Reviewer #2:

R25: General comments and my recommendation: After carefully reading the manuscript titled "Hydrodynamic simulation of the effects of in-channel large woody debris on the flood hydrographs of a low mountain range creek, Ore Mountains, Germany" and pondering the aspects of scientific relevance of the study and the specific findings and reflecting upon the coherence between the declared scope and practical utility of the work and the presented contents, I suggest that major revisions are necessary to enhance the manuscript and make it publishable in Hydrology and Earth System Sciences. The title of the presented work promises to simulate the effects of in-channel LW on the flood hydrographs of a low mountain range creek and, therefore I expected insights on how the presence of LW affects the shape or form of the hydrograph and why. This would be of crucial importance for flood risk assessment. Instead the authors provided a detailed study on how to adjust the different model parameters (i.e. roughness both locally at single LW locations and globally on a reach scale) to obtain the best fit between measured hydrographs and simulated ones. I'm not contending that, per se, this exercise in not worth being done and hasn't been done rigorously and accurately; I rather surmise that the generated knowledge is only partially capable of explaining how hydromorphology linked to the presence of LW can be studied and the generated knowledge can, henceforth, inform decision makers in optimally implementing the water framework directive. Moreover, I miss a presentation and comparison of different hydrodynamic models capable to simulate different aspects of LW dynamics in rivers. The authors used HYDRO-AS-2D for their declared scope augmenting that this software is standardly employed in Germany (mainly for flood hazard assessment I suppose). This argumentation line is rather week. There should be a rigorous assessment of the best tool to be applied to analyze the considered processes. In the title I'd use the wording 'stable in-channel Large Wood', since, in essence, with the chosen modelling approach only stable LW can be considered, by adjusting the topographic mesh to the presence of these objects. It might well be the case that in the studied 282 m long section of the Ullersdorfer Teichbächl LW has been anchored to the river bed and morphodynamic change does not play a major role and, hence, given these circumstances HYDRO-AS-2D is applicable, but this mirrors only a minority of water courses in Europe. So, how can the generated knowledge be transferred to managers who have to deal with a broad variety of river systems? Imagine managers facing problems related to the WFD in very dynamic river system where LW is entrained and transported and interacts with obstacles continuously creating and destroying habitats, changing the river planform and its 3D structure, sorting sediment and, as a consequence of this conundrum of phenomena altering flood risk to a large extent. In such a case, working with HYDRO-AS-2D might not be the most recommendable option. Given these considerations, I argue that attaching your work the broad scope of the WFD to enhance European rivers from various perspectives is a bit too far reaching and could inconveniently generate false expectations. In fact, you conclude the introduction by stating that "understanding its effects and the ability of predicting hydraulic impacts of LW in hydraulic simulations can be highly important for the use of LW in stream restoration projects and ecological-oriented management approaches in the scope of WLD", the paper, however, largely lacks a discussion on how, based on your findings, these ambitious goals can be accomplished. Based on the afore mentioned general comments I think that the introduction has to be reworked to assure full coherency between scopes, goals, what has been accomplished and how it contributes to the specific goals and the general scopes.

A25: Comment R25 contains several aspects we would like to respond to. It should be noted, that we modified several large sections of the original manuscript and not all modifications are stated in the author responses separately. Therefore, the complete modified manuscript can be found at the end of this document:

R25a: "The title of the presented work promises to simulate the effects of in-channel LW on the flood hydrographs of a low mountain range creek and, therefore I expected insights on how the presence of LW affects the shape or form of the hydrograph and why. This would be of crucial importance for flood risk assessment. Instead the authors provided a detailed study on how to adjust the different model parameters (i.e. roughness both locally at single LW locations and globally on a reach scale) to obtain the best fit between measured hydrographs and simulated ones."

A25a: We agree. Information about the influence of stable large wood on flood hydrographs should be mentioned and were added to the introduction chapter.

R25b: "I rather surmise that the generated knowledge is only partially capable of explaining how hydromorphology linked to the presence of LW can be studied and the generated knowledge can, henceforth, inform decision makers in optimally implementing the water framework directive."

A25b: We agree. We will reformulate the introduction of the manuscript to precisely state the objectives of this study and an additional chapter was added to the discussion chapter summarising the limitations of the present study. This includes a differentiation between large wood that can be assumed as stable and those elements that a potentially mobile.

R25c: "Moreover, I miss a presentation and comparison of different hydrodynamic models capable to simulate different aspects of LW dynamics in rivers."

A25c: We partly agree. We will add further information on hydrodynamic modelling and modelling different aspects of large wood (stable and mobile) to the introduction chapter and give references on recent reviews containing information about hydrodynamic model applications and simulation large wood, but a full review of existing models and individual model capabilities is beyond the scope of this case study.

R25d: "The authors used HYDRO-AS-2D for their declared scope augmenting that this software is standardly employed in Germany (mainly for flood hazard assessment I suppose). This argumentation line is rather week. There should be a rigorous assessment of the best tool to be applied to analyze the considered processes."

A25d: We disagree. We do not argue that we use the model because it is one of the standard modelling systems in Germany. We use this model because it is capable of simulation high-gradient streams with an irregular shape and a high variance in depth and width (Nujić, 2006). For clarification we changed the corresponding section of the original manuscript in the following way.

Original:

"In this study, the two-dimensional hydrodynamic model HYDRO_AS-2D (version 2.2) is used to simulate the flow in the study reach with and without LWD. HYDRO_AS-2D was developed for practical applications in water management (Nujić, 2006) and is used in several studies simulating flow conditions in river sections (i.e. Lange et al. 2015) as well as in flood risk management applications. Especially in southern Germany and Austria, HYDRO_AS-2D became a standard 2D modelling system for hydrodynamic model applications (Faber et al., 2012). Due to the numerical approaches used in the modelling system, HYDRO_AS-2D is capable of accurately simulating mass exchange between channel and forelands, streams comprising hydraulic jumps, steep channel sections as well as high variability of channel width (Nujić, 2006)."

Modification:

"In this study, the two-dimensional hydrodynamic model HYDRO_AS-2D (version 2.2) is used to simulate the flow in the study reach with and without LW. HYDRO_AS-2D was developed for practical applications in water management (Nujić, 2006) and is used in several studies simulating flow conditions in river sections for flood risk management (i.e. Rieger and Disse, 2013) or with an ecological focus (i.e. Lange et al., 2015) and can produce a higher goodness-of-fit compared to other two-dimensional models as exemplarily shown in Lavoie and Mahdi (2017). Especially in southern Germany and Austria, HYDRO_AS-2D became a standard 2D modelling system for hydrodynamic model applications (Faber et al., 2012). Due to the numerical approaches used in the modelling system, HYDRO_AS-2D is capable of simulating mass exchange between channel and forelands, streams comprising hydraulic jumps, steep channel sections and a high variability of channel width as well as dike breaches (Nujić, 2006). The latter is to some extent comparable with the rapid release of water initiated by opening the flap gate weir used in the field experiments (see chapter 3.2). For the above-named reasons, HYDRO_AS-2D was chosen for the present study."

R25e: "In the title I'd use the wording 'stable in-channel Large Wood', since, in essence, with the chosen modelling approach only stable LW can be considered, by adjusting the topographic mesh to the presence of these objects."

A25e: We agree. The word "stable" was added accordingly.

R25f: "It might well be the case that in the studied 282 m long section of the Ullersdorfer Teichbächl LW has been anchored to the river bed and morphodynamic change does not play a major role and, hence, given these circumstances HYDRO-AS-2D is applicable, but this mirrors only a minority of water courses in Europe. So, how can the generated knowledge be transferred to managers who have to deal with a broad variety of river systems? Imagine managers facing problems related to the WFD in very dynamic river system where LW is entrained and transported and interacts with obstacles continuously creating and destroying habitats, changing the river planform and its 3D structure, sorting sediment and, as a consequence of this conundrum of phenomena altering flood risk to a large extent. In such a case, working with HYDRO-AS-2D might not be the most recommendable option. Given these considerations, I argue that attaching your work the broad scope of the WFD to enhance European rivers from various perspectives is a bit too far reaching and could inconveniently generate false expectations. In fact, you conclude the introduction by stating that "understanding its effects and the ability of predicting hydraulic impacts of LW in hydraulic simulations can be highly important for the use of LW in stream restoration projects and ecological-oriented management approaches in the scope of WLD", the paper, however, largely lacks a discussion on how, based on your findings, these ambitious goals can be accomplished. Based on the afore mentioned general comments I think that the introduction has to be reworked to assure full coherency between scopes, goals, what has been accomplished and how it contributes to the specific goals and the general scopes."

A25f: We agree that linking or case study to the broad scope of the WFD might be too far reaching. According to the suggestion of reworking the introduction, we removed the WFD from the introduction, redefined or goals and reformulated the introduction accordingly. The original and modified version of the introduction can be found below:

Original:

"**1 Introduction**

The introduction of the European Union's Water Framework Directive (WFD) in 2000 led to a reorganisation of water policy and management in the member states of the European Union (Bosenius and Holzwarth, 2006). New aims of a good ecological and chemical status were set for managing surface water bodies and groundwater (Korn et al., 2005). In Germany, only 8.2 % of the inland surface waters had reached the targeted good ecological status by the end of March 2016, while the majority of 89.1 % still fails to achieve this aim (UBA/BMUB, 2016). The main reasons for not reaching the good ecological status are agricultural nutrient immissions and in particular, the lack of hydromorphological diversity of most watercourses (UBA/BMUB, 2016).

A natural structural element of rivers and streams with forested catchments is large woody debris (LWD) (Gurnell et al., 2002; Roni et al., 2015). It is part of the permanently produced amount of plantal detritus in terrestrial ecosystems before it enters rivers and surrounding riparian areas (Wohl, 2015). In fluvial systems, large woody debris can be defined as dead organic matter with woody texture, having diameters of at least 10 cm (Kail and Gerhard, 2003). Unlike in the definition of Kail and Gerhard (2003), several studies include the length of large wood debris of at least 1 m for distinction (i.e. Gurnell et al., 2002; Andreoli et al., 2007; Comiti et al., 2008; Bocchiola, 2011; Kramer and Wohl, 2017; Wohl, 2017) and is adapted in the present study.

Large woody debris improves the physical structure of watercourses as it increases streambed heterogeneity by forming scour pools (Abbe and Montogomery, 1996), causing sediment sorting and altering water depth as well as flow velocity (Pilotto et al., 2014). Hence, the presence of large woody debris can lead to increased habitat availability in rivers and streams (Wohl, 2017). Positive ecological impacts of LWD on fish species (i.e. Kail et al., 2007; Roni et al., 2015) and the macro-invertebrate fauna (i.e. Seidel and Mutz, 2012; Pilotto et al., 2014; Roni et al., 2015) are documented.

Therefore, in stream restoration projects, the presence of large woody debris can result in rapid hydromorphological improvements (Kail et al., 2007). Consequently, wood placements have a high potential for stream restoration measures in the scope of the WFD in Germany (Kail and Hering 2005), which in turn may also function positively for the implementation of several other legal regulations on European level such as the EU's floods and habitats directive (Pander and Geist, 2013).

On the contrary, in case of drifting large woody debris during floods, elements may jam at bridges or other infrastructure and cause increased water levels, damage or completely destroy anthropogenic goods and structures (Schmocker and Hager, 2011). For this reason, LWD is removed from European rivers and streams for more than a century (Wohl, 2015) also to ensure navigability (Young, 1991) and water conveyance (Wenzel et al., 2014). As a result, the usage of LWD in river restoration in the form of leaving naturally transported woody debris in-stream or artificial wood placements is discussed controversially (Roni et al., 2015; Wohl, 2017).

With respect to the potential risks of large woody debris for anthropogenic goods on the one hand and high ecological benefits on the other, it may be necessary to distinguish river sections in which large wood can remain or be introduced from those where it needs to be removed (Wohl, 2017). Large wood related segmentation of rivers and streams requires knowledge of the physical effects caused by mobile and stable in-channel large woody debris. Although several studies investigate the general hydraulic impact of LWD in field studies (i.e. Daniels and Rhoads, 2004; Daniels and Rhoads, 2007; Wenzel et al., 2014) and laboratory experiments (i.e. Young, 1991; Davidson and Eaton, 2013; Bennett et al., 2015) regarding the alteration of water level, flow pattern, flow velocity and discharge, a project and site specific examination is necessary to evaluate local consequences of intended stream restoration measures.

The resulting physical effects of stable in-channel LWD can be addressed using hydrodynamic models (Smith et al., 2011). Several studies consider large woody debris in the scope of one- and two-dimensional hydrodynamic simulations for example for investigating its influence on flood hydrographs (Thomas and Nisbet, 2012), on floodplain connectivity (Keys et al., 2018) or are considered in research applications with an ecological focus (i.e. He et al., 2009; Hafs et al., 2014; Lange et al., 2015). Furthermore, representing and integrating of large woody debris elements in hydrodynamic models is addressed in different studies using three-dimensional hydrodynamic models (i.e. Smith et al., 2011; Allen and Smith, 2012; Lai and Bandrowski, 2014; Xu and Liu, 2017).

Despite the necessity of a discrete representation of large woody debris elements in the calculation mesh of hydrodynamic models for obtaining accurate results, LWD elements are often accounted for using roughness coefficients in hydrodynamic model applications (Smith et al., 2011). The impact of large woody debris on in-channel roughness is investigated by Gregory et al. (1985), Shields and Smith (1992), Shields and Gippel (1995), Dudley et al. (1998), MacFarlane and Wohl, (2003) and Wilcox and Wohl (2006). In addition, Curran and Wohl (2003) and Wilcox et al. (2006) have studied its partial contribution to channel roughness coefficients. However, a methodological lack remains in quantitatively estimating LWD related changes of in-channel roughness coefficients (Wohl, 2017), especially under field conditions (Wilcox et al., 2006).

Against this background, the aim of the present study is to quantify the influence of LWD elements on in-channel roughness coefficients in a creek in low mountain ranges using a two-dimensional hydrodynamic model and previously conducted field experiments, explicitly described in Wenzel et al. (2014). The field data offer the opportunity to validate simulated large wood related hydraulic effects on hydrographs of small flood events. In addition, different methods of implementing stable LWD are examined and evaluated, for example by altering reach-wise in-channel roughness coefficients on the one hand or as discrete roughness elements in the calculation mesh on the other.

By investigating the effects of stable LWD on reach-wise roughness coefficients and possibilities to represent LWD elements in hydrodynamic models, the present study will contribute to the understanding of the hydraulic impact of large woody debris in fluvial environments as well as its simulation and prediction. Understanding its effects and the ability of predicting hydraulic impacts of LWD in hydrodynamic simulations can be highly important for the use of LWD in stream restoration projects and ecological-orientated management approaches in the scope of the WFD.”

Modification:

“**1 Introduction**

Large wood (LW) is a natural structural element of rivers and streams with forested catchments (Gurnell et al., 2002; Roni et al., 2015). It is part of the permanently produced amount of plantal detritus in terrestrial ecosystems before it enters rivers and surrounding riparian areas (Wohl, 2015). In fluvial systems, large wood can be defined as dead organic matter with woody texture, having diameters of at least 0.1 m (Kail and Gerhard, 2003). Unlike in the definition of Kail and Gerhard (2003), several studies include the length of large wood of at least 1 m for distinction (i.e. Gurnell et al., 2002; Andreoli et al., 2007; Comiti et al., 2008; Bocchiola, 2011; Kramer and Wohl, 2017; Wohl, 2017). The latter definition is adapted in the present study.

