is a typical meandering lowland stream, located at the northern side of the Western European loess belt in central Belgium (Fig. 1). The main river channel is well connected with a drainage network in the floodplains that facilitates water flows during raising or lowering of flooding water depth. The river reach between Sint-Joris-Weert and Korbeek Dijle has a length of 6 km with an average slope of 0.0457 m/100 m and is a relative naturally maintained area where four tributaries join the main river channel. The cumulative discharge of these tributaries is approximately 12.3% of the total river discharge. Since 1973 and 1982 daily water levels at Sint-Joris-Weert and Korbeek Dijle have been recorded and are freely available on the website of the Flemish Environmental Agency (VMM): waterinfo.be. Discharge at Sint-Joris-Weert can be calculated using a stage-discharge rating curve developed by the Flemish government. Discharges of the tributaries have not been measured, however, after estimating their discharges, a stage-discharge (HQ) rating curve for Korbeek Dijle can also be developed. To obtain discharge time series for missing days, the STREAM model is used. Like other Belgian rivers, the Dijle has peak flows during winter months which can exceed 26 m^3/s. The gauge station at Sint-Joris-Weert can measure discharges up-to maximum 29.38 m.a.s.l. Even though the river discharge has been showing an increasing trend in both high frequency and peak discharge magnitude [4, 6].

Bathymetric surveys of the Dijle river from Grez-Doiceau to Heverlee have been conducted in 1969 and 1999 at an average longitudinal sampling interval of 21 m. The sampling interval between cross sections is lower where the river curves or is strongly meandering and vice versa. Surveys conducted in 1999 and 2018 are projected in the Belgian Lambert 72 coordinate system, while the non-digitalized survey in 1969 can be converted into the same coordinate system using geospatial software such as ArcGIS or MATLAB or python, etc. A very detailed 1.0 m x 1.0 m resolution light detection and ranging (LiDAR) surface elevation survey of the whole Dijle floodplain conducted in 2014 is also available. More details about LiDAR surveys and their application at the Dijle river can be found in [3].

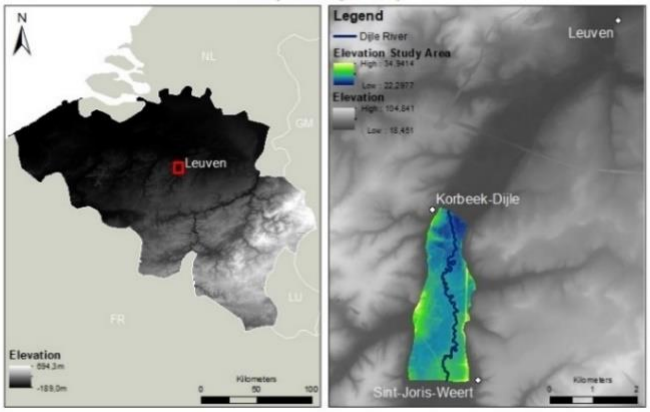

Fig. 1: Location of the study area within the Dijle floodplain (right) and within Belgium (left).

III. METHODS

There are strong evidences that together with incising/widening of the channel, discharges in the Dijle river channel have also been increasing [3, 6].However, there remains a research gap with respect to the impact of increase in discharge on the different types of channel geometries in our study area. Therefore we simulated four different geometries using the STREAM model's estimated discharges at Sint-Joris-Weert (SW), at four tributaries, and at Korbeek Dijle (KD) as shown in Fig. 2. Although measured discharges at Sint-Joris-Weert and water levels at Korbeek Dijle are available since 1973 and 1982, respectively, (waterinfo.be), we want to analyze the flooding frequency over a larger time span. The STREAM model provides us an opportunity to quantify the flooding frequencies on a larger time scale by providing the discharges of missing period, i.e. before 1973 or 1982. The STREAM model simulate the discharges record using climate (precipitation and temperature), soil and land-use (Fig. 2) and has also previously been applied on the Dijle river [4]. In the modelling process we use discharges at Sint-Joris-Weert and at four tributaries as upstream boundary conditions while using stage-discharge rating curve (QH) calculated in eq. (3) we converted discharge at Korbeek Dijle into water levels and used as downstream boundary conditions (Fig. 2)

