Spatio-temporal variability of suspended sediments in rivers and ecological implications of reservoir flushing operations

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Abstract
High suspended sediment concentrations during reservoir flushing are known to be harmful to biota in downstream river stretches. Therefore, it is common practice to set legal concentration limits for upstream reservoir management operations such as flushings or controlled drawdowns. However, as shown by measurements, there is a considerable spatio-temporal variability of suspended sediment concentrations both in the longitudinal profile of rivers and in river cross-sections. To consider this variability in management operations, SED-FISH—a three-dimensional modelling approach—was developed to study this variability in a wider context by upscaling cross-sectional measurements of suspended sediments to high-resolution three-dimensional information on the reach scale in an alpine river. The resulting patterns of suspended sediment concentrations were integrated over their respective time of occurrence for various scenarios in order to calculate severity of harmful impacts for target fish species. The modelling results identified refugial habitats with reduced negative impacts in near-bank zones even for relatively high suspended sediment concentrations in the centre of the river. Moreover, a substantially larger variability of both suspended sediment concentrations and associated harmful impacts was found for a winding riverbed morphology as compared with a straight reach. Both these findings and the developed modelling tool could assist in establishing individual case-based concentration limits for reservoir management operations in the future and should also be taken into account when planning river regulation or restoration measures.

KEYWORDS
3D numerical modelling, reservoir flushing, river flow, severity index, suspended sediment

1 INTRODUCTION

The downstream propagation of suspended sediments in natural rivers is, in principle, a straightforward phenomenon, driven by transport, pick-up, and deposition processes (Van Rijn, 1984). These are dependent on the prevailing flow conditions and thus may vary over space and time. However, a large proportion of our rivers is in an anthropogenically modified state, which also affects the transport processes of sediment in suspension. This interaction with morphodynamics causes the management of fine sediments in rivers to pose a challenging task, in
particular when flushing operations of upstream reservoirs have to be considered (Walling & Fang, 2003). Numerical modelling tools have evolved over time as valuable planning instruments connecting suspended sediment transport, engineering measures, and river morphodynamic response (e.g., Glock, Tritthart, Gmeiner, Pessenlehner, & Habersack, 2017). In related studies, the governing equations of sediment in suspension are often formulated in a two-dimensional, depth-averaged notation (Tritthart, Schober, & Habersack, 2011; Villaret, Hervouet, Kopmann, Merkel, & Davies, 2013; Hostache, Hissler, Matgen, Guignard, & Bates, 2014; Haimann et al., 2018). This simplification, however, disregards the vertical variability over the cross-section area. Hence, three-dimensional formulations gained increased importance and have already been applied successfully to estuaries (e.g., Bai, Wang, & Shen, 2003) and reservoirs (Esmæeli et al., 2017; Fang & Rodi, 2003; Khosronejad, Rennie, Neyshabouri, & Gholami, 2008; Tritthart, 2000). However, applications of modelling and interpreting the three-dimensional variability of suspended sediment concentrations (SSCs) within a river reach continuum downstream of a reservoir have not been reported so far.

In principle, it is well known that SSC exhibits spatial and temporal variability depending on natural boundary conditions, such as seasonal changes in flow rates (Ashmore & Church, 2001), and anthropogenic influences, such as land use change or flushing operations (Walling & Fang, 2003). Also, the characteristics of the river system and the corresponding catchment play an important role (Walling, 2005).

Aquatic organisms such as fish therefore have to adapt to accommodate a range of different sediment loads (Kemp, Sear, Collins, Naden, & Jones, 2011). The impact of suspended sediments on biota is essentially a function of time and concentration (Newcombe & Jensen, 1996). In this context, some studies have described the impact caused by a long period of increased SSC downstream of a reservoir (Brandt & Swenning, 1999; Crosa, Castelli, Gentili, & Espa, 2010; Espa, Brignoli, Crosa, Gentili, & Quadrioni, 2016; Beckendorfer, Badura, & Schütz, 2019; Shen, 1999). It is known that increases in SSC can trigger changes in invertebrate drift (Bejar, Gibbins, Vericat, & Batalla, 2017). However, recent literature concludes that there is a need for an improved mechanistic understanding of the functional responses of riverine organisms to excess fine sediment (Mathers, Collins, England, Brierley, & Rice, 2017). Especially reservoir flushes can possibly decrease downstream fish (Buermann, Du Preez, Steyn, Harmse, & Deacon, 1995; Grimardias, Guillard, & Cattanéo, 2017) and macroinvertebrate abundance and biomass (Rabeni, Doisy, & Zweig, 2005; Quadrioni et al., 2016; Doretto et al., 2019). However, for benthic organisms (some species), a recovery within several weeks (Gray & Ward, 1982) or months (Crosa et al., 2010) has been documented.