Large wood improves the physical structure of watercourses as it increases streambed heterogeneity by forming scour pools (Abbe and Montogomery, 1996), causing sediment sorting and altering water depth as well as flow velocity (Pilotto et al., 2014). Hence, the presence of large wood can lead to increased habitat availability in rivers and streams (Wohl, 2017). Positive ecological impacts of LW on fish species (i.e. Kail et al., 2007; Roni et al., 2015) and the macro-invertebrate fauna (i.e. Seidel and Mutz, 2012; Pilotto et al., 2014; Roni et al., 2015) are documented.

Therefore, in stream restoration projects, the presence of large wood can result in rapid hydromorphological improvements (Kail et al., 2007). Consequently, wood placements have a high potential for stream restoration measures (Kail and Hering, 2005); for instance in Germany, where many water courses lack of a high hydromorphological diversity (BMUB/UBA, 2016). Here, potentially mobile large wood and stable large wood have to be distinguished. Large wood assemblages and elements may be assumed stable when the median element length exceeds channel width (i.e. Gurnell et al., 2002), likely to occur in small first order streams and rivers, which in turn are the most abundant order of water courses on the planet (Downing et al., 2012). However, even in small but steep headwater streams, large wood may be transported during hydrogeomorphic events of high magnitude such as debris flows (Galia et al., 2018) or extreme floods. A conceptual model for a first estimate of large wood transport in water courses is given in Kramer and Wohl (2017) including hydrological as well as morphological variables. Further detailed information about large wood dynamics in river networks can be found in recent reviews of Ruiz-Villanueva et al. (2016a) and Wohl (2017). Potentially mobile large wood may drifts during floods, elements jam at bridges or other infrastructure and cause increased water levels, damage or completely destroy anthropogenic goods and structures (Schmocker and Hager, 2011). On the contrary, stable large wood remains in place, reduces water conveyance (Wenzel et al., 2014) and leads to increased water levels upstream and in turn, increased risk of flooding and water logging in surrounding areas. For these reasons, LW is removed from European rivers and streams for more than a century (Wohl, 2015) also to ensure navigability in larger rivers (Young, 1991). As a result, the usage of LW in river restoration in the form of leaving naturally transported woody debris in-stream or artificial stable wood placements is discussed controversially (Roni et al., 2015; Wohl, 2017).

With respect to the potential risks of large wood for anthropogenic goods on the one hand and high ecological benefits on the other, it may be necessary to distinguish river sections in which large wood can remain or be introduced from those where it needs to be removed (Wohl, 2017). Large wood related segmentation of rivers and streams requires knowledge of the physical effects caused by mobile and stable in-channel large wood. Although several studies address the general hydraulic impact of LW in field studies (i.e. Daniels and Rhoads, 2004; Daniels and Rhoads, 2007; Wenzel et al., 2014), laboratory experiments (i.e. Young, 1991; Davidson and Eaton, 2013; Bennett et al., 2015) and reviews (i.e., Gippel, 1995; Montgomery et al., 2003) regarding the alteration of water level, flow pattern, flow velocity and discharge, a project and site specific examination is necessary to evaluate local consequences of intended stream restoration measures.

The mobility, transport and deposition of large wood (i.e. Ruiz-Villanueva et al., 2014; Ruiz-Villanueva et al., 2016b) as well as the resulting physical effects of stable in-channel LW (Smith et al. 2011) can be addressed using numerical hydrodynamic models. Numerical hydrodynamic models for the simulation of open-channel hydraulics can be classified by their dimension and solve the shallow water equations in their one-, two- or three-dimensional form for simulating channel flow in just one (x-)direction (1D), horizontally resolved (x- and y-direction) but depth-averaged (2D) or fully resolved in x-, y- and, z-direction

(Liu, 2014). Due to i.e. the increasing effort of work and computational time with increasing dimension, the applicability of 1D, 2D or 3D models depends on the scale and phenomena of interest (Liu, 2014). For simulating the general hydraulic behaviour on reach-scale, 2D models are useful tools (Liu, 2014). A detailed description of the different model types and examples of application can be found in Liu (2014) or Tonina and Jorde (2013) with focus on ecohydraulics. For instance, Ruiz-Villanueva et al. (2014) and Ruiz-Villanueva et al. (2016b) simulate large wood transport and remobilization using a two-dimensional hydrodynamic model. Several studies also consider stable large wood in the scope of one- and two-dimensional hydrodynamic simulations for example for investigating its influence on flood hydrographs (Thomas and Nisbet, 2012), on floodplain connectivity (Keys et al., 2018) or are considered in research applications with an ecological focus by investigating the effect of stable LW on habitat availability or suitability (i.e. He et al., 2009; Hafs et al., 2014). In addition, Lange et al. (2015) simulate the effect of roughness elements including stable LW in the scope of stream restoration analyses. Regarding the hydraulic impact of stable large wood on flood hydrographs, Thomas and Nisbet (2012) simulate large wood to delay flood passage but no attenuation of peak discharge is modelled. Similar effects of stable LW on flood hydrographs were investigated by Wenzel et al. (2014) in field experiments, where a delay and a narrower shape through a transformation from higher to lower discharges, but only a minor attenuation of the average flood hydrograph was observed. Furthermore, representing and integrating of large wood elements in hydrodynamic models is addressed in different studies using three-dimensional hydrodynamic models (i.e. Smith et al., 2011; Allen and Smith, 2012; Lai and Bandrowski, 2014; Xu and Liu, 2017). However, the modelling approach applied varies with studies. As an extensive review of applicable numerical hydrodynamic modelling systems and approaches for simulating large wood is beyond the scope of the present study, a recent overview with focus on LW dynamics as well as the representation of large wood and vegetation in simulations can be found in Bertoldi and Ruiz-Villanueva (2017).

Despite the necessity of a discrete representation of stable large wood elements in the calculation mesh of hydrodynamic models for obtaining accurate results (Smith et al., 2011), as conducted in different studies (i.e. Hafs et al., 2014; Lange et al., 2015; Keys et al., 2018), LW elements are often accounted for using roughness coefficients in hydrodynamic model applications (Smith et al., 2011). The impact of large wood on in-channel roughness is investigated by Gregory et al. (1985), Shields and Smith (1992), Shields and Gippel (1995), Dudley et al. (1998), MacFarlane and Wohl, (2003) and Wilcox and Wohl (2006). In addition, Curran and Wohl (2003) and Wilcox et al. (2006) have studied its partial contribution to channel roughness coefficients. However, a methodological lack remains in quantitatively estimating LW related changes of in-channel roughness coefficients (Wohl, 2017), especially under field conditions (Wilcox et al., 2006).

Against this background, the aim of the present study is to simulate the physical effects of stable in-channel LW elements on flood hydrographs in a creek reach in low mountain ranges using a two-dimensional hydrodynamic model and previously conducted field experiments, explicitly described in Wenzel et al. (2014). The field data offer the rare opportunity to validate simulated large wood related hydraulic effects on hydrographs of small flood events. By conducting different hydrodynamic simulations, we aim (1) for the quantification of the change of channel roughness coefficients in the entire channel or at LW positions, necessary to obtain most accurate model results of flood hydrographs with stable large wood elements in the channel.

As discrete LW elements are required for most accurate model results (Smith et al. 2011), we aim (2) for comparing previous model results with simulations with discrete large wood elements created through manipulating the calculation mesh. However, the integration of discrete elements into the calculation mesh can be highly time- and work-intensive (Lai and Bandrowski, 2014), which becomes especially true for larger scale applications. Hence, a comparison of the simulation accuracy between incorporating large wood through a rather quick change of channel roughness coefficients and as time-demanding simplified mesh elements can be provide beneficial information for future studies simulating stable large wood related effects on stream hydraulics and ecology. This is underlined by Grabowski et al. (2019) who identified remaining uncertainties for the use of large wood in river restoration and natural flood risk management in practice. Knowledge gaps remain for instance regarding the alteration of channel roughness and hydraulic impacts such as backwater effects for the identification of local risks (Grabowski et al., 2019) which can be addressed with hydrodynamic models.

Although limited to smaller streams and rivers were large wood jams and elements can be assumed as stable or situations in which large wood elements are fastened, the present study can contribute to the ability of predicting hydraulic impacts of stable in-channel large wood within hydrodynamic simulations and can also provide beneficial practical information for conducting simulation-based impact assessments of stream restoration projects considering stable large wood by comparing different methods of large wood integration.”

R26: Abstract: Personally the abstract is too long. As it is, I’d rather call it an extended abstract. I think that greater synthesis is required to inform the reader about tackled scientific problems, the adopted methodological approach (without details), a key message about the main finding and a brief concluding remark about the real broader implications of your work.

A26: We reworked the abstract in the following way:

<u>Original:</u>

“**Abstract.** Fifteen years after introducing the European Union's water framework directive (WFD), most of the German surface water bodies are still far away from having the targeted good ecological status or potential. One reason are insufficient hydromorphological diversities such as riverbed structure including the absence of natural woody debris in the channels. The presence of large woody debris (LWD) in river channels can improve the hydromorphological and hydraulic characteristics of rivers and streams and therefore act positively on a river’s ecology. On the contrary, floating LWD is a potential threat for anthropogenic goods and infrastructure during flood events. Concerning the contradiction of potential risks as well as positive ecological impacts, addressing the physical effects of large woody debris is highly important, for example to identify river sections in which large woody debris can remain or can be reintroduced. Hydrodynamic models offer the possibility of investigating the hydraulic effects of fastened large woody debris. In such models roughness coefficients are commonly used to implement LWD, however, because of the complexity of the shape of LWD elements this approach seems to be too simple and not appropriate to simulate its diverse effects especially on floodhydrographs. Against this background a two-dimensional hydraulic model is set up for a mountain creek to simulate the hydraulic effects of LWD and to test different methods of LWD implementation. The study area comprises a 282 m long reach of the Ullersdorfer Teichbächel, a creek in the Ore Mountains (South-eastern Germany). In previous studies, field experiments with artificially generated flood events have been performed with and without LWD in the channel. Discharge time series from the experiments allow a validation of the model outputs with field observations. Methodically, in-channel roughness coefficients are changed iteratively for retrieving the best fit between mean simulated and observed flood hydrographs with and without LWD at the downstream reach outlet. In addition, roughness values are modified at LWD positions only and, simplified discrete elements representing LWD were incorporated into the calculation mesh. In general, the model results reveal a good simulation of the observed flood hydrographs of the field experiments without in-channel large woody debris. This indicates the applicability of the model used in the studied reach of a creek in low mountain ranges. The best fit of simulation and mean observed hydrograph with in-channel LWD can be obtained when increasing in-channel roughness through decreasing Strickler coefficients by 30 % in the entire reach or 55 % at LWD positions only. However, the increase of roughness in the entire reach shows a better simulation of the observed hydrograph, indicating that LWD elements affect sections beyond their own dimensions i.e. by forming downstream wake fields. The best fit in terms of the hydrograph's general shape can be achieved by integrating discrete elements into the calculation mesh. The emerging temporal shift between simulation and observation can be attributed to mesh impermeability and element dimensions causing too intense water retention and flow alteration. The results illustrate that the mean observed hydrograph can be satisfactorily modelled using roughness coefficients. Nevertheless, discrete elements result in a better fitting shape of the simulated hydrograph.

In conclusion, a time-consuming and work-intensive mesh manipulation is suitable for analysing detailed flow conditions using computational fluid dynamics (CFD) on small spatio-temporal scale. Here, a close-to-nature design of discrete LWD objects is essential to retrieve accurate results. In contrast, the reach-wise adjustment of in-channel roughness coefficients is useful in larger scale model applications such as 1D-hydrodynamic or rainfall-runoff simulations on catchment scale.”

Modification:

“Abstract. The presence of large wood (LW) in river channels can improve the hydromorphological and hydraulic characteristics of rivers and streams and therefore act positively on a river’s ecology. On the contrary, floating as well as stable LW is a potential threat for anthropogenic goods and infrastructure during flood events. Concerning the contradiction of potential risks as well as positive ecological impacts, addressing the physical effects of mobile and stable large wood is highly important. Hydrodynamic models offer the possibility of investigating the hydraulic effects of fastened large wood. In this study, a two-dimensional hydraulic model is set up for a mountain creek to simulate the hydraulic effects of stable LW and to test different methods of LW implementation.

The study area comprises a 282 m long reach of the Ullersdorfer Teichbächel, a creek in the Ore Mountains (South-eastern Germany). Discharge time series from field experiments allow a validation of the model outputs with field observations with and without stable LW. Methodically, in-channel roughness coefficients are changed iteratively for retrieving the best fit between mean simulated and observed flood hydrographs with and without LW at the downstream reach outlet and, simplified discrete elements representing LW were incorporated into the calculation mesh.

In general, the model results reveal a high goodness-of-fit of between the observed flood hydrographs of the field experiments without and with stable in-channel large wood. The best fit of simulation and mean observed hydrograph with in-channel LW can be obtained when increasing in-channel roughness through decreasing Strickler coefficients - in the entire reach instead of a reduction at LW positions only. The best fit in terms of the hydrograph's general shape can be achieved by integrating discrete elements into the calculation mesh. The results illustrate that the mean observed hydrograph can be satisfactorily modelled using an alteration of roughness coefficients.

In conclusion, a time-consuming and work-intensive mesh manipulation is suitable for analysing more detailed effects of stable LW on small spatio-temporal scale where high precision is required. In contrast, the reach-wise adjustment of in-channel roughness coefficients suggests to provide similarly accurate results on the reach-scale and thus, can be helpful for practical applications of model-based impact assessments of stable large wood on flood hydrographs small streams and rivers."

R27: Section 1: Introduction: Page 2; Line 22: Instead of LWD, I'd use LW (Large Wood) which is the commonly accepted terms in the scientific community dedicated to wood in world rivers.

A27: Corrected (see A22).

R28: Personally I think that the literature review about the LW hydrodynamic modelling is insufficient. There is much more out there that should be acknowledged and briefly described.

A28: We partly agree and added information about hydrodynamic modelling in general. Extensive reviews about LW hydrodynamic modelling are given elsewhere (i.e. Ruiz-Villanueva et al., 2016a, Bertoldi and Ruiz-Villanueva, 2017) and are named in the modified introduction (see A25). However, reviewing all aspects of LW hydrodynamic modelling such as large wood dynamics is beyond the scope of this case study focussing on stable large wood.

R29: Page 3; Line 13: The issue of flood risk due to LW mobility is introduced here. But how can one assess the LW contribution to flood risk if LW is assumed as fixed? Only through the change of local topography and roughness I suppose, which to my mind has to be better acknowledged as a limiting factor of the chosen approach.

A29: This study focusses on large wood under stable conditions. We acknowledge that this needs to be clarified as a limiting factor and was added in the modified introduction and the discussion chapter (see A25 and A21).

R30: Section 3: Methods: Beyond the above mentioned suggestion to compare existing potentially applicable hydrodynamic models, I think that a figure with a workflow that explains the followed methodological steps might enhance the structure of the paper.