The river surveys of 1969 and 1999 were used to develop two meshes for calculating bank-full discharges. The bank-full discharges were used as boundary conditions for the floodplain meshes developed using the river bathymetric surveys and the 2014 LiDAR survey. Since no major land use changes took place in the floodplain itself, [10], we used the 2014 survey for the area outside of the main river channel for both the 1969 and 1999 periods. Similarly, a higher resolution (1 m x 1 m) LiDAR survey also provides us with an opportunity to precisely represent the small channels and ditches within our floodplain. These small anthropogenic channels act as drainage networks to help with spreading of bank-full discharges and draining water during the lowering of water level in the river channel. We have no indication that these drainage channels have been adjusted in the past decades.

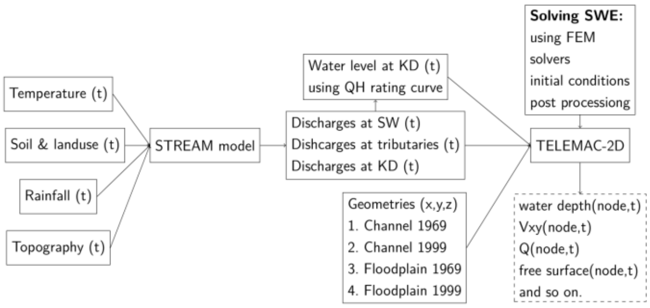

Fig. 2: Schematic diagram of the modelling process. The STREAM model predicts discharges and water levels from 1955 to 2018 using environmental input data, whereas, TELEMAC-2D outputs flooding frequency and flooding water depths for different morphologies of Dijle river channel and floodplain.

Using USBR guidelines, we specified a higher Manning roughness (0.05) for the whole floodplain as it has vegetation [11]. For the main river channel and all other draining networks, we use a Manning coefficient equal to 0.028. The river channel has vegetative banks that acts to increase the lateral roughness; therefore, we used a higher Manning value of 0.032 for both left and right river banks. To obtain discharge boundary conditions before 1973 we use a well calibrated STREAM model. The calibration period was from 1973 to 2018 with a Nash-Sutcliffe model efficiency of 0.35 for the daily discharges and R^2 was at 0.51 for the monthly discharges.

To simulate flooding, we used TELEMC-2D model on the supercomputing machines of the Vlaams Supercomputer Centrum (VSC). The TELEMAC model is compiled on the VSC cluster (Leuven site) using the Intel compiler version 18.0.1 and CentOS 7.7 operating system. Our simulations are launched on compute nodes with Intel SkyLake or CascadeLake processors. The explicit MPI launching command that is used in the systel.cfg file is: mpi_cmdexec: mpirun --hostfile $PBS_NODEFILE -np <ncsize> <exename>, where, at runtime, the $PBS_NODEFILE environment variable expands to the list of all hostnames and cores used to run the compute job.

As our study objective was to analyse the impact of geomorphological changes on flooding, we used the constant eddy viscosity model in our computations which can provide us stable solutions at a lower computational cost. To avoid negative depths in our study domain we specified the minimum value of water depth equal to 1.0 cm. To efficiently utilize memory and computational time, we saved our results after each 12 hours using variable time step option. We fix courant number equal to 0.9 while using upwind scheme with the modified SUPG method [12]. The detail of computation grid, boundary conditions, model setup, and modelling parameters is given below.

A. Construction of channel and floodplain meshes

Initially we delineated the main river and drainage channels in the floodplain using the official hydrological atlas of Flanders. To precisely represent the river channel and its connectivity with the drainage channels, we constructed meshes with resolution ranging from 0.5 to 10.0 m. Mesh nodes in 0.5 m resolution are four times more than 1.5 m, however, there is a slight different in their fitness with the measured elevation points (Fig. 3). At both resolutions the drainage channels are better represented, therefore, we selected a 1.5 m mesh resolution. For the entire floodplain (excluding drainage channels) we also constructed meshes with resolution ranging from 1.0 to 20.0 m, however, the floodplain was more precisely represented with 5.0 m resolution. Although, BlueKenue is an efficient tool for creating selafin format files for TELEMAC-2D computation, its processing time for finalizing sub-mesh and island edges connectivity was approximately 3 to 5 hours for our study area. Details of our all four computational grids is tabulated in Table 1.