The environmental impacts by sediment flushing can be summarized to an increase in SSC with impacts on the water quality, the organic content of sediment, the water temperature, the flow regime, and the related turbulence intensity (e.g., Crosa et al., 2010; Garric, Migeon, & Vindimian, 1990; Gray & Ward, 1982; WohI & Cenderelli, 2000) and consequently rapid dissolved oxygen (DO) decrease. In addition, the negative impacts also depend on comprehensive factors such as sediment particle grading, exposure duration, and fish species (Kemp et al., 2011; Suni, Kantoush, Esmæeli, & Ock, 2016). In a review of Kemp et al. (2011) and extended by Hauer et al. (2018), three different temporal scales concerning the responses of fish to fine sediments have been determined: (a) short-term responses such as stress (Redding & Schreck, 1982), reduced feeding (Henley, Patterson, Neves, & Lemly, 2000), or reduced oxygen acquisition (Bruton, 1985); (b) intermediate responses such as reduced tolerance to toxicants (Lloyd, 1987), lower resistance to disease (Sutherland & Meyer, 2007), physical damage to gills (Herbert & Merkins, 1961), disrupted and blocked oxygen supply (Giller & Malmqvist, 1998), or retarded growth (Shaw & Richardson, 2001); and (c) long-term responses on the population level (Birtwell, Hartman, Anderson, McLeay, & Malick, 1984). Moreover, negative impacts on other groups of aquatic organisms are given, such as the downstream drift of macroinvertebrates (Gray & Ward, 1982) or sediment abrasion on benthic algal communities (Francoeur & Biggs, 2006).

The environmental impact assessment of increased fines was mostly done in experimental studies (e.g., Auld & Schuel, 1978; Greig, Sear, & Carling, 2005; Newcombe & Jensen, 1996) and by field measurement campaigns (e.g., Rosenberg & Snow, 1975; Waters, 1995). Even though there are some studies evaluating reach-scale impacts of anthropogenically increased fines (e.g., reservoir flushing on fish communities; Crosa et al., 2010) there is (a) a lack of reach-scale characterization and (b) a lack of tools for reach-scale quantification of suspended sediment dynamics. Measurements are limited to river transects (e.g., Kostaschuk, Best, Villard, Peakall, & Franklin, 2005) with limited options of a spatially high-resolution quantification of SSC for longer distances. This lack of evaluation tools with missing features of a combined ecological impact assessment was identified as one major shortcoming in terms of hydro-power management (Hauer et al., 2018).

Therefore, the objectives of this study are to (a) develop a modelling framework that allows studying the fully three-dimensional spatio-temporal variability of SSC in a river reach, (b) test the model on field data, (c) extend the model by an analysis tool that evaluates both duration and SSC for a volume-based assessment of the potential impact on fish, and (d) foster the understanding of differences between different river morphologies in terms of the variability of SSC and their ecological implications.

## 2 STUDY REACH

The study area is located in the western Austrian province of Tyrol, comprising a reach of the river Inn of 2.50-km length in the municipality of Haiming (E10°15′/N47°15′). The reach consists of two equally long (1.25 km) but morphologically different subreaches (Figure 1a). The morphology of the upper subreach can be characterized as winding, with an initial 90° bend to the right, followed by a 120° left bend and a sharp 130° right bend. The average thalweg bed slope of that reach is 0.0058. In contrast, the lower subreach is a straight river section with a substantially smaller thalweg bed slope of 0.0020. Visible from Figure 1a, the slope of the upper reach is mostly due to two even steeper sections in the two right bends, whereas the remainder of the upper subreach is otherwise characterized by a similar slope than the
lower subreach. The width of the riverbed varies between 45 and 90 m in the winding subreach and between 40 and 50 m in the straight subreach.