A30: We added a figure to manuscript showing the schematic methodological workflow:

Additional figure:

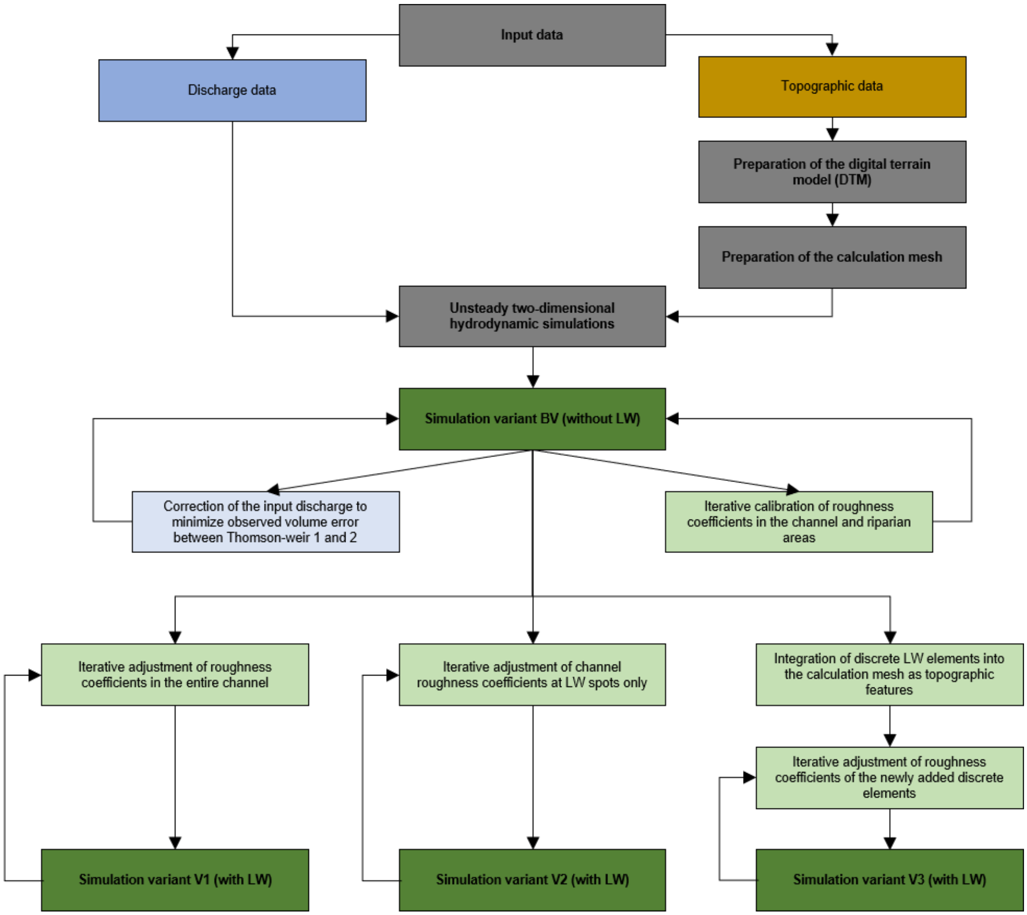

Figure 3: Schematic illustration of the methodological workflow

R31: Section 5: Discussion: To enhance this section, I invite the authors to carefully address the general concerns summarized in the first section of this review. Ideally departing from the obtained results one should be able to address the main issues which have been anticipated in the introduction either "positively" (i.e. underlining the contribution of the obtained results to the clarification of the risen issue) or "negatively" (i.e. expanding upon the necessity to integrate knowledge and to further investigate and specifically address open questions partially applicable findings).

A31: We added a chapter to the discussion describing limitations of this study and implications for further research. Additionally, we reworked the conclusion to match the aims stated in the introduction (see A21).

R32: 3) Minor corrections and observations: With respect to the suggestion of minor corrections and observations I reaffirm the importance of carefully enhancing the paper according to amendments indicated by the anonymous referee 1.

A32: Done.

Complete reworked manuscript with all modifications shown (red figures were modified):

Hydrodynamic simulation of the effects of stable in-channel ~~large woody debris~~large wood on the flood hydrographs of a low mountain range creek, Ore Mountains, Germany

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Abstract. ~~Fifteen years after introducing the European Union's water framework directive (WFD), most of the German surface water bodies are still far away from having the targeted good ecological status or potential. One reason are insufficient hydromorphological diversities such as riverbed structure including the absence of natural woody debris in the channels.~~ The presence of ~~large woody debris~~large wood (~~LWD~~LW) in river channels can improve the hydromorphological and hydraulic characteristics of rivers and streams and therefore act positively on a river's ecology. On the contrary, floating as well as stable ~~LWD~~LW is a potential threat for anthropogenic goods and infrastructure during flood events. Concerning the contradiction of potential risks as well as positive ecological impacts, addressing the physical effects of ~~large woody debris~~mobile and stable large wood is highly important.~~, for example to identify river sections in which large woody debris can remain or can be reintroduced.~~

Hydrodynamic models offer the possibility of investigating the hydraulic effects of fastened ~~large woody debris~~large wood. ~~In such models roughness coefficients are commonly used to implement LWD, however, because of the complexity of the shape of LWD elements this approach seems to be too simple and not appropriate to simulate its diverse effects especially on flood hydrographs. Against~~ In this ~~background~~ study, a two-dimensional hydraulic model is set up for a mountain creek to simulate the hydraulic effects of stable ~~LWD~~LW and to test different methods of ~~LWD~~LW implementation.

The study area comprises a 282 m long reach of the Ullersdorfer Teichbächel, a creek in the Ore Mountains (South-eastern Germany). ~~In previous studies, field experiments with artificially generated flood events have been performed with and without LWD in the channel.~~ Discharge time series from field~~the~~ experiments allow a validation of the model outputs with field observations with and without stable LW.~~.~~ Methodically, in-channel roughness coefficients are changed iteratively for retrieving the best fit between mean simulated and observed flood hydrographs with and without ~~LWD~~LW at the downstream reach outlet. ~~. In addition, roughness values are modified at LWD positions only~~ and, simplified discrete elements representing ~~LWD~~LW were incorporated into the calculation mesh.

In general, the model results reveal a high goodness-of-fit of between ~~simulation of~~ the observed flood hydrographs of the field experiments without and with stable in-channel ~~large woody debris~~large wood. ~~This indicates the applicability of the model used in the studied reach of a creek in low mountain ranges.~~ The best fit of simulation and mean observed hydrograph with in-channel ~~LWD~~LW can be obtained when increasing in-channel roughness through decreasing Strickler coefficients ~~by 30 %~~ in the entire reach instead of a reduction ~~or 55 %~~ at ~~LWD~~LW positions only. ~~However, the increase of roughness in the entire reach shows a better simulation of the observed hydrograph, indicating that LWD elements affect sections beyond their own dimensions i.e. by forming downstream wake fields.~~ The best fit in terms of the hydrograph's general shape can be achieved by integrating discrete elements into the calculation mesh. ~~The emerging temporal shift between simulation and observation can be attributed to mesh impermeability and element dimensions causing too intense water retention and flow alteration.~~ The results illustrate that the mean observed hydrograph can be satisfactorily modelled using an alteration of roughness coefficients. ~~Nevertheless, discrete elements result in a better fitting shape of the simulated hydrograph.~~

In conclusion, a time-consuming and work-intensive mesh manipulation is suitable for analysing more detailed ~~flow conditions~~ effects of stable LW ~~using computational fluid dynamics (CFD)~~ on small spatio-temporal scale where high precision is required. ~~Here, a close-to-nature design of discrete LWD objects is essential to retrieve accurate results.~~ In contrast, the reach-wise adjustment of in-channel roughness coefficients ~~is useful in larger scale model applications such as 1D-hydrodynamic or rainfall-runoff simulations on catchment scale~~ suggests to provide similarly accurate results on the reach-scale and thus, can be helpful for practical applications of model-based impact assessments of stable large wood on flood hydrographs small streams and rivers.~~.~~

1 Introduction

~~The introduction of the European Union's Water Framework Directive (WFD) in 2000 led to a reorganisation of water policy and management in the member states of the European Union (Bosenius and Holzwarth, 2006). New aims of a good ecological and chemical status were set for managing surface water bodies and groundwater (Korn et al., 2005). In Germany, only 8.2 % of the inland surface waters had reached the targeted good ecological status by the end of March 2016, while the majority of 89.1 % still fails to achieve this aim (UBA/BMUB, 2016). The main reasons for not reaching the good ecological status are agricultural nutrient immissions and in particular, the lack of hydromorphological diversity of most watercourses (UBA/BMUB, 2016).~~

Large wood (LW) is a ~~A~~ natural structural element of rivers and streams with forested catchments ~~is large woody debris (LWD)~~ (Gurnell et al., 2002; Roni et al., 2015). It is part of the permanently produced amount of plantal detritus in terrestrial ecosystems before it enters rivers and surrounding riparian areas (Wohl, 2015). In fluvial systems, ~~large woody debris~~large wood can be defined as dead organic matter with woody texture, having diameters of at least ~~10 cm~~0.1 m (Kail and Gerhard, 2003). Unlike in the definition of Kail and Gerhard (2003), several studies include the length of large wood ~~debris~~ of at least

1 m for distinction (i.e. Gurnell et al., 2002; Andreoli et al., 2007; Comiti et al., 2008; Bocchiola, 2011; Kramer and Wohl, 2017; Wohl, 2017). The latter definition ~~and~~ is adapted in the present study.

~~Large woody debris~~Large wood improves the physical structure of watercourses as it increases streambed heterogeneity by forming scour pools (Abbe and Montogomery, 1996), causing sediment sorting and altering water depth as well as flow velocity (Pilotto et al., 2014). Hence, the presence of ~~large woody debris~~large wood can lead to increased habitat availability in rivers and streams (Wohl, 2017). Positive ecological impacts of ~~LWD~~LW on fish species (i.e. Kail et al., 2007; Roni et al., 2015) and the macro-invertebrate fauna (i.e. Seidel and Mutz, 2012; Pilotto et al., 2014; Roni et al., 2015) are documented.

Therefore, in stream restoration projects, the presence of ~~large woody debris~~large wood can result in rapid hydromorphological improvements (Kail et al., 2007). Consequently, wood placements have a high potential for stream restoration measures ~~in the scope of the WFD in Germany~~ (Kail and Hering, 2005); for instance in Germany, where many water courses lack of a high hydromorphological diversity (BMUB/UBA, 2016).~~, which in turn may also function positively for the implementation of several other legal regulations on European level such as the EU's floods and habitats directive (Pander and Geist, 2013).~~

Here, potentially mobile large wood and stable large wood have to be distinguished. Large wood assemblages and elements may be assumed stable when the median element length exceeds channel width (i.e. Gurnell et al., 2002), likely to occur in small first order streams and rivers, which in turn are the most abundant order of water courses on the planet (Downing et al., 2012). However, even in small but steep headwater streams, large wood may be transported during hydrogeomorphic events of high magnitude such as debris flows (Galia et al., 2018) or extreme floods. A conceptual model for a first estimate of large wood transport in water courses is given in Kramer and Wohl (2017) including hydrological as well as morphological variables. Further detailed information about large wood dynamics in river networks can be found in recent reviews of Ruiz-Villanueva et al. (2016a) and Wohl (2017). Potentially mobile large wood

~~On the contrary, in case~~ may drifts~~of drifting large woody debris~~ during floods, elements ~~may~~ jam at bridges or other infrastructure and cause increased water levels, damage or completely destroy anthropogenic goods and structures (Schmocker and Hager, 2011). On the contrary, stable large wood remains in place, reduces water conveyance (Wenzel et al., 2014) and leads to increased water levels upstream and in turn, increased risk of flooding and water logging in surrounding areas. For these~~is~~ reasons, ~~LWD~~LW is removed from European rivers and streams for more than a century (Wohl, 2015) also to ensure navigability in larger rivers (Young, 1991) ~~and water conveyance (Wenzel et al., 2014)~~. As a result, the usage of ~~LWD~~LW in river restoration in the form of leaving naturally transported woody debris in-stream or artificial stable wood placements is discussed controversially (Roni et al., 2015; Wohl, 2017).

With respect to the potential risks of ~~large woody debris~~large wood for anthropogenic goods on the one hand and high ecological benefits on the other, it may be necessary to distinguish river sections in which large wood can remain or be introduced from those where it needs to be removed (Wohl, 2017). Large wood related segmentation of rivers and streams requires knowledge of the physical effects caused by mobile and stable in-channel ~~large woody debris~~large wood. Although several studies ~~investigate~~ address the general hydraulic impact of ~~LWD~~LW in field studies (i.e. Daniels and Rhoads, 2004; Daniels and Rhoads, 2007; Wenzel et al., 2014), ~~and~~ laboratory experiments (i.e. Young, 1991; Davidson and Eaton, 2013;

Bennett et al., 2015) and reviews (i.e., Gippel, 1995; Montgomery et al., 2003) regarding the alteration of water level, flow pattern, flow velocity and discharge, a project and site specific examination is necessary to evaluate local consequences of intended stream restoration measures.

The mobility, transport and deposition of large wood (i.e. Ruiz-Villanueva et al., 2014; Ruiz-Villanueva et al., 2016b) as well as the resulting physical effects of stable in-channel ~~LWD~~LW (Smith et al. 2011) can be addressed using numerical hydrodynamic models ~~(Smith et al., 2011)~~. Numerical hydrodynamic models for the simulation of open-channel hydraulics can be classified by their dimension and solve the shallow water equations in their one-, two- or three-dimensional form for simulating channel flow in just one (x-)direction (1D), horizontally resolved (x- and y-direction) but depth-averaged (2D) or fully resolved in x-, y- and, z-direction (Liu, 2014). Due to i.e. the increasing effort of work and computational time with increasing dimension, the applicability of 1D, 2D or 3D models depends on the scale and phenomena of interest (Liu, 2014). For simulating the general hydraulic behaviour on reach-scale, 2D models are useful tools (Liu, 2014). A detailed description of the different model types and examples of application can be found in Liu (2014) or Tonina and Jorde (2013) with focus on ecohydraulics. For instance, Ruiz-Villanueva et al. (2014) and Ruiz-Villanueva et al. (2016b) simulate large wood transport and remobilization using a two-dimensional hydrodynamic model. Several studies also consider stable ~~large woody debris~~large wood in the scope of one- and two-dimensional hydrodynamic simulations for example for investigating its influence on flood hydrographs (Thomas and Nisbet, 2012), on floodplain connectivity (Keys et al., 2018) or are considered in research applications with an ecological focus by investigating the effect of stable LW on habitat availability or suitability ~~-~~(i.e. He et al., 2009; Hafs et al., 2014~~;~~). In ~~Lange~~addition, Lange et al. ~~,~~ (2015) simulate the effect of roughness elements including stable LW in the scope of stream restoration analyses. Regarding the hydraulic impact of stable large wood on flood hydrographs, Thomas and Nisbet (2012) simulate large wood to delay flood passage but no attenuation of peak discharge is modelled. Similar effects of stable LW on flood hydrographs were investigated by Wenzel et al. (2014) in field experiments, where a delay and a narrower shape through a transformation from higher to lower discharges, but only a minor attenuation of the average flood hydrograph was observed. Furthermore, representing and integrating of ~~large woody debris~~large wood elements in hydrodynamic models is addressed in different studies using three-dimensional hydrodynamic models (i.e. Smith et al., 2011; Allen and Smith, 2012; Lai and Bandrowski, 2014; Xu and Liu, 2017). However, the modelling approach applied varies with studies. As an extensive review of applicable numerical hydrodynamic modelling systems and approaches for simulating large wood is beyond the scope of the present study, a recent overview with focus on LW dynamics as well as the representation of large wood and vegetation in simulations can be found in Bertoldi and Ruiz-Villanueva (2017).

Despite the necessity of a discrete representation of stable ~~large woody debris~~large wood elements in the calculation mesh of hydrodynamic models for obtaining accurate results (Smith et al., 2011), as conducted in different studies (i.e. Hafs et al., 2014; Lange et al., 2015; Keys et al., 2018), ~~,~~ ~~LWD~~LW elements are often accounted for using roughness coefficients in hydrodynamic model applications (Smith et al., 2011). The impact of ~~large woody debris~~large wood on in-channel roughness is investigated by Gregory et al. (1985), Shields and Smith (1992), Shields and Gippel (1995), Dudley et al. (1998), MacFarlane and Wohl, (2003) and Wilcox and Wohl (2006). In addition, Curran and Wohl (2003) and Wilcox et al. (2006) have studied its partial contribution to channel roughness coefficients. However, a methodological lack remains in quantitatively estimating ~~LWD~~LW related changes of in-channel roughness coefficients (Wohl, 2017), especially under field conditions (Wilcox et al., 2006).