TABLE 1: INFORMATION ABOUT CHANNEL AND FLOODPLAIN MESHES

Computational grids	**No of nodes**	**Maximum elevation (m)**	**Area (10^6 m^2)**
Channel morphology in 1969	1,13,116	35.50	0.22
Channel morphology in 1999	1,12,764	35.48	0.22
Floodplain morphology in 1969	4,48,580	31.45	4.16
Floodplain morphology in 1999	4,52,056	31.29	4.16

B. Initial and boundary conditions

As an initial condition we filled all four of our computational domains slightly higher (0.1 m) then their maximum bottom level (Table 1), so that the models can attain stable conditions at the beginning. The daily discharges obtained using the STREAM model at Sint-Joris-Weert and four tributaries were applied as upstream boundary conditions while the daily water levels were kept as the downstream boundary condition at Korbeek Dijle. The modelling flow chart used in the study is shown in Fig. 2. The climate data (mean daily temperature and total daily precipitation) used in the STREAM model was collected at six gauging stations, Ukkel, Zaventem, Beauvechain, Chastre, Marbais and Braine L'alleud, all located around the study area (Fig. 4). The soil input data is derived from the Belgian soil map along with the European dataset "Soil Hydrogrids" for the hydrological properties of the soil such as soil moisture storage. The land use input data is obtained from the European scale CORINE-land cover map from 1990 [13]. The land elevation within the floodplain (from Sint-Joris-Weert to Korbeek Dijle (Fig. 1)) has barely been changed from 1990 until 2008 [10, 13]. This means that during the last 30 years the elevation would have a negligible impact on changes in flood frequencies in the study area.

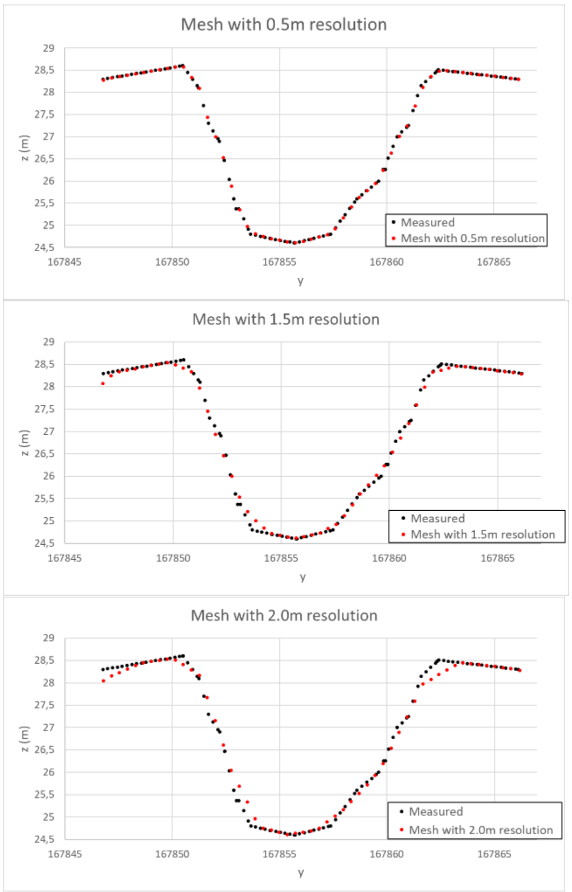

Fig. 3: Measured and modelled river channel cross sections, with a mesh resolution of 0.5 (R^2=0.999), 1.5 (R^2=0.994) , and 2 (R^2=0.990); for the Dijle river channel between Sint-Joris-Weert and Korbeek-Dijle.

Discharges at Sint-Joris-Weert are calculated using the following stage-discharge rating curves developed by the Flemish Environmental Agency (VMM).:

Until 1/1/1985: $Q_{SW} = 9.5 * (H_{SW} - 27.21)\ for\ H_{SW} < 27.21$ (1)