The existing morphological and ensuing flow conditions are also reflected in the surface layer of the bed sediments. The steep sections present in the upper subreach are characterized by rock material with a median diameter $d_{50}$ of 0.25 m or higher, whereas the sections in between feature comparably finer sediment material with a $d_{50}$ in the range of 0.015 to 0.05 m. Particularly the lower, straight subreach consistently exhibits bed surface material close to the lower bound of this range. Both banks of the lower straight subreach are protected by rip-rap, whereas in the upper subreach, only the outer banks of the bends are artificially protected.

Based on long-term time series from 1971 to 2015, the mean annual discharge at the gauging station Haiming-Magerbach/Inn (E47°15′32″/N10°52′28″) is 146 m$^3$ s$^{-1}$ and the average annual flood peak discharge is 674 m$^3$ s$^{-1}$ (Bundesministerium für Nachhaltigkeit und Tourismus, 2018). Statistical values of suspended sediment transport are only available for the gauging station Innsbruck/Inn, located 43 km downstream. The longest available time series from 2005 to 2014 shows a mean transport of 55.9 kg s$^{-1}$ and an average concentration of 153 mg L$^{-1}$ (BMNT, 2018), resulting in a mean annual suspended sediment yield of 1.76 million tons. The fish region in the project area of the Inn River is defined as large hyporithral, with the salmonids grayling (Thymallus thymallus) and brown trout (Salmo trutta) as target species (cf. Schletterer, Reindl, & Thonhauser, 2017).

3 | METHODOLOGY

3.1 | Field measurements

Field measurements were carried out during the monitoring of a controlled drawdown of the Gepatsch reservoir (E46°57′/N10°44′) in the years 2015–2016. Details on the monitoring can be found in Hauer et al. (2019). For the presented study, the suspended sediment transport measurements and the variability of SSC were used as calibration and validation data for the developed numerical model, respectively. In order to investigate the distribution of suspended sediments, an acoustic Doppler current profiler (ADCPs; Teledyne RDI 1,200-kHz Workhorse Rio Grande and Teledyne RDI 2,000-kHz Stream Pro) was deployed with a cableway located at the measurement station Haiming-Magerbach. To calibrate the measurement data, a point-integrating suspended-sediment sampler (US P-61-A1) was used to derive water samples (and subsequently SSCs) in prespecified verticals and various depths across the river transects.
Hydrodynamics were calculated using the three-dimensional numerical model RSim-3D (Tritthart & Gutknecht, 2007). The model employs the finite volume method to solve the Reynolds-averaged Navier–Stokes equations on a mesh composed of arbitrary polyhedrons. Convective fluxes at cell boundaries are interpolated using a second-order upwind scheme. Pressure–velocity coupling is performed by means of the SIMPLE algorithm (Patankar & Spalding, 1972) in a generalized formulation. The hydrodynamic model implements both the standard k-ε (Launder & Spalding, 1974) and the improved k-ω (Wilcox, 2008) turbulence closure models; in this study, the standard k-ε model was used due to practical experience in a river context (Farhadi, Mayrhefer, Tritthart, Glas, & Habersack, 2018) showing that both models yield comparable results with the k-ε model being faster. The elevation of the free water surface is derived iteratively from the computed nonhydrostatic pressure field by evaluating the resulting pressure value at the surface of every cell in a way that a surplus is translated into a rise of the surface elevation and a deficit into a decrease. This procedure is repeated until a pressure equilibrium, that is, a relative pressure of zero, is obtained for every cell at the water surface during the solution cycle of the Reynolds-averaged Navier–Stokes equations. Previous studies (e.g., Tritthart, Liedermann, & Habersack, 2009; Krapesch, Tritthart, & Habersack, 2009; Tritthart, Liedermann, et al., 2011; Glock et al., 2017; Glas, Glock, Tritthart, Liedermann, & Habersack, 2018; Haimann et al., 2018) have shown good performance of the model RSim-3D particularly in river applications with associated ecological or sediment-related research questions.