Against this background, the aim of the present study is to simulate the physical effects~~quantify the influence~~ of stable in-channel ~~LWD~~LW elements on flood hydrographs ~~on in-channel roughness coefficients~~ in a creek reach in low mountain ranges using a two-dimensional hydrodynamic model and previously conducted field experiments, explicitly described in Wenzel et al. (2014). The field data offer the rare opportunity to validate simulated large wood related hydraulic effects on hydrographs of small flood events. By conducting different hydrodynamic simulations, we aim (1) for the quantification of the change of channel roughness coefficients in the entire channel or at LW positions, necessary to obtain most accurate model results of flood hydrographs with stable large wood elements in the channel. As discrete LW elements are required for most accurate model results (Smith et al. 2011), we aim (2) for comparing previous model results with simulations with discrete large wood elements created through manipulating the calculation mesh. However, the integration of discrete elements into the calculation mesh can be highly time- and work-intensive (Lai and Bandrowski, 2014), which becomes especially true for larger scale applications. Hence, a comparison of the simulation accuracy between incorporating large wood through a rather quick change of channel roughness coefficients and as time-demanding simplified mesh elements can be provide beneficial information for future studies simulating stable large wood related effects on stream hydraulics and ecology. This is underlined by Grabowski et al. (2019) who identified remaining uncertainties for the use of large wood in river restoration and natural flood risk management in practice. Knowledge gaps remain for instance regarding the alteration of channel roughness and hydraulic impacts such as backwater effects for the identification of local risks (Grabowski et al., 2019) which can be addressed with hydrodynamic models.

Although limited to smaller streams and rivers were large wood jams and elements can be assumed as stable or situations in which large wood elements are fastened, the present study can contribute to the ability of predicting hydraulic impacts of stable in-channel large wood within hydrodynamic simulations and can also provide beneficial practical information for conducting simulation-based impact assessments of stream restoration projects considering stable large wood by comparing different methods of large wood integration.

~~In addition, different methods of implementing stable LWD are examined and evaluated, for example by altering reach-wise in-channel roughness coefficients on the one hand or as discrete roughness elements in the calculation mesh on the other.~~

~~By investigating the effects of stable LWD on reach-wise roughness coefficients and possibilities to represent LWD elements in hydrodynamic models, the present study will contribute to the understanding of the hydraulic impact of large woody debris in fluvial environments as well as its simulation and prediction. Understanding its effects and the ability of predicting hydraulic impacts of LWD in hydrodynamic simulations can be highly important for the use of LWD in stream restoration projects and ecological-orientated management approaches in the scope of the WFD.~~

2 Study ~~area~~reach

The study ~~area~~ reach comprises a 282 m long section of the Ullersdorfer Teichbächel, a small first order headwater creek located in the Ore Mountains, south-eastern Germany. The catchment of the Ullersdorfer Teichbächel (50°36'48.52" N, 13°15'51.24" E, WGS84) covers an area of 1.8 km² and drains into the river Elbe via several higher order tributaries including Schwarze Pockau, Flöha, Zschopau and Mulde.

The study reach is located in the catchment's centre and approximately 50 m downstream of an artificial rafting pond built in the 16th century. Two Thomson-weirs mark the study reach's upper and lower limits at elevations of 754.1 and 744.5 a.s.l. (Fig. 1) resulting in a difference in elevation of 10.4 m and an average channel gradient of 3.7 %. Channel dimensions vary strongly along the study reach i.e. channel width ranges from < 0.8 to 2 m.~~0.3 m (Wenzel et al., 2014).~~ Similarly, a high variability of stream bed grain sizes can be detected (Fig. 2).~~.~~ Moderately steep sections with a sand and fine gravel dominated bed structure alternate with reach sections of higher gradients dominated by coarse gravel, cobbles and small boulders with sizes of up to 0.3 m in diameter. The boulders consist of gneiss varieties representing the dominating bed rock formations in the catchment. Beside a highly variable stream width, alternating slope gradients and grain sizes lead to a highly diverse distribution of stream depth along the study reach and hence, a generally complex channel structure.

The overall morphological character along the 282 m study reach consists of riffle-pool sequences in moderately steep sections as well as step-pool morphologies along sections having smaller channel widths and larger in-channel boulders (Fig. 2). In the latter, channel-spanning steps with corresponding hydraulic jumps and eroded pools have been observed in May 2017.

The majority of the catchment of the Ullersdorfer Teichbächel is covered with coniferous forest on largely cambisols and podzols including scattered deciduous trees sprinkled in. The dominating species is spruce (*Picea abies*) with occasional occurrence of mountain pines (*Pinus mugo*) and beech trees (*Fagus sylvatica*) (Wenzel et al., 2014). Trees occur only scatteredly in the narrow floodplain along the channel of the study reach with grassy vegetation on fluvic gleysols covering most parts. However, smaller floodplain sections are covered with bare soil or leaf litter. Perpendicular to the direction of flow, the maximum width of the floodplain measured from channel banks varies between 7 and 0 m, when channel banks immediately change into the embankments confining the study reach in length.

At the nearest gauging station Zöblitz, which is located approximately 13 km downstream the catchment's outlet at the river Schwarze Pockau and drains an area of 125 km², the mean annual discharge is 2.29 m³ s^{-1}. If the value is extrapolated using a ~~regional analyses~~regional analysis based on drainage areas the mean discharge at the outlet of the study reach is 16 l s^{-1}. The flow regime of the study area is dominated by snow melt generating high flows in March and April (gauge Zöblitz, period 1937 to 2015; LfULG, 2017a). Floods of low to medium magnitudes are generated by intense snowmelt and rainfall on snow in spring or by storm events in summer. Larger flood events are caused by summer storms only (Petrow et al., 2007) but the flood magnitudes are strongly influenced by land use and are greatly affected by past forest changes (Reinhardt-Imjela et al., 2018).

3. Material and mMethods

3.1 The hydrodynamic model HYDRO_AS-2D

In this study, the two-dimensional hydrodynamic model HYDRO_AS-2D (version 2.2) is used to simulate the flow in the study reach with and without LWDLW. HYDRO_AS-2D was developed for practical applications in water management (Nujić, 2006) and is used in several studies simulating flow conditions in river sections for flood risk management (i.e. Rieger and Disse, 2013) or with an ecological focus (i.e. Lange et al., 2015) as well as in flood risk management applications and. can produce a higher goodness-of-fit compared to other two-dimensional models as exemplarily shown in Lavoie and Mahdi (2017). Especially in southern Germany and Austria, HYDRO_AS-2D became a standard 2D modelling system for hydrodynamic model applications (Faber et al., 2012). Due to the numerical approaches used in the modelling system, HYDRO_AS-2D is capable of accurately simulating mass exchange between channel and forelands, streams comprising hydraulic jumps, steep channel sections andas well as a high variability of channel width as well as dike breaches (Nujić, 2006). The latter is to some extent comparable with the rapid release of water initiated by opening the flap gate weir used in the field experiments (see chapter 3.2). For the above-named reasons, HYDRO_AS-2D was chosen for the present study..

HYDRO_AS-2D solves the two-dimensional shallow water equations (SWC) at each node of a linear calculation mesh composed of quadrilateral and triangular elements of different sizes, representing a digital terrain model of the channel and the forelands. Shallow water equations are solved using finite volume approximations for spatial discretion, while time is discretized using second order Runge-Kutta methods (Nujić, 2006). Water flow is computed through all sides of the control volume around each node using different order polynomials and upwind schemes (Nujić, 2006). Surface roughness is represented by Strickler coefficients defined for each element of the calculation mesh. Similarly, local viscosity can be defined for each mesh element. Mesh generation, pre-processing, the setting of model boundary conditions as well as simulation result visualisation of HYDRO_AS-2D v2.2 is conducted using the software Surface Water Modelling System (SMS) v10.1 (Aquaveo Inc., USA). An overview of the methodological procedure described in the following sections can be found in figure 3.

3.2 Datasets and mesh generation

The presented study is based on data previously collected during field experiments in March 2008 (Wenzel et al. 2014) in the river section under investigation. In this earlier study, the pond upstream the experimental reach was dammed using a flap gate weir and multiple flood waves of equal magnitude (return period of 3.5 years) were generated. The first 8 experimental runs were conducted with 9 large woody debrislarge wood elements (spruce tree tops with a length ranging from 3 to 11.5 m, mean length 8.5 m), which were placed and fastened in the channel lengthwise 9 months earlier. After the experimental runs with LWDLW, all LWDLW elements were removed and 12 additional flood waves were generated without the trees. During all experimental runs, water levels were continuously recorded with a temporal resolution of 1 s at the beginning and end of the river section using Thomson-weirs equipped with pressure gauges. For each Thomson-weir, the averaged (mean) hydrograph of experimental runs with and without ~~LWD~~LW is calculated and used as the upper model boundary condition (Thomson-weir 1) and for the validation of model outputs (lower boundary condition, Thomson-weir 2), respectively.

During the development of the hydraulic model, a measurement error was detected in the water level measurement at Thomson-weir 1 (input weir), which results in a significantly lower discharge volume at Thomson-weir 2, although larger water inflows between both weirs were not observed in the field. The measurement error of the input weir was corrected by increasing water levels in the original water level time series of the pressure gauge and recalculating discharge. The measured water levels at the first weir had to be increased by a maximum of ~~2.4 cm~~ 0.024 m until the total flood volume at both weirs was nearly equal.

To generate a digital terrain model (DTM) for the studied river section, data from a cross-sectional geodetic survey conducted with Spectra Precision AB Geodimeter 400 in 2008 were available. To improve the implementation of the channel in the hydrodynamic model the channel width was surveyed again in intervals of 5 m using a measuring stick in May 2017. Furthermore, a digital elevation model with a spatial resolution of 2 x 2 m (Saxon State Office of Geoinformation and Surveying, 2008) is used for better reproduction of the floodplain morphology. The final DTM for the model is generated from processing and combining all topographic datasets in the software environment ArcGIS v10.5 (ESRI Inc., USA) using the implementation based on the procedure described in Hutchinson (1989) for interpolation. The resulting DTM is exported as equally spaced elevation points with a spatial resolution of approximately 0.5 x 0.5 m for the entire study reach including riparian areas and embankments. From the point grid the calculation mesh required for simulations with HYDRO_AS-2D is created. Mesh generation is done in the software environment SMS v10.1 and according to mesh quality requirements of HYDRO_AS-2D, such as minimum and maximum angle of mesh elements or maximum number of element connections per node (Nujić, 2006). The calculation mesh is composed of quadrilateral and triangular elements. In the channel of the study reach, quadrilateral elements are created by stepwise mesh generation between cross-sectional point elevation profiles through linear interpolation of elevation between profiles. A triangular mesh is generated in the riparian areas and along embankments by using equally spaced elevation points. After merging quadrilateral channel elements and triangular foreland elements as well as including additional topographic features to the calculation mesh (~~fig. 3~~Fig. 4) to match field observations, roughness coefficients are assigned to each mesh element. The Strickler coefficients k_{st} were estimated during field surveys in May 2017 with reference to established roughness coefficient classifications for different land cover and surface material types (i.e. Chow, 1959) as well as in accordance with observed ground cover during field experiments in 2008.

3.3 Hydrodynamic modelling

Boundary conditions for the unsteady hydrodynamic simulations are defined in SMS v10.1. For flow simulations of the experimental reach without ~~LWD~~LW, the averaged discharge time series without ~~LWD~~LW at Thomson-weir 1 (Fig. 5~~2~~) is defined as the water inflow into the study reach. Water influx is defined at the location of Thomson-weir 1 in the calculation mesh, represented by the uppermost cross-sectional nodestring in the channel. For the simulations with in-channel ~~LWD~~LW, the averaged time series with ~~LWD~~LW at Thomson-weir 1 (Fig. 5~~2~~) is used as the system input.

For the simulations without and with ~~LWD~~LW, the inflow hydrographs at Thomson-weir 1 are extended forwardly by 5400 seconds using the first discharge value of the corrected mean experimental hydrograph without and with ~~LWD~~LW. This is done to achieve field conditions of minor flow through the channel in the study reach before the experimental flood waves enter the channel. This results in a total simulation time of 9000 seconds for each simulation with and without ~~LWD~~LW with a temporal resolution of 1 second.

Simulation results are obtained at the location of Thomson-weir 2 in the calculation mesh represented by the lowermost cross-sectional nodestring in the channel of the study reach. Model performance is assessed by visual comparison of mean observed and simulated flood hydrographs without and with ~~LWD~~LW at Thomson-weir 2 as well as by calculating the statistical goodness-~~-~~of-~~-~~fit parameters Nash-Sutcliff-Efficiency (NSE), percent bias (PBIAS) and RSR (ratio of the root mean square error to the standard deviation of observed values) using the hydroGOF package by Zambrano-Bigiarini (2017) in R (R Core Team, 2017).

3.4 Hydrodynamic simulation variants

In the scope of this study, four different simulation variants are applied to investigate effects of in-channel ~~large woody debris~~large wood on flood hydrographs in a small low mountain stream: (1) the base variant BV representing the simulation of field experiments without in-channel ~~LWD~~LW and (2-4) variants V1 to V3 for simulating field experiments with ~~LWD~~LW.

Variant BV is used to obtain the best fit of the mean observed and simulated hydrograph without ~~LWD~~LW at Thomson-weir 2 through iteratively adjusting Strickler roughness coefficients in the channel and in riparian areas. In the base variant and all other simulation variants calibration is performed to achieve the best possible simulation of the moment of rise, the rising limb and peak discharge of the mean observed hydrograph at Thomson-weir 2. Calibrated roughness coefficients leading to the best fit in variant BV will be used as initial roughness coefficients in the calculation mesh of variants V1, V2 and V3.

Variant V1 represents the first simulation with ~~LWD~~LW. Calibrated Strickler coefficients from variant BV are iteratively adjusted for the entire channel (integrated roughness). Adjustments are made percent-wise and with equal magnitude to enable equal scaling of spatially varying roughness coefficients of mesh elements in the channel. This approach was included because the integrated channel roughness of a river section is an important input parameter for rainfall-runoff models at mesoscale or of larger watersheds, which often use only one Strickler (or Manning) coefficient per section.

Similarly, roughness is scaled in **variant V2**, in which Strickler coefficients from variant BV are adjusted at the positions of all ~~LWD~~LW elements only. ~~LWD~~LW element locations and corresponding ~~LWD~~LW influenced channel sections (length of each ~~LWD~~LW element) are derived from Wenzel et al. (2014). For each channel section roughness coefficients are adjusted percent-wise and with equal magnitude.