From 2/1/1985: $Q_{SW} = 10.97 * (H_{SW} - 27.0)\ for\ H_{SW} < 27.0$ (2)

whereas Q_{sw} and H_{sw} are discharges (m^3/s) and water levels (m) at Sint-Joris-Weert, respectively. Next, a relation between the water level at the gauging stations at Sint-Joris-Weert (H_{SW}) and Korbeek Dijle (H_{KD}) could be fitted, which has an R^2=0.77:

$$H_{KD} = 0.975 * H_{SW}{}^{0.973} \quad (3)$$

This formula can be used to calculate the water level at Korbeek-Dijle for missing days (between 1973 and 1982) and for a longer time span (from 1953). Although the gauge station at Korbeek Dijle does not record water levels above 26.28 m.a.s.l., hypothetically we extrapolated it with eq. (3) for 42 discharge events above 27.9 m^3/s in our time series (Fig. 5). Using formula (3) we also defined downstream boundary conditions while our upstream boundary conditions were the STREAM estimated discharges from 1953 to 2018 (Fig. 5) . The STREAM model estimated maximum and minimum discharge of 140.21 and 1.73 m^3/s at Sint-Joris-Weert, respectively. The maximum and minimum water levels at Korbeek Dijle were 24.22 and 35.11 m, respectively (Fig. 5). As we are simulating flooding events, we used discharges slightly above mean estimated discharge at Korbeek Dijle, i.e. 7.0 m^3/s which corresponds to 1,028 days or 4.3% of the total time series. In both channel meshes, 36 processors of VSC machines can simulate approximately 70 days in one day while in floodplain meshes 180 processors can simulate approximately 18 days in one day.

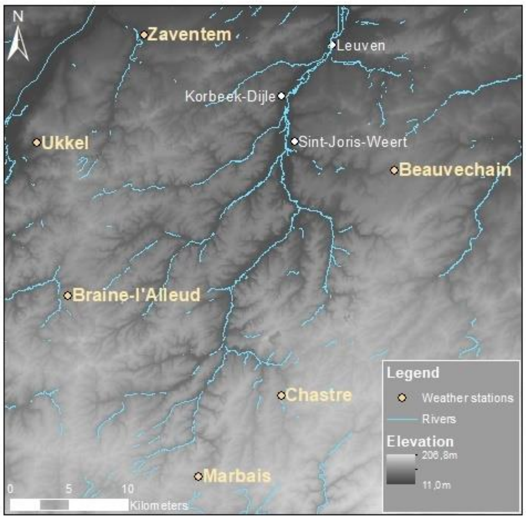

Fig. 4: Location of the rain gauge stations nearby the study area used in STREAM model for discharge calculations. For location, see Fig. 1.

IV. RESULTS AND DISCUSSION

With the 1969 channel' geometry a 7.02 m^3/s reached the bank-full level while in 1999 a 9.54 m^3/s discharge was required. Therefore, with the 1999 geometry we observed only 24 events of bank-full discharges compared to 173 events in 1969' geometry indicating that more than 80% reductions in the occurrences of bank-full discharges over 30 years.

Using the 1969 channel bank-full discharges as boundary conditions for both the 1969 and the 1999 floodplain meshes, the TELEMAC model shows that the average flooding area and water depth remains low in the 1999's floodplain mesh (Fig. 6). For the highest hypothetical exceptional flood event (142.42 m^3/s at Korbeek Dijle- (Fig. 5)) mean water level in the 1969 floodplain was approximately at 37.5 m.a.s.l. while it is simulated 1.5 m lower for the 1999 floodplain. Similarly in all flooding events, the average flooding water depth was also approximately 0.5 to 1.0 m lower in 1999 floodplain. For example on 28th August 1996 at discharge of approximately 90 m^3/s and water level of 28.0 m at Korbeek Dijle, the flood water depth at cross section AA in 1999's river mesh was 8.0 cm lower compared to the river form in 1969 (Fig. 5 and Fig. 7 to Fig. 9). Similarly, the area under flood was also approximately 10 to 20 % less in 1999 river mesh. Comparing both river geometries at cross section AA shows that the riverbed elevation in 1999 floodplain was 24 cm lower compared to 1969. Therefore, it can accommodate higher discharges in the river channel. Comparison of both river channel beds shows that widening and deepening of the river channel from 1969 to 1999 resulted in a total increase of channel volume for the 6 km reach amounting to 52,236 m^3 (Fig. 7 to Fig. 9). This volume corresponds to an average channel erosion rate of 146.6 g/s since 1969. Although the average channel erosion rate is very low compared to an average suspended sediment load (approximately 5.50 kg/s) at Korbeek Dijle calculated by [14] (from 1998 to 2000), it nevertheless has increased the threshold of over-bank discharges from 7.02 m^3/s to 9.54 m^3/s.

