Science of the Total Environment 647 (2019) 814–826

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

An integrated approach for investigating the correlation between floods and river morphology: A case study of the Saalach River, Germany

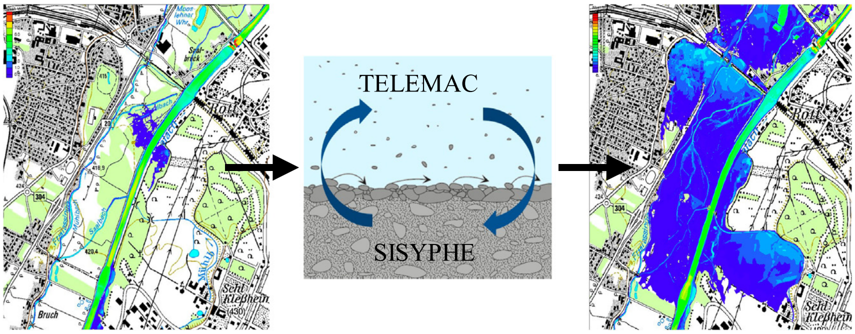
Markus Reisenbüchler [a,*], Minh Duc Bui [a], Daniel Skublics [b], Peter Rutschmann [a]

[a] Technical University of Munich, Arcisstrasse 21, 80333 Munich, Germany
[b] Wasserwirtschaftamt Rosenheim, Königstrasse 19, 83022 Rosenheim, Germany

HIGHLIGHTS

- Morphological developments and activities influence inundation.
- River engineering structures and straightening alter the morphology of the river.
- Stationary hydrodynamic models underestimate the flood risk.
- The developed integrative model represents flood events more accurate and realistic.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 18 December 2017
Received in revised form 24 July 2018
Accepted 2 August 2018
Available online 04 August 2018

Keywords:
Saalach
Telemac
Sisyphe
Numerical modeling
Flood
Morphology

ABSTRACT

Man-made structures in the Saalach River have changed the hydromorphological characteristics of the river regime. In some river reaches, the Saalach has lost the high morphological versatility and high variation in sediment transport characteristic of a mountain river. Among the negative effects, an extreme flow discharge in combination with riverbed variation could be one of the possible causes of flood disasters along the river. For example, the heavy and long lasting rainfall in June 2013 led to a peak discharge of 1100 m^3/s, which was slightly above the 100-year flood return period, inundating a nearby city. However, the influence of the man-made structures on this flood event in this reach is unclear. In this study an integrative hydromorphological model is applied to evaluate this impact by a comparison with a standard clear water model with fixed bed. Moreover, a comparative analysis of a three-and two-dimensional flow model is performed to assess the models suitability representing the flow in this river stretch. The integrative model concept is based on the software TELEMAC-MASCARET, in an enhanced version for better representing graded sediment transport in rivers. In contrast to our integrative model, the standard clear water model with fixed bed overestimates the water elevations as it cannot take the significant changes in morphology into account. Results demonstrate that our proposed model more accurately represents the inundation in the floodplain and could thus be used to provide more reliable predictions to decision-makers for improved flood protection strategy.

1. Introduction

Flood events are frequent and often disastrous events worldwide. They are not usually directly linked to specific spatial conditions but can occur almost everywhere, triggered by long lasting or heavy rainfall

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[*] Corresponding author.
E-mail address: markus.reisenbuechler@tum.de (M. Reisenbüchler).

https://doi.org/10.1016/j.scitotenv.2018.08.018
0048-9697/

or the combination of both (Bronstert, 2003). In 2013, middle Europe was affected once again by an extreme flood event. This caused losses of over €8 billion nationwide in Germany and can be classified as the most severe flood event in Germany for the last 60 years (Thieken et al., 2016). In order to mitigate the impact of future events, a lot of research and post-processing on this event has been done to understand the causes leading to the flooding (Blöschl et al., 2013; DKKV, 2015; LfU, 2014; Thieken et al., 2016). In the past, flood inundation maps were used to ascertain whether certain areas are likely to be affected by floods or not. In flood management, this is now extended by including a risk assessment based on the following considerations: overall hazard (e.g. flood magnitude, effect of climate change, etc.), spatial exposure (number of people affected and impact on infrastructure) and vulnerability (i.e. the sensitivity to a hazard). Röthlisberger et al. (2017) employed a spatial clustering approach identifying highly endangered regions. The Free State of Bavaria, Germany, implemented a similar approach, which was improved, adapted and extended after each flood event (StMUV, 2015). Many of these measures and suggested methodologies are based on the representation of flood events from numerical models. These models simulate the extension of 'design floods' and assess whether the floodplain and cities are at risk. In Germany, the design flood for river defense systems refers to a flood discharge with a return period of 100 years (LAWA, 2010a). Such models are commonly used to determine countermeasures, risk-maps and insurance premiums, and are therefore an important factor in the total flood risk management context (LAWA, 2010b; Thieken et al., 2016).