In contrast to variants V1 and V2, where ~~LWD~~LW is represented by reach-wise and section-wise adjustment of Strickler coefficients of quadrilateral in-channel calculation mesh elements, **variant V3** includes the integration of simplified discrete roughness elements by manipulating the existing calculation mesh used in variant BV. Therefore, discrete elements with the maximum stem length and width (without branches) of each individual ~~LWD~~LW are incorporated into the calculation mesh by creating corresponding rectangular polygons overlying the mesh. Polygons are positioned in order to have the largest possible part located in the channel of the study reach. Based on the existing calculation mesh, new mesh nodes are positioned in ~~20 cm~~0.2 m intervals along polygon boundaries and within a ~~10 cm~~ 0.1 m distance outside polygons. Nodes along polygon boundaries receive the elevation of the closest upstream node increased by ~~150 cm~~1.5 m. The elevation of nodes within ~~10 cm~~0.1 m distance ~~are~~ is interpolated from the existing calculation mesh. As mesh quality requirements (see chapter 3.2) need to be maintained, positions of some added nodes are slightly shifted. Additional quadrilateral and triangular mesh elements are created between nodes added to the mesh. All newly created mesh elements representing discrete ~~LWD~~LW elements (Fig. 4~~3~~) are parameterized with the same Strickler coefficient in order to retrieve the best fit between simulated and mean observed hydrograph with ~~LWD~~LW at Thomson-weir 2. Strickler coefficients of mesh elements representing discrete ~~large woody debris~~large wood elements are used to account for i.e. branches of real spruce tree tops implemented into the channel during the field experiments. Coefficients are determined iteratively during calibration of simulation variant V3.

4~~.~~ Results

4.1 Simulation variant BV

In the base variant, the best fit in the unsteady hydrodynamic simulation without ~~LWD~~LW was achieved with in-channel Strickler coefficients ranging from 6 $m^{1/3}\ s^{-1}$ for channel sections with larger boulders to 12 $m^{1/3}\ s^{-1}$ in channel sections where fine gravel forms the stream bed. A Strickler coefficient of 3.5 $m^{1/3}\ s^{-1}$ was defined for riparian areas during calibration. Observed and simulated hydrographs of the simulation are shown in fig. 6~~4~~. In general, the model closely simulates the characteristics of the observed hydrograph~~ very well~~. Only the crest is slightly wider in the model and a slight model underestimation can be observed at the beginning and in the second half of the simulation time. The good model performance is reflected by a high NSE of 0.99 as well as a low RSR (0.11) and PBIAS (-3.5 %). The statistical goodness-of-fit parameters of all simulation variants are summarized in table 2. The cumulative maximum inundated area comprises 739 m², defined as the total area of mesh elements inundated during simulation.

4.2 Variant V1 - Integrated increase of roughness in the channel

In the first simulation variant V1 of field experiments with in-channel ~~large woody debris~~large wood, Strickler coefficients were decreased in the entire channel based on the coefficients of the simulation without large wood (variant BV). A decrease of Strickler values and hence, an increase of roughness of 30 % in the entire channel resulted in the best fit between mean observed and simulated hydrograph. Consequently, in-channel Strickler coefficients range from 4.2 to 8.4 $m^{1/3}\ s^{-1}$ in variant V1. The 9 ~~LWD~~LW elements in the field investigations cover 75.1 m of the 282 m long channel reach, i.e. the simulated 30 % increase of the integrated channel roughness refers to a ~~LWD~~LW percentage of 27 % of the channel length.
The resulting simulated hydrograph of variant V1 shows a good representation of the time of rise as well as the rising limb of the observed hydrograph (Fig. 6~~4~~). However, in the peak discharge phase the simulated hydrograph does not rise continuously

until peak values are reached. If the Strickler coefficients in the channel foreland (riparian area) were decreased from 3.5 to 2.4 $m^{1/3}$ s^{-1} in addition to the channel roughness, the break in the crest of the hydrograph disappears. After adjusting roughness coefficients in riparian areas, rising limb and peak phase of the observed hydrograph are represented slightly better. Nevertheless, discharge values during peak phase show a distinct underestimation of observed values. Similarly, differences can be found along the falling limb between observation and simulation. The maximum inundated area comprises 861 m² before and 880 m² after riparian roughness adjustment. Nash-Sutcliffe-Efficiency values of 0.97 before and 0.98 after adjustment of roughness coefficients in riparian areas were achieved. The RSR shows values of 0.18 and 0.14 before and after adjustment, while PBIAS slightly increases after adjustment from -3.6 to -3.7 %. (Table 2).

4.3 Variant V2 - Increase of roughness at ~~LWD~~LW spots

In simulation variant V2, in-channel roughness coefficient derived from variant BV were altered in ~~large woody debris~~large wood affected channel spots only. Here, a reduction of Strickler coefficients of 55 % resulted in the best fit of observed and simulated hydrographs. Depending on the ~~LWD~~LW affected channel section, Strickler coefficients between 3.6 and 5.4 $m^{1/3}$ s^{-1} were derived. The resulting simulated hydrograph properly represents the time of rise. Compared to variant V1, the rising limb is less accurately modelled. Similarly to variant V1, a discontinuous peak phase is generated in the simulations. Again, an increase of the roughness in riparian areas is necessary to simulate a hydrograph with a more realistic, continuous rise of discharge up to the crest of the hydrograph. Strickler coefficients in riparian forelands were reduced from 3.5 to 1.9 $m^{1/3}$ s^{-1}. In addition, both simulated hydrographs (with and without subsequent adjustment of riparian roughness coefficients) show an overestimation of the observed discharge along the falling limb of the flood wave, while a distinct underestimation can be observed during the peak phase as well as in the beginning and the end of the experiments (Fig. ~~4~~6). Before adjusting riparian surface roughness, the maximum cumulative inundation area is 859 m². After subsequent adjustment inundated area rises to 892 m². NSE values range from 0.94 before to 0.96 after adjusting riparian Strickler coefficients, while RSR decreased from 0.24 to 0.19 and PBIAS from -4.2 to -4.0 (Table 2). With regard to the general shape of simulated hydrographs as well as the statistical model performance assessment, variant V1 reveals a better representation of the observed hydrograph of the field experiments with in-channel ~~large woody debris~~large wood.

4.4 Variant V3 - Implementation of ~~LWD~~LW as discrete elements

In the last simulation variant (V3), ~~large woody debris~~large wood is integrated into the model as simplified discrete elements by manipulating the calculation mesh. The created mesh elements representing discrete ~~LWD~~LW elements received a Strickler coefficient of 8.5 $m^{1/3}$ s^{-1} to account for branches and in order to obtain the best fit between mean observed and simulated hydrograph. As shown in fig. 6~~4~~, the simulated hydrograph rises slightly later than the mean observed hydrograph, which results in differences between simulation and observation along the falling limb. Additionally, a slight overestimation of peak discharges can be observed as well as the underestimation of discharges in the beginning and end of the simulation. The maximum water covered area comprises 927 m² and is much larger than in previous simulation variants. Statistical goodness-of-fit parameters show a NSE value of 0.90, a RSR value of 0.32 and PBIAS of -7.7 %. Especially the PBIAS of variant V3 is much higher than in all other simulation variants (Table 2). According to the classification of Moriasi et al. (2007), goodness-of-fit parameter values calculated for variant V3 as well as for all other simulation variants in this study indicate very good simulation results of high accuracy. Despite the temporal shift between the average simulated and observed flood hydrograph as well as the lower goodness-of-fit according to the classification of Moriasi et al. (2007), the general narrow shape of the flood hydrograph of the field experiments with in-channel LWDLW is most accurately modelled in variant V3.

5. Discussion

5.1 Simulations of flood hydrographs in the investigated creek section

In general, the 2D hydrodynamic model closely mimics the flow conditions of the field experiments without LWDLW (variant BV) very well. Especially the time of rise, the rising limb and the flood peak are well accurately represented, minor deviations can be observed along the hydrograph's falling limb only due to the broader shape of the simulated hydrograph. However, it has to be noted that measurement errors may also occur in the field data demonstrated by the fact that the input time series measured at Thomson weir-1 had to be corrected to reduce the volume error between both weirs. After the correction, the cumulated volume error between both weirs was reduced to 4 $m^3 h^{-1}$ without LWDLW and 5 $m^3 h^{-1}$ for the field experiments with LWDLW (1 l s^{-1}/s) (Table 1). The remaining difference between both weirs lies in the range of what can be estimated as natural water influx between both weirs based on runoff per km^2 estimations from regional analyses of the nearest gauging station for the days of the field experiments (LfLUG, 2017b). Depending of the spatial resolution of the DTM used for calculation (2 and 5 m), the average water influx ranges from 3 to 6 $m^3 h^{-1}$. Hence, the remaining volumetric difference can be attributed to diffuse lateral water influx during the run time of each experiment and are likely to be responsible for the modelled (Fig. 46) and observed (Fig. 52) lower discharges before and after flood passage at Thomson-weir 2. However, after correction it can be assumed that the measured data are a reliable reference for the hydrodynamic simulation.

The broader shape of the simulated hydrograph is likely to be caused by the calculation mesh used, representing the terrain surface. The calculation mesh is based on topographic field data gathered in the scope of the field experiments in 2008 to find most suitable locations to position large woody debrislarge wood elements (Wenzel et al., 2014). Therefore, small topographic features in the channel and adjacent riparian areas are not included in the elevation data set and hence, in the calculation mesh. This especially applies to step-pool sequences in the study reach. Steps and pools produce rapid flow energy losses caused by corresponding hydraulic jumps and resulting in a deceleration of flow (Wilcox et al., 2011), where the amount of energy loss dynamically depends on water level (Comiti et al., 2009). Furthermore, erosion and transport of bed material leads to flow energy losses (Yen, 2002). As such features are missing in the calculation mesh, roughness coefficients are used to account for their impact on water flow. However, calibrating in-channel roughness coefficients may lead to a much more continuous decrease of flow velocities instead of intense, punctual flow decelerations with implications for downstream flow conditions, in turn resulting in a broader peak of the simulated flood hydrograph. This illustrates the necessity of a high resolutionhighresolution calculation mesh including small scale topographic features in the channel and microtopography in riparian areas to obtain accurate model results.

Despite the discrepancies described above, the simulation of variant BV shows a very precise simulation of the observed hydrograph of the field experiments without ~~large woody debris~~large wood, which is also indicated by the statistical goodness-of-fit parameters revealing a very high model accuracy according to the classification of Moriasi et al. (2007). Hence, averaged flood hydrographs of the field experiments without ~~large woody debris~~large wood can be accurately simulated using the set-up model, illustrating its applicability for simulating the flow conditions in the study reach.

5.2 Simulating the hydraulic impact of stable in-channel ~~LWD~~LW using roughness coefficients

In simulation variants V1 and V2, roughness coefficients are used to represent ~~large woody debris~~large wood in the study reach. Both variants show a correct simulation of the time of rise of the flood hydrograph. Differences occur along the rising limb as well as the hydrograph's peak. Here, variant V1 produces a better fitting hydrograph. Compared to the simulation result of the mean observed hydrograph of the field experiments without in-channel ~~LWD~~LW, variants V1 and V2 produce less ~~well~~ closely fitting simulated hydrographs, which is also indicated by the slightly lower values of statistical goodness-of-fit parameters. Nevertheless, these values still indicate a very high model accuracy.

For both simulation variants, subsequent adjustment of riparian roughness coefficients is necessary to improve the goodness-of-fit. Only increasing riparian roughness by decreasing Strickler coefficients results in a smooth crest as it can be originally observed in the field experiments. In the model, water flows too fast through adjacent riparian areas without subsequent adjustment of roughness. Emerged rigid elements such as riparian vegetation can lead to an increase of Manning's n and hence, a decrease of Strickler coefficients due to increasing friction exerted on flow (Shields et al., 2017). Therefore, generally low flow depths, a largely continuous cover of dense grassy vegetation as well as an uneven microtopography due to i.e. elevated grass root wads observed in adjacent riparian areas during field experiments ~~may~~ could have led to the necessity of increasing local roughness in this study; especially due to the lack of such features in the model's calculation mesh.

Simulation variant V1 produces a better representation of the average observed hydrograph of field experiments with in-channel ~~LWD~~LW by increasing roughness in the entire channel of the study reach instead of increasing roughness at ~~LWD~~LW affected spots only (V2). In-channel ~~LWD~~LW elements decelerate flow beyond their own dimensions by generating upstream backwater areas and downstream wake fields of substantial length (i.e. Young, 1991; Bennett et al., 2015). Such features were also observed during field experiments (Wenzel et al., 2014). That means that ~~LWD~~LW affects flow upstream and downstream in an area which is larger than the wood piece itself, which can be one reason for the slightly better simulation results in V1 compared to V2.

Decreasing Strickler coefficients by 30 % in variant V1 compared to 55 % in ~~LWD~~LW affected spots only (V2) are in the range of previous studies. For instance, Gregory et al. (1985) detected an ~~LWD~~LW related increase in Manning's n by 48.5 % and Dudley et al. (1998) show an average increase of 36 %. Furthermore, MacFarlane and Wohl (2003) compare streams with and without ~~LWD~~LW and find Darcy-Weisbach's f on average 58 % higher in streams containing in-channel ~~LWD~~LW.

However, it should be noted that boundary conditions, such as discharge, river size, ~~LWD~~LW volume, etc. as well as the methodological approaches greatly vary between studies. For example, MacFarlane and Wohl (2003) investigate high-gradient mountain streams while Shields and Gippel (1995) focus on lowland rivers.~~, illustrating~~ This illustrates the need of a common framework for better comparability of studies on ~~large woody debris~~large wood previously proposed by Wohl et al. (2010). This becomes especially true regarding the influence of stable in-channel ~~LWD~~LW on roughness coefficients.

5.3 Representation of in-channel ~~LWD~~LW as discrete elements

Although roughness coefficients are often used to account for the hydraulic influence of stable in-channel ~~large woody debris~~large wood, the implementation of ~~LWD~~LW as discrete elements in the calculation mesh may further improve simulation results (Smith et al., 2011). However, field data are an essential reference to compare the implementation of wood by altering in-channel roughness coefficients with the implementation of discrete elements in the calculation mesh.

Nevertheless, one problem of discrete ~~LWD~~LW elements in hydrodynamic models is that wood pieces have a complex shape, which strongly varies from piece to piece (and over time) concerning their geometry with twigs, branches, needles and floating debris caught up in the twigs. This complex shape as well as a permeability of ~~LWD~~LW elements and jams cannot be implemented in depth-averaged hydrodynamic models in detail and has to be simplified. The simplified implementation can be the reason, why variant V3 produces a temporal shift between mean simulated and observed flood hydrograph causing a slightly delayed rise and falling limb of the flood hydrograph and hence, a delayed passage of the flood wave at Thomson-weir 2. This indicates too strong flow alterations in the model resulting in higher amounts of water retained in the study reach. In this study, ~~LWD~~LW elements are implemented as discrete parts of the calculation not allowing water flowing through. Hence, they are designed with too extensive simplifications to account for the complexity of real ~~LWD~~LW elements.

Nevertheless, the variant V3 generates the best simulated hydrograph in regard to its overall shape compared to the mean observed hydrograph of field experiments with ~~LWD~~LW, indicating that discrete elements are ~~a very good~~an ~~starting~~appropriate starting point for an advancement of model implementation and further studies on the hydrodynamics of in-channel ~~LWD~~LW. This is in accordance with previous studies using three-dimensional hydrodynamic models (computational fluid dynamics, CFD).~~:~~ For example, ~~O~~on the one hand, general flow patterns caused by large wood can be simulated using impermeable discrete elements, when an accurate simulation of flow near ~~LWD~~LW objects is neglectable (Xu and Liu, 2017). On the contrary, simplifications of ~~LWD~~LW objects made during the integration process into the calculation mesh may cause deviations and inaccuracies (Allen and Smith, 2012). Impermeability, dimensions and positions of elements result in too strong flow alterations and a temporal shift of the modelled hydrograph, while its general shape indicates the best simulation of flow processes in the study reach. Intense flow alterations may also account for the fact that a subsequent adjustment of riparian roughness coefficients is not required in variant V3, as too strong energy losses and flow declarations caused by discrete ~~LWD~~LW objects account for roughness originally caused by other roughness elements not represented in the calculation mesh such as riparian vegetation and microtopography.