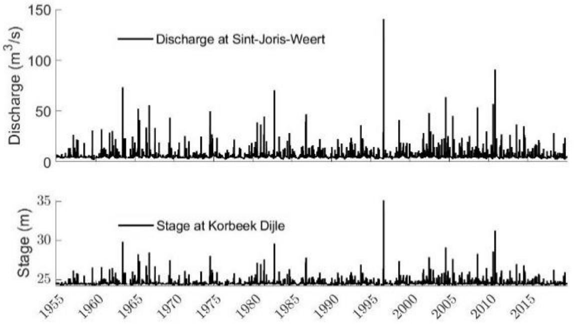

Fig. 5: Discharge data at Sint-Joris-Weert and stage data at Korbeek-Dijle, for the period 1955 -2018

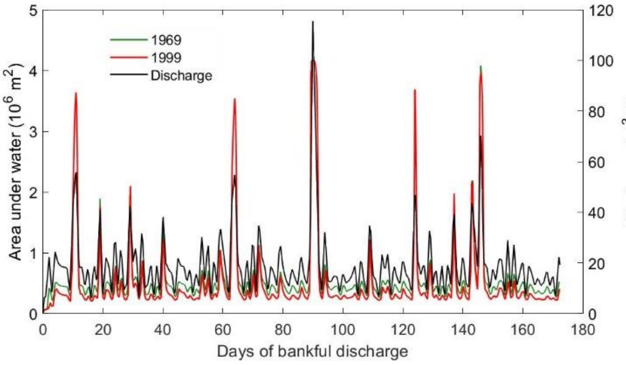

Fig. 6: Floodplain area under water while applying 1969' channel bank-full discharges.

On the same boundary conditions (Fig. 6). our modelling results shows that an average 2.0 m decrease in riverbed elevation may reduce the flooding frequencies up to 10 to 20% in the Dijle Valley (Fig. 10). Similarly the lower riverbed elevation can reduce the flooding water depth up to 0.5 to 1.0 m in the floodplain. However, the river channel has also been changing, due to change in discharges and sediment supply, over the time which has not been included in the modelling process. Additionally, the hydrodynamic calculations, without a hydrodynamic calibration, are very much simplified and can only be used for evaluation purpose of different topographic scenario before moving to morphodynamic modelling. Inclusion of morphodynamic modelling can precisely estimate the rate of change in flooding frequencies with respect to change in discharges and river morphology.

Nevertheless the deeper river channel which is well connected with huge drainage network can also increase groundwater loss into the channel. Most of the studies relate groundwater depletion with urbanization, land use change [15] However, less ground water recharge can also be relevant to decrease flooding in the valley. Moreover, entry of groundwater though the drainage channels and riverbanks can not only effect ecology (by depleting groundwater level) but can also increase pore water pressure which may also have been contributing in bank erosion. Therefore, the current findings can aid our understanding how a complex web of controlling factors such as the frequency of peak discharges, urbanization, land-use/cover, and changes in catchment surface sediment supply are affecting channel morphology which are consequently altering flooding and perhaps the groundwater dynamics in the floodplain. Similarly, our findings can help to understand the impact of channel morphological changes on flooding and its impact on groundwater and ecology in the valley.

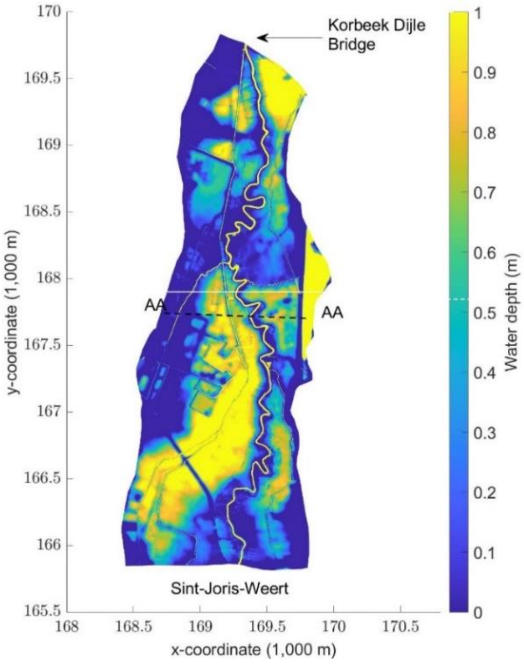

Fig. 7: Flooding on 28 August 1996 in floodplain of 1969. Transect AA shows location of Fig. 9.