However, floods are not of course confined to clear water phenomena, and rivers are not stable over time. Different fields of research focus on the broader morphodynamic influence on flooding. Rickenmann et al. (2016) highlight the significant influence of sediment motion during flood events in alpine catchments and their damage potential. The profound influence of riverbed dynamics on flood events becomes even clearer when comparing the historic states of rivers with their present state, as Skublics et al. (2016) shows for the Danube River. Morphological activities can lead to an increase in the flood peak and to more severe situations. Guan et al. (2015) and Guan et al. (2016) confirmed this in experimental and real-world conditions using numerical hydromorphological modeling. Similarly, Carr et al. (2015) and Tu et al. (2017), analyzed the magnitude of flood inundation under changing morphological conditions using numerical models. In the framework of hydromorphological modeling, a morphological model is connected to a hydrodynamic one, using different coupling approaches (Duc et al., 2005; Nelson et al., 2016; Wu, 2004). In this procedure, the hydrodynamic model provides information on the flow, turbulence and shear stress, from which the morphological model calculates sediment transport rates, which in turn lead to erosion or deposition. However, the calculation of sediment transport rates commonly applies to several empirical formulae derived from regression or dimensional analyses of laboratory experiments as no formula sufficiently describes all processes (Meyer-Peter and Müller, 1948; van Rijn, 1984; Wilcock and Crowe, 2003; Wu, 2007). The variability of available formulas includes several adjustable parameters, representing the site-specific conditions and characteristics of sediments (e.g. a threshold of motion after Shields (1936)), which means they cannot be simply extrapolated from one river to another. In short, the complexity and heterogeneity of fluvial sediments and the difficulty of measuring them - for instance, bedload transport rates over time - makes the modeling process and defining reliable boundary conditions challenging (Habersack et al., 2017).

This brief survey of the literature makes clear that the representation of the effects of hydrodynamics and morphodynamics cannot be considered in isolation. However, the application of hydromorphodynamic models is not yet the standard for representing a flood event. It is evident that excluding morphological changes can lead to a false impression of the real situation when we examine the event in June 2013, which led to the 100-year flood in the Saalach River, located in southern Bavaria, Germany. In this river reach, several man-made structures might influence the flood wave propagation and produce feedback on the inundation. However, taking measurements during events is difficult and information is often only available after the event. In order to understand and represent the processes during the event, especially at man-made river structures, we developed a numerical hydromorphological model for a section of the Saalach. Such numerical models can extend the knowledge about the effects of man-made structures on flood events and morphology and contribute to sustainable river management. To demonstrate that a two-dimensional hydrodynamic model is able to accurately represent the flow situation even close to structures in the absence of detailed measurements, we performed a comparison with a three-dimensional flow model. Our model was then compared with a standard clear water model with a fixed bed for the same flood event to test the hypothesis that an integrative approach would provide more accurate and realistic results. For the simulations, we applied TELEMAC-MASCARET software, extended with a newly-developed morphological module, which provides stable and reliable results (Reisenbüchler et al., 2016). The present work serves to illustrate: (1) applicability of a two-dimensional flow model to this river stretch, (2) accurate representation and analysis of the processes during the 2013 flood event, and (3) remarks on possible measures for flood impact reduction taking morphological changes into account.

2. Study area

We studied the Saalach River, which is located in the southeastern part of Germany close to the Austrian border. All elevations in this study are therefore referenced to the German vertical elevation system in meters above sea level. The Saalach River has its source in the Austrian Alps at 1940 m, and after 103 km flows into the Salzach River at a level of 404 m, close to Salzburg in Austria. The river length is defined according to the German system, starting at $x = 0.0$ km at the confluence to the Salzach River, and increases towards to the river source in the Alps. The data used in this study was provided by the regional water agency, the Wasserwirtschaftsamt Traunstein (abbr.: WWA-TS) (WWA-TS, 2013). The study area is confined to the lower part of the Saalach River from $x = 20.6$ km to $x = 2.4$ km, Fig. 1. This section of the river forms the border between Bavaria (Germany) on the orographic left and the county of Salzburg (Austria) on the right bank. At the Siezenheim gauge at $x = 5.5$ km, the river still has the typical characteristics of an Alpine river with a high variation in discharge (statistical mean discharge $MQ = 39.1\ m^3/s$; statistical mean flood discharge $MHQ = 440.0\ m^3/s$ and a statistical 100 year return period flood discharge $HQ_{100} = 1093\ m^3/s$; from the time series 1976–2013) (BMLFUW, 2013) and rapid morphological activity (WWA-TS, 2016). However, the shape of the river has changed greatly over the last 200 years, (BVV, 2017). Based on the comparison of the estuary of the rivers Saalach and Salzach in their historical and current state, this change is shown in Fig. 2, which is representative of the entire river. The historical river had a winding and meandering shape, changing morphologically after every flood event. In 1820, in order to create a clear border and facilitate river management, regulation and straightening were performed along the national border (Schramm, 2012). Further benefits of this measure were the gain in land for agricultural use and the increase of flood protection due to higher flow velocities in a trapezoidal, straight channel. These higher velocities not only affect the flood wave propagation but also increase the shear stress acting on the bed and therefore the sediment transport capacity of the river. However, river training is not the only influencing factor. At the beginning of the 19th century, energy demand increased, particularly for the railway which connected the rural area around the city of Freilassing with the then urban center of Berchtesgaden. To this end, the hydropower plant (HPP) Saalach was constructed in Bad Reichenhall ($x = 20.6$ km), including the Kibling dam, in 1913 (Zitka, 1959), (Fig. 1). To counteract sedimentation of this reservoir, the accumulated gravel has