Nevertheless, variant V3 still shows a very high goodness-of-fit. A similarly high Nash-Sutcliff-Efficiency was obtained in the study of Keys et al. (2018), who use discrete weirs to represent ~~large woody debris~~large wood objects for simulating their effects on floodplain connectivity. However, although variant V3 reveals the best simulation result, the temporal shift results in a lower goodness-of-fit and hence, model quality compared to simulation variants V1 and V2. Therefore, solely relying on statistical goodness-of-fit indicators on such high spatio-temporal scale may not be sufficient and visual interpretation should not be excluded when assessing model results.

5.4 General limitations and implications for further research

The present case study investigates the impact of large wood on the flood hydrographs under stable (fastened) conditions. This is often done in model-based impact assessments (i.e. Hafs et al. 2014, Lange et al., 2015) but does not necessarily represent reality. Large wood stability depends on several hydrological and morphological factors (see Kramer and Wohl, 2017) and may mostly occur in small streams and rivers, where large wood elements are large compared to the channel dimensions (i.e. Gurnell et al., 2002). Consequently, the validity of the results presented is limited to these hydromorphological conditions. A first assessment of potential large wood transport and hence, mobility can be evaluated with the conceptual model presented in Kramer and Wohl (2017). If wood transport can be expected or wood elements are not fastened, i.e. in the scope of a restoration measure, hydrodynamic simulations of large wood dynamics may be necessary as presented in Ruiz-Villanueva et al. (2014).

In addition, the model results are restricted to the specific set-up of boundary conditions of the field experiments in Wenzel et al. (2014). Thus, the results are valid for i.e. the amount of large wood, its volume and orientation as well as the channel morphology and hydrological conditions of the field experiments but might not be transferable without adjustment. Further simulations of the approaches presented in this study with varying boundary conditions regarding channel morphology and discharge are necessary to validate the results and further compare approaches of incorporating stable large wood in hydrodynamic models. This is also true for the increase of roughness determined during calibration and resulting in the best fit of the model. When modelling the potential impact of stable large wood as a change of in-channel roughness coefficients with different boundary conditions and without data of large wood-influenced discharge for calibration, the application of ensemble-simulations with literature-based values of large wood induced increase of roughness may be used for a first assessment. Here, estimation methods for large wood induced roughness increase in small, high-gradient streams and rivers, as previously developed by Shields and Gippel (1995) for large lowland rivers or reviews of recent advances in research on the hydraulics of LW in fluvial systems would be highly beneficial, as it is the case for recent reviews and meta-analyses addressing ecological implications (i.e. Roni et al., 2015), large wood dynamics (i.e. Ruiz-Villanueva et al., 2016a; Kramer and Wohl, 2017), related risks for anthropogenic infrastructure (i.e. De Cicco et al., 2018) and large wood in fluvial systems in general (Wohl, 2017).

Although the roughness coefficient approach presented in this study is feasible with all models which are based on the SWE, only models enabling the simulation of two- and three-dimensional flow conditions can be used for the incorporation of simplified discrete large wood elements. Here, further restrictions may apply corresponding to the model-specific discretion methods and hence, restrictions regarding the design of the underlying calculation mesh. Thus, different models available should be compared with similar boundary conditions. This also true for the design of discrete LW elements as part of the calculation mesh. In this study, only a single design of discrete large wood elements was incorporated as topographic features into the calculation mesh. Other designs may be also suitable such as discrete weirs (Keys et al., 2018) or arrays of pillars allowing water to flow through. Further research including a comparison of different designs of discrete large wood elements in 2D-simulations under equal boundary conditions could be beneficial. Furthermore, in the present study calibration is solely conducted using the hydrograph at Thomson-weir 2. As point measurements of flow depth, velocity and inundation extent in the field could improve model accuracy assessments, multi-criteria calibration approaches may be considered in future studies simulating the hydraulic effects of stable in-channel large wood.

6~~.~~ Conclusion

The hydrodynamic simulations conducted in the present study show that average flood hydrographs of previously conducted field experiments without in-channel ~~LWD~~LW can be accurately simulated in the small and high-~~-~~gradient study reach using HYDRO_AS-2D. Nevertheless, minor discrepancies need to be ~~taken into account~~considered. The effect of stable in-channel LW was satisfactorily simulated using roughness coefficients. However, differences in model quality can be detected between increasing in-channel roughness in the entire reach or in LW affected spots only, where the latter results in a lower statistical goodness-of-fit. Visually, most accurate simulations of LW related impacts on flood hydrographs regarding its overall shape can be obtained using discrete large wood elements as proposed in previous studies (Smith et al., 2011) but comes with a temporal shift between observation and simulation due to the impermeability of the LW elements as well as a higher demand of effort and time for their incorporation into the model. Therefore, using channel roughness coefficients for simulating the impact of stable large wood elements on discharge time series suggests to be similarly accurate as the implementation of discrete elements on reach or larger (i.e. catchment) scale, where minor differences are smaller than the overall model uncertainty. Although constrained to limitations and uncertainties presented in chapter 5, the results of this study indicate that the impact of stable in-channel large wood may be simulated with a reduced amount of time and work required for model set-up and incorporation of discrete large wood elements through the use of roughness coefficients. Thus, model-based impact assessments of, for instance, stream restoration measures considering stable large wood, may become more feasible; especially on larger scale or in less critical channel-sections, where a fully resolved flow assessment with three-dimensional models is not required or practical. However, the present study is restricted to narrow boundary conditions, in turn illustrating the need of further research comparing methods of stable large wood incorporation in different models with varying model-dimensions and boundary conditions regarding channel morphology, large wood characteristics and water flow. Nevertheless, by comparing methods for simulating the impact of stable large wood on the reach scale, the present study can provide helpful information for practical applications in modelling stable large wood related effects in small, first order streams and rivers.

, which can be attributed to lateral water influx between both weirs as well as a calculation mesh based terrain datasets lacking of small scale topographic features such as step-pool sequences and riparian microtopography. For this reason, high resolution topographic datasets acquired with high resolution survey techniques such as terrestrial LiDAR are required to obtain most accurate model results on such high spatio-temporal scale. In addition, in the present study calibration is solely conducted using the hydrograph at Thomson-weir 2. As point measurements of flow depth, velocity and inundation extent in the field would improve model accuracy assessments, multi-criteria calibration approaches may be considered in future studies simulating the hydraulic effects of stable in-channel large wood.

The effect of stable in-channel LWD can be accurately simulated using roughness coefficients as it is often done in hydrodynamic model applications. However, differences in model quality can be detected between increasing in-channel roughness in the entire reach or in LWD affected spots only. A reach-wise decrease of Strickler coefficients and in turn, increase of Manning's n by 30 % is comparable to previous studies investing the impact of LWD on channel roughness coefficients. This reveals better simulation results than solely increasing roughness in LWD spots by 55 %, due to large woody debris elements affecting channel flow in sections beyond their own dimensions by i.e. forming downstream wake fields. Therefore, a reach-wise alteration of in-channel roughness coefficients results in the best simulation of LWD related hydraulic effects on reach scale flood hydrographs.

Most accurate simulations of LWD related impacts on flood hydrographs regarding its overall shape can be obtained using discrete large wood elements as proposed in previous studies (Smith et al. 2011). Here, a close-to-nature design of discrete elements in the calculation mesh is essential for precise model results and in order to reduce uncertainties caused by element simplification, dimensioning and positioning (Allen and Smith, 2012). A close-to-nature representation does include element or jam permeability. However, naturally occurring flow through branches, under and over large woody debris objects cannot be accounted for in depth-averaged two-dimensional hydrodynamic models. Combined with the high amount of work and time consumption required for implementing discrete elements in a calculation mesh (Lai and Bandrowski, 2014), discrete large woody debris objects may be most applicable in detailed investigations with three-dimensional models on high spatial-temporal scales, where a detailed simulation of the resulting flow conditions is required. Discrete elements in two-dimensional hydrodynamic model applications may be used in the scope of preliminary studies where minor deviations are neglectable.

In contrast, altering roughness coefficients to represent stable large woody debris is less work-intensive and time-consuming. Hence, it may be applied to represent in-channel large woody debris on a larger spatio-temporal scale such as the catchment scale using one- and two-dimensional hydrodynamic models or in rainfall-runoff simulations, where minor differences are smaller than the overall model uncertainty. As the impact of large wood on reach-wise in-channel roughness coefficients depends on several factors including channel-width, water level, slope as well as LWD size, amount, orientation and position, ensemble-simulations with literature-based values of roughness increase may be used to simulate the influence of large woody debris. Here, reviews of recent advances in research on the hydraulics of LWD in fluvial systems would be highly beneficial; similar to recent reviews and meta-analyses addressing ecological implications (i.e. Roni et al., 2015), large wood dynamics

~~(i.e. Ruiz-Villanueva et al., 2016; Kramer and Wohl, 2017), related risks for anthropogenic infrastructure (i.e. De Cicco et al., 2018) and large wood in fluvial systems in general (Wohl, 2017).~~

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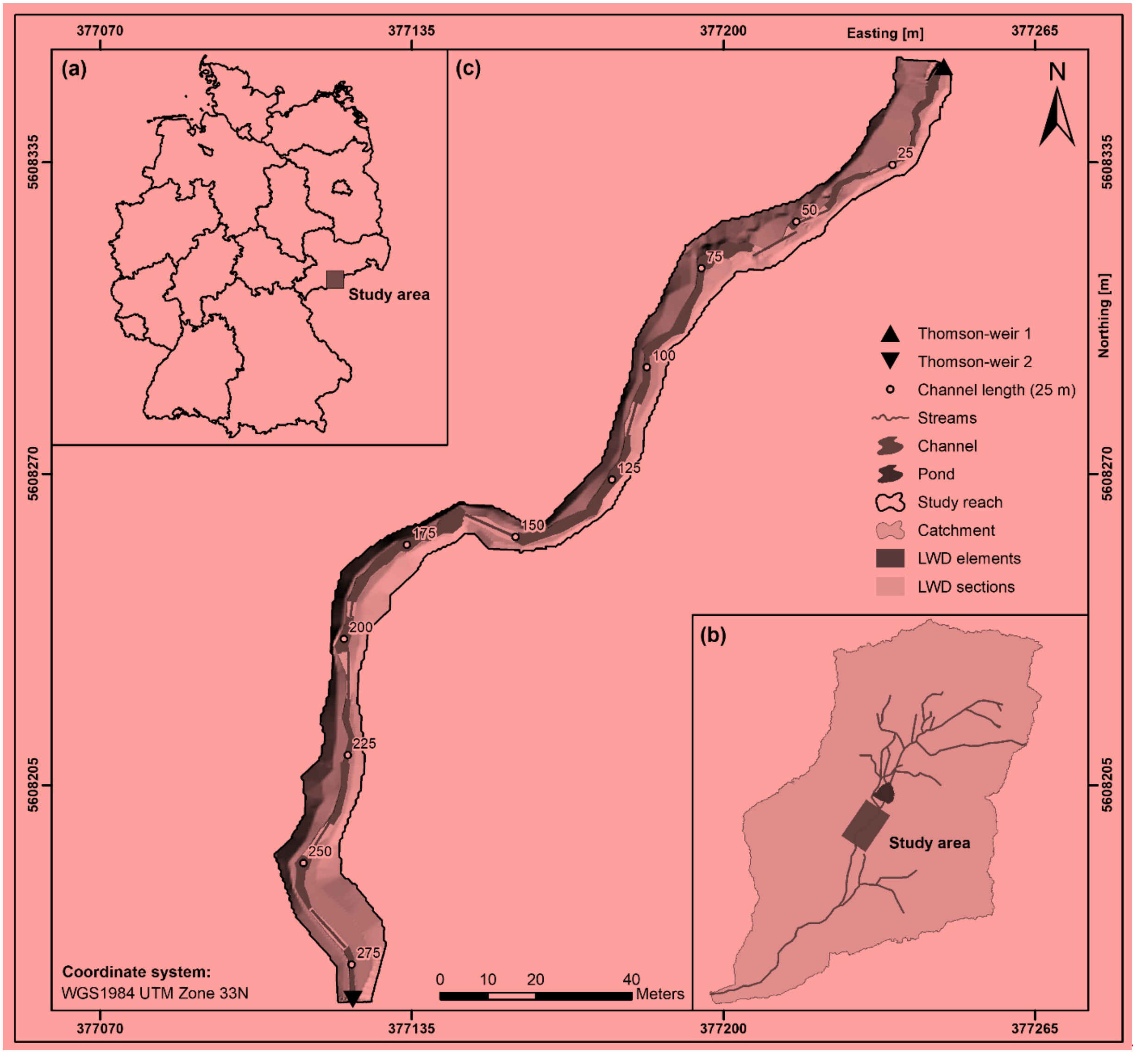


Figure 1: (a) Location of the study area in Germany (administrative units: BKG, 2018) and (b) position of the study reach in the catchment of the Ullersdorfer Teichbächel (stream network: LVA, 2002). (c) LWD affected sections and positions of discrete LWD elements in the study reach.