For the Inn study reach, an unstructured polyhedral mesh with 297,896 cells in 3D, subdivided into eight depth layers, was set up. The horizontal distance of adjacent cell centroids was 2.5 m. Bed roughness was calibrated for a mean flow discharge \( Q = 141 \, \text{m}^3 \, \text{s}^{-1} \) based on the ADCP measurements detailed in Section 3.1, performed at cross-section CS1 (cf. Figure 1a). Located at the orographic left bank of this cross-section is the gauging station Haiming-Magerbach/Inn, which provided the water levels for the outflow boundary condition. The resulting bed roughness, parameterized as equivalent sand roughness \( k_s \), was 0.195 m on average in the riverbed of the study reach. Bank roughness values were fixed using a value of \( k_s = 0.50 \, \text{m} \) for rip-rapped areas in line with previous experience (e.g., Tritthart et al., 2009). Model validation was performed for a high-flow discharge of \( Q = 347 \, \text{m}^3 \, \text{s}^{-1} \); the results are detailed in Section 4.1.

3.3 Modelling of SSC

In order to simulate sediment transport, the hydrodynamic model RSim-3D can be coupled with the integrated sediment transport model iSed (Tritthart, Liedermann, et al., 2011). Due to the comparably short-time spans considered and the focus on SSC, neither bedload transport nor morphodynamics were modelled in this study. In terms of suspended sediment, the model solves the corresponding two-dimensional advection-diffusion equations in different size classes as detailed in Haimann et al. (2018). For the purpose of this study, the vertical component of the advection-diffusion equation was added to the implementation. The fall velocity of sediment particles in suspension was parameterized for the diameter of each size class using a power function derived by Atkinson, Chakraborti, and VanBenschoten (2004) based on experimental data from the Buffalo River. Moreover, the three-dimensional implementation of suspended sediment transport requires the determination of a reference concentration as wall boundary condition next to the riverbed. This value was determined for a reference elevation equal to the roughness height (Section 3.2), according to the corresponding equations proposed by Van Rijn (1984). However, because the reference concentration originates from an exchange between sediment in suspension with both bedload and the riverbed material (characterized by the median diameter \( d_{50} \)), in a nonuniform formulation for several size fractions, the use of a hiding function is recommended by some authors (e.g., Malcherek & Söhngen, 2003); this function was implemented according to Parker (1990).

The model for the study reach at the Inn River was set up using six measured suspended grain size classes as shown in Table 1, adopted to characterize the simulated inflowing sediment, which was uniformly distributed over the cross-section. A bed cover layer of characteristic \( d_{50} \) sediment diameters was created representing the variability of this diameter according to the subreaches as discussed in Section 2 and used for calculating the reference concentrations in the model. During the calibration procedure of the suspended sediment model, the values for \( d_{50} \) were fine-tuned to achieve a match of the simulated concentrations in cross-section CS1 with the data measured for a mean flow discharge \( Q = 141 \, \text{m}^3 \, \text{s}^{-1} \) using the ADCP device. This resulted in a constant value of \( d_{50} = 0.02 \, \text{m} \) in the lower subreach; the same value was used for the small-sloped sections of the upper subreach. The values for the steeper areas could not be directly calibrated due to unavailability of measurement data in these inaccessible areas and were assigned \( d_{50} \) values of 0.30 m. Rip-rap protected bank zones received values of \( d_{50} = 0.50 \, \text{m} \). The calibrated values were validated for a high-flow discharge of \( Q = 347 \, \text{m}^3 \, \text{s}^{-1} \) as detailed in Section 4.2.

The suspended sediment transport model was coupled with the three-dimensional hydrodynamic model and run for 24 hr of model time with time steps of 15 min for four different study cases.

| Diameter (μm) | Percent finer (%) |
|--------------|-------------------|
| 2            | 11                |
| 6.3          | 34                |
| 20           | 53                |
| 63           | 65                |
| 200          | 99                |
| 630          | 100               |

TABLE 1 Characteristic grain size distribution of the transported suspended sediment as measured on August 5, 2015, during a river discharge of \( Q = 237 \, \text{m}^3 \, \text{s}^{-1} \) at the gauging station Innsbruck/Inn (BMNT, 2018)
I. Constant mean flow discharge $Q = 141 \text{ m}^3 \text{ s}^{-1}$ with a corresponding constant measured average sediment influx concentration of $c = 141.1 \text{ mg L}^{-1}$;

II. Constant high-flow discharge $Q = 347 \text{ m}^3 \text{ s}^{-1}$ with a corresponding constant measured average sediment influx concentration of $c = 504.3 \text{ mg L}^{-1}$;

III. A measured hydrograph of a rainfall event (Figure 2) with discharges ranging from 54 to 109 m$^3$ s$^{-1}$ and measured average sediment influx concentrations between 140 and 903 mg L$^{-1}$;

IV. Constant mean flow discharge $Q = 141 \text{ m}^3 \text{ s}^{-1}$ with a fictitious constant average sediment influx concentration of $c = 1,000 \text{ mg L}^{-1}$, for example, representing a flushing event upstream.