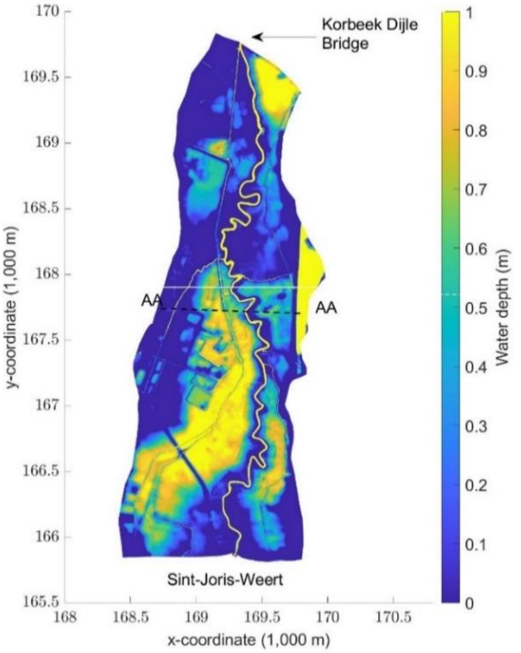

Fig. 8: Flooding on 28 August 1996 in floodplain of 1999. Transect AA shows location of Fig. 9.

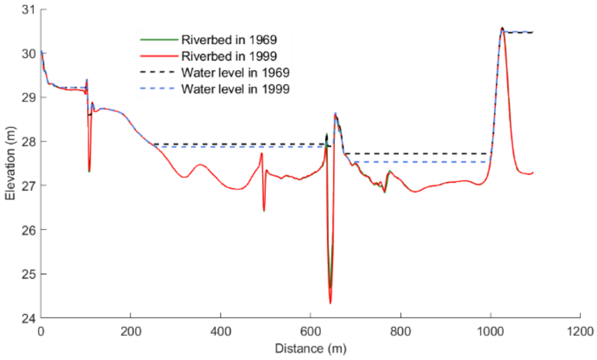

Fig. 9: Riverbed and water level in 1969 and 1999 for a transect perpendicular on the Dijle river. For location, see Fig 7 and Fig. 8.

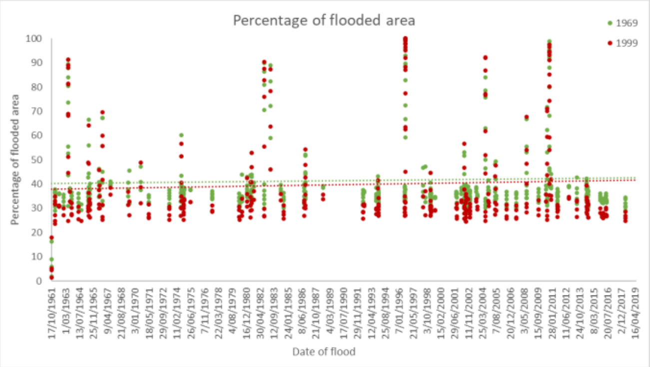

Fig. 10: Percentage of floodplain area flooded in 1969 and 1999 floodplain meshes showing low flooding in 1999 due to incising and widening of the river channel.

V. CONCLUSION

The TELEMAC-MASCARET modelling environment is a very power tool to analyse flooding problems. High spatio-temporal resolution outputs of water depth, velocity, and discharge at any desired location can provide an opportunity for researchers to not only analyse flooding in a more detailed way but TELEMAC's output can also be used as an input in groundwater or ecological models. The finding that flooding frequency and flooding water depths have been decreasing since 1969 due to widening and deepening of the Dijle river channel contrast with the observed increase in high discharge events. Thus, our modelling results show that local channel morphological changes have a stronger impact on local flood risk than changes in discharge. Although together with incising, channel discharge has been increasing, it is still unclear whether sediment supply was also influenced and played a role in incising and widening of the river channel.

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