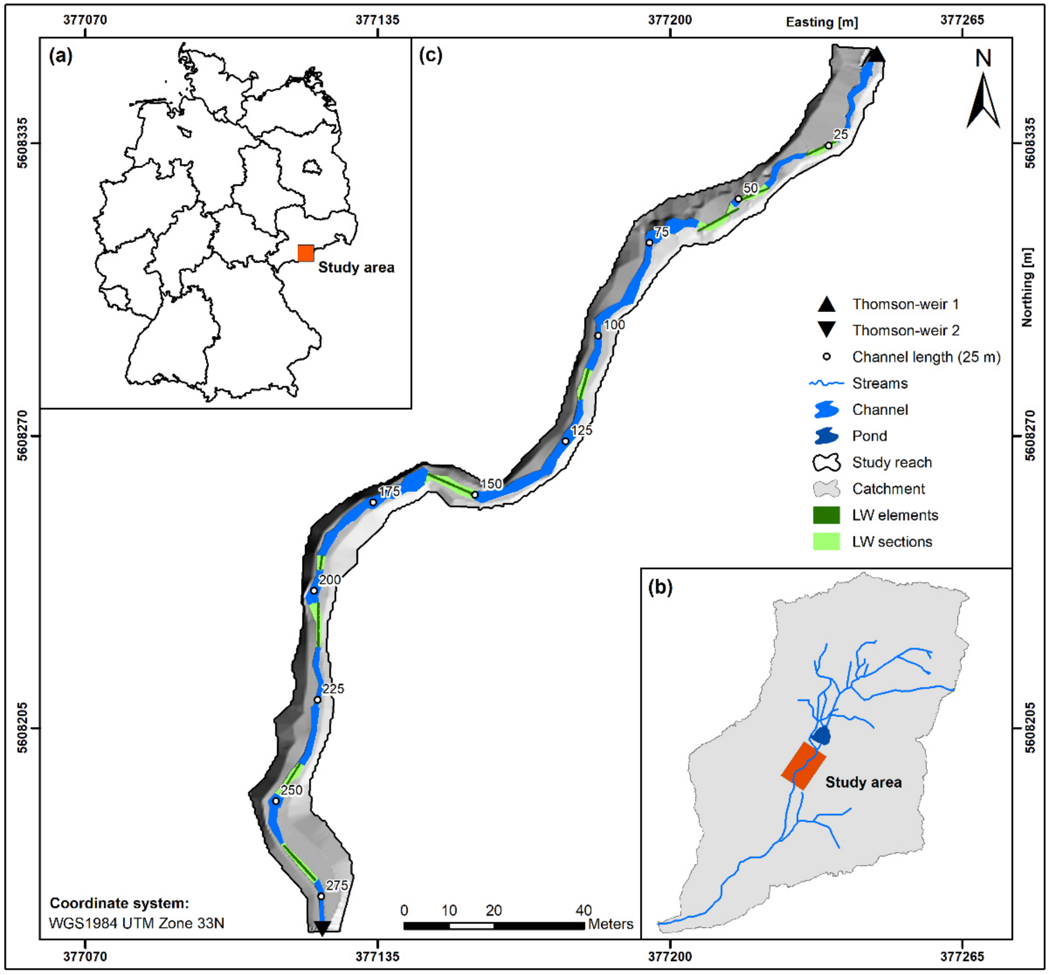
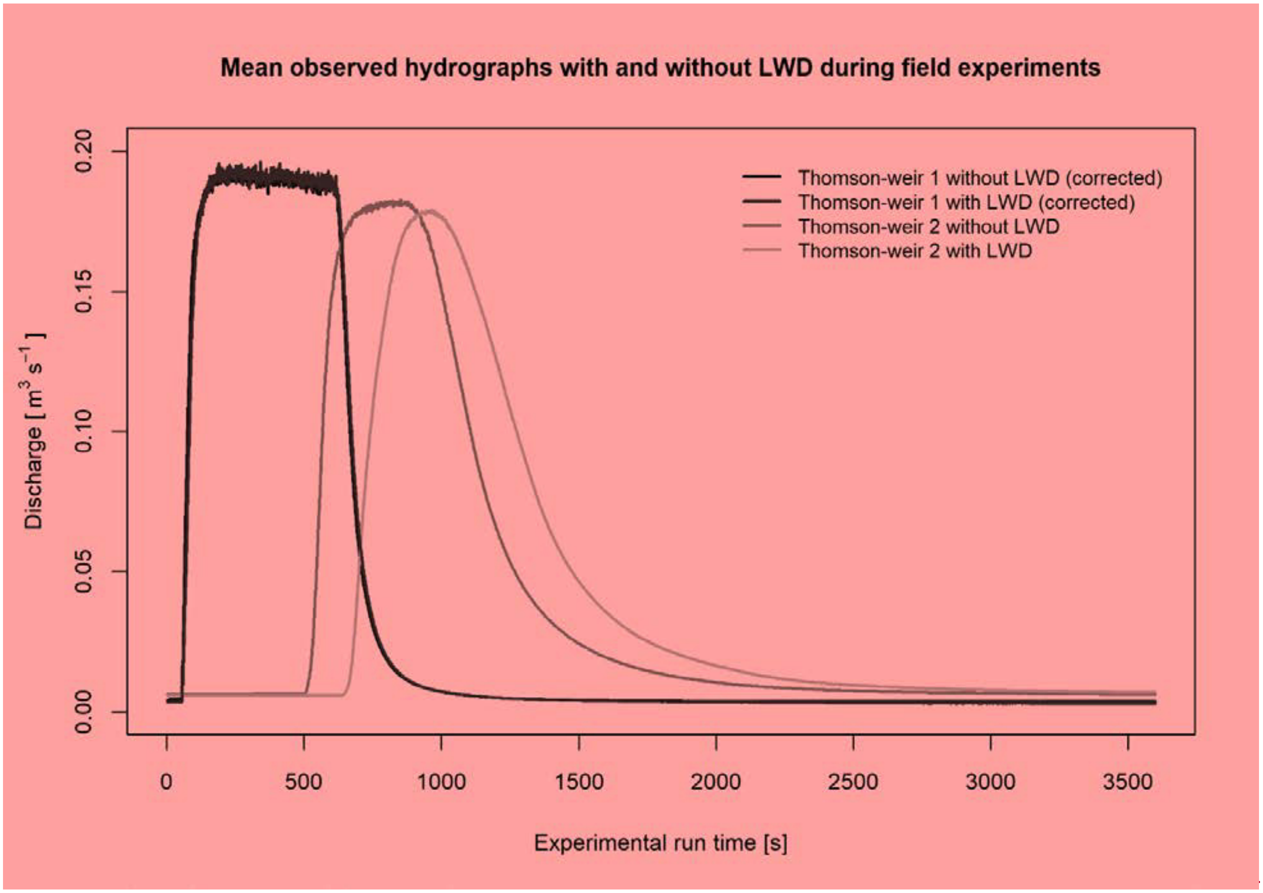
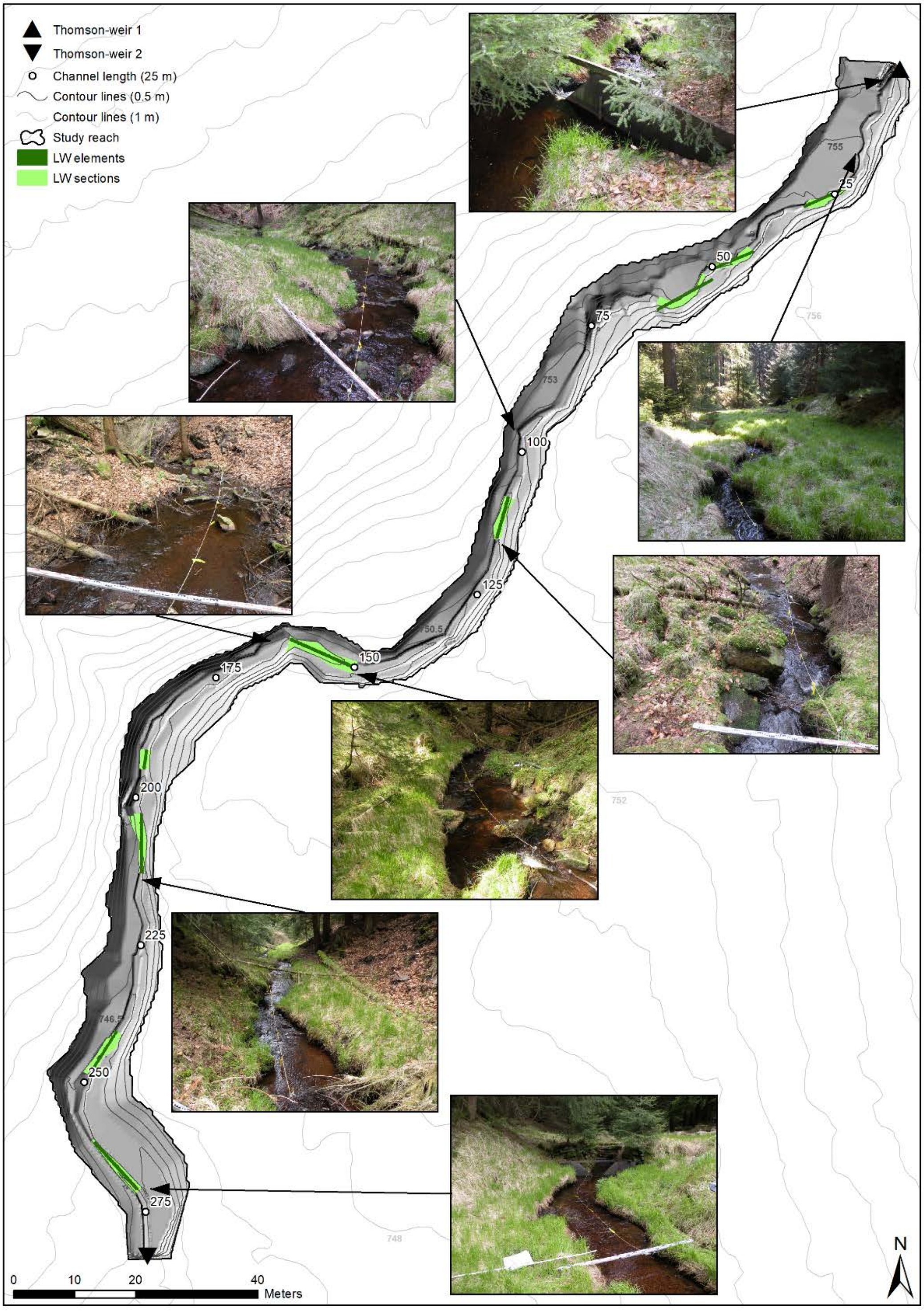


Figure 1: (a) Location of the study area in Germany (administrative units: BKG, 2018) and (b) position of the study reach in the catchment of the Ullersdorfer Teichbächel (stream network: LVA, 2002). (c) LW affected sections and positions of discrete LW elements in the study reach.


Mean observed hydrographs with and without LWD during field experiments
Thomson-weir 1 without LWD (corrected)
Thomson-weir 1 with LWD (corrected)
Thomson-weir 2 without LWD
Thomson-weir 2 with LWD
Discharge [m³ s⁻¹]
0.00
0.05
0.10
0.15
0.20
0
500
1000
1500
2000
2500
3000
3500
Experimental run time [s]



Thomson-weir 1
Thomson-weir 2
Channel length (25 m)
Contour lines (0.5 m)
Contour lines (1 m)
Study reach
LW elements
LW sections
25
50
75
100
125
150
175
200
225
250
275
755
756
753
750.5
752
746.5
748
0
10
20
40
Meters
N

Figure 2: Detailed map of the study reach (topographic data outside reach: GeoSN, 2008). Photographs were taken in May 2017 in the direction of flow (north to south).~~**Figure 2: Average measured and corrected flood hydrographs observed during field experiments with and without stable in-channel large woody debris at both Thomson-weirs (after Wenzel et al., 2014).**~~

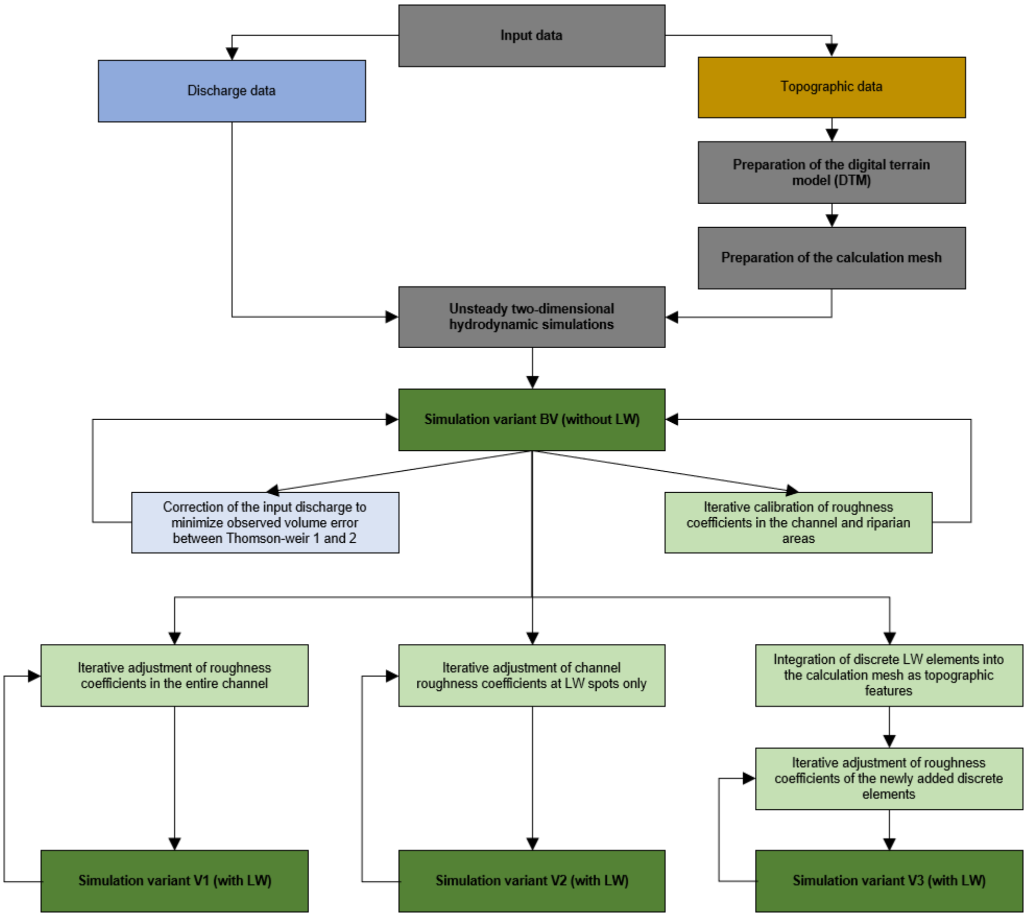


Figure 3: Schematic illustration of the methodological workflow

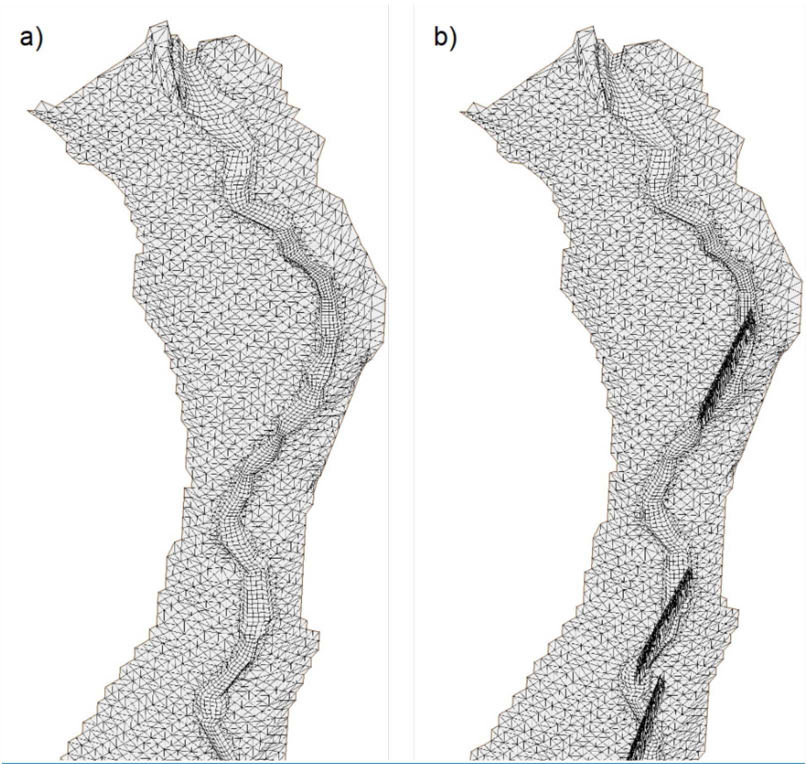
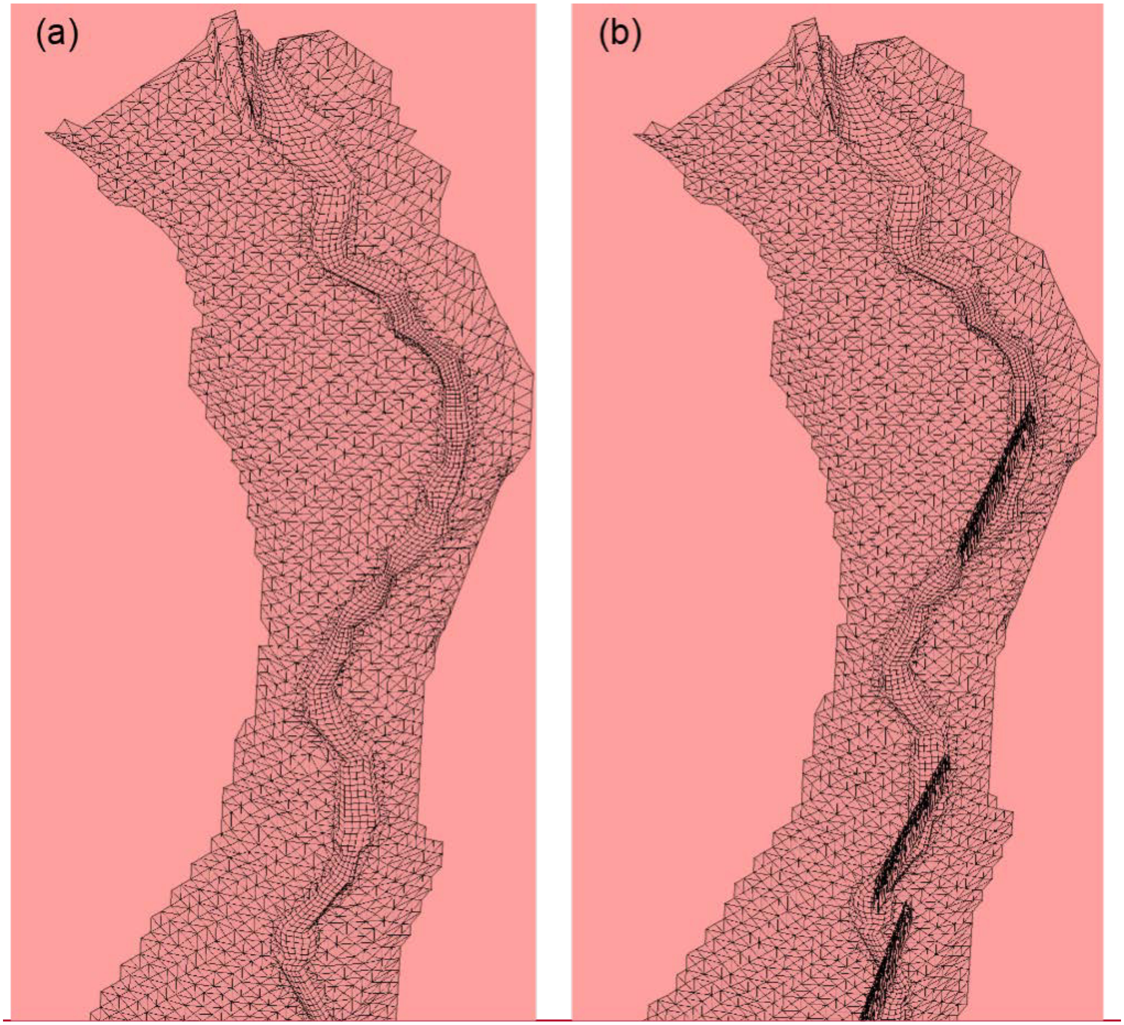


Figure 4: a) Calculation mesh of the hydrodynamic model used in simulation variants BV, V1 and V2 with the use of variable Strickler coefficients adjusted for the entire channel (V1) or adjusted at the positions of all LW elements only (V2) and b) mesh with discrete LW elements used in variant V3. Example of the first 60 m of the study reach.



~~**Figure 3: (a) Calculation mesh of the hydrodynamic model used in simulation variants BV, V1 and V2 with the use of variable Strickler coefficients adjusted for the entire channel (V1) or adjusted at the positions of all LWD elements only (V2) and (b) mesh with discrete LWD elements used in variant V3. Example of the first 60 m of the study reach.**~~

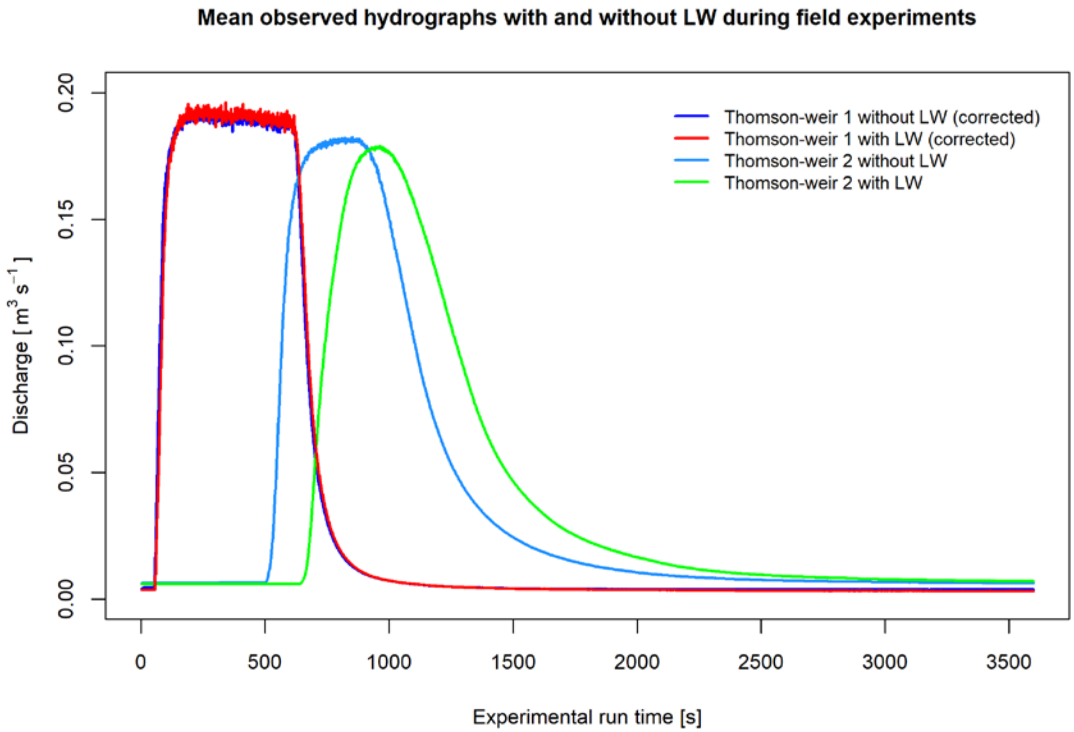


Figure 5: Average measured and corrected flood hydrographs observed during field experiments with and without stable in-channel large wood at both Thomson-weirs (after Wenzel et al., 2014).

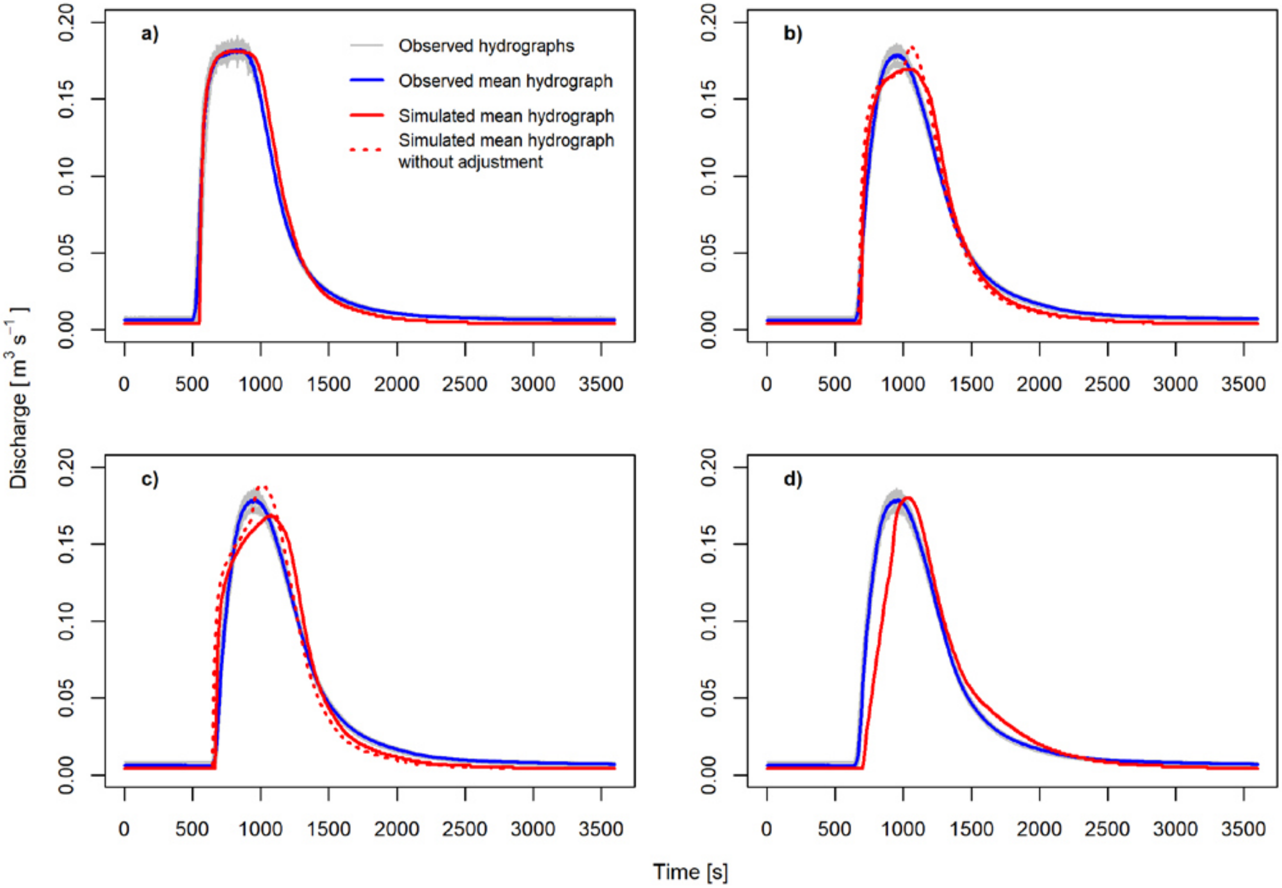


Figure 6: Best simulated mean flood hydrographs of all simulation variants with and without LW at Thomson-weir 2: a) results of the base variant BV without LW, b) variant V1 with stable LW as an increase of roughness in the entire channel, c) variant V2 with stable LW as an increase of roughness at element positions only and, d) variant V3 with LW as discrete topographic elements of the calculation mesh. For simulation variants V1 and V2 the best fit with and without subsequent adjustment of riparian Strickler coefficients is displayed.~~Figure 4: Best simulated mean flood hydrographs of all simulations variants with and without LWD at Thomson-weir 2. In variant V1 and V2 the best fit with and without subsequent adjustment of riparian Strickler coefficients is displayed.~~

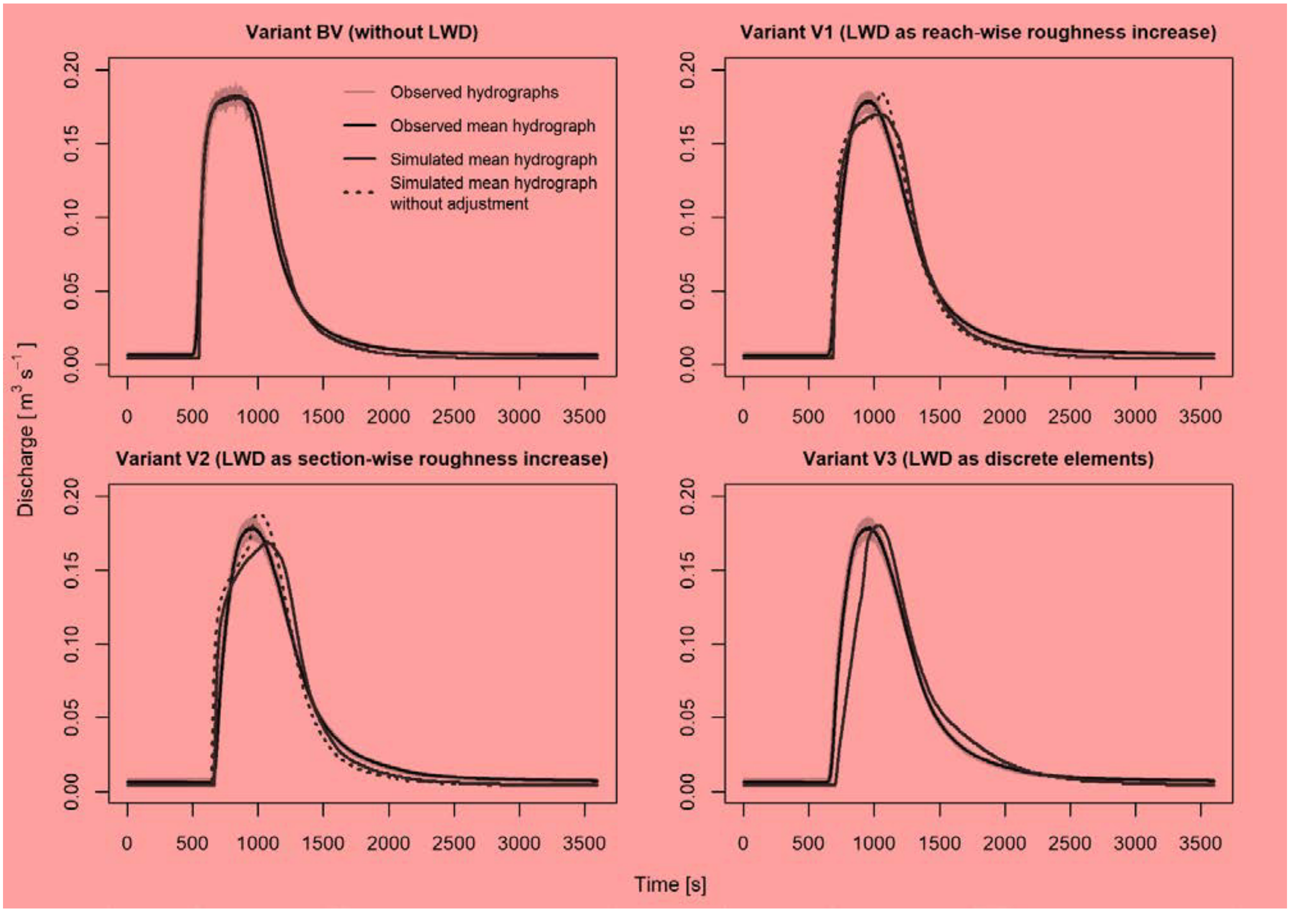

Variant BV (without LWD)
Variant V1 (LWD as reach-wise roughness increase)
Variant V2 (LWD as section-wise roughness increase)
Variant V3 (LWD as discrete elements)
Observed hydrographs
Observed mean hydrograph
Simulated mean hydrograph
Simulated mean hydrograph without adjustment
Discharge [m3 s-1]
Time [s]
0.00
0.05
0.10
0.15
0.20
0
500
1000
1500
2000
2500
3000
3500

Table 1: Average observed and simulated discharge sums ($m^3 h^{-1}$) at both Thomson-weirs for all simulation variants. For variant V1 and V2 discharge sums with subsequent adjustment of riparian Strickler coefficients are displayed.

Discharge sums (3600 s) for each variant ($m^3 h^{-1}$)	Base-Variant	Variant 1	Variant 2	Variant 3
Thomson-weir 1 (observed, corrected)	128	128	128	128
Thomson- weir 2 (observed)	132	133	133	133
Thomson-weir 1 (simulated)	128	128	128	128
Thomson-weir 2 (simulated)	128	128	128	123
Difference between observed and simulated values (Thomson-weir 2)	-4	-5	-5	-10
Observed difference between Thomson-weir 1 and 2	-4	-5	-5	-5

Table 2: Calculated statistical goodness-of-fit parameters for all simulation variants. For variant V1 and V2 goodness-of-fit parameters with and without subsequent adjustment of riparian Strickler coefficients are displayed.

Goodness-of-fit parameters	Basie-Variant	Variant 1 without adjustment	Variant 1	Variant 2 without adjustment	Variant 2	Variant 3
NSE	0.99	0.97	0.98	0.94	0.96	0.90
RSR	0.11	0.18	0.14	0.24	0.19	0.32
PBIAS (%)	- 3.5	- 3.6	- 3.7	- 4.2	- 4.0	- 7.7