3.4 Calculation of severity of ill indices

Newcombe and Jensen (1996) introduced the severity of ill index (SEV), a concept for evaluating such a potential impact. In their experiments, they found the severity of ill effect SEV to be dependent logarithmically both on the duration of exposure $t$ as well as on the SSC $c$, resulting in the equation $\text{SEV} = a_1 + a_2 \ln t + a_3 \ln c$, where $a_1$ is the intercept and $a_2$ and $a_3$ are slope coefficients to be determined empirically. In the novel modelling tool SED-FISH, linking three-dimensional hydraulics and SSC to the SEV after Newcombe and Jensen (1996), the SEV is grouped into 15 classes from 0 to 14, where 0 indicates no behavioural effects and 14 indicates up to 100% mortality. Important index groups are values smaller than 3, which correspond to relatively minor behavioural effects, and index values from 4 to 8, which indicate sublethal effects (e.g., a value of 8 corresponding to major physiological stress and a long-term reduction in feeding rates). An SEV of 9 corresponds to paralethal effects, such as reduced growth rates or delayed hatching, and lethal effects occur from SEV 10 upwards in increments of 20% mortality per index class. In this study, we consider juvenile and adult salmonids (target fish species at the Inn River) for which $a_1 = 1.0642$, $a_2 = 0.6068$, and $a_3 = 0.7384$ when $t$ is supplied in hours and $c$ in milligrams per litre (Newcombe & Jensen, 1996).

For each of the cells in the computational domain of SED-FISH, the calculated hydrograph of SSC was evaluated in a loop starting from zero up to the respective maximum concentration in increments of 1 mg L$^{-1}$, in order to determine the maximum SEV corresponding to this concentration within the model time. The resulting SEV was obtained as the maximum of each SEV value calculated from the duration $t$ of every single peak of SSC within the hydrograph exceeding the respective evaluation value $c$ in the loop. For instance, a short peak with a high SSC may yield a higher SEV than a lower concentration for longer duration, or vice versa depending on the occurring concentrations and durations; the step-wise evaluation guarantees to find the maximum SEV for a given cell. For the purpose of result evaluation, the SEV-assigned cell volumes were finally grouped into velocity classes (for a specific time instant in the case of unsteady calculations) with an increment of 0.5 m s$^{-1}$ up to a maximum of $\geq 2.0$ m s$^{-1}$.

4 RESULTS

4.1 Model validation

Cross-sectional profiles of depth-averaged flow velocities measured using an ADCP device at CS1 are compared with results of the hydrodynamic model for $Q = 141 \text{ m}^3 \text{ s}^{-1}$ (calibration discharge) and $Q = 347 \text{ m}^3 \text{ s}^{-1}$ (validation discharge) in Figure 3. In general, a good match can be observed. The only notable deviation occurs in steeper velocity gradients near the left bank as visible in measured data, which lead to local maxima at a station between 10 and 15 m; this phenomenon is present in both discharges and could not be reproduced numerically.

A comparison between measured and simulated vertical profiles of SSC is shown in Figure 4 for both aforementioned discharges (left column: $Q = 141 \text{ m}^3 \text{ s}^{-1}$, calibration discharge; right column: $Q = 347 \text{ m}^3 \text{ s}^{-1}$, validation discharge). All modelled profiles show a non-linear increase towards the riverbed; however, due to the fact that close to
the bed and also near the surface, an ADCP device is unable to provide reliable results, no measurement data are available for these regions. Hence, several profiles yield a larger maximum value in the model results than in the measurements. For most profiles investigated, the distribution patterns of SSC follow two different slopes: a smaller gradient throughout the upper half to two thirds of the water column (transport region) and a larger gradient near the bed. These gradients are well predicted by the model, even though the location where the transport region meets the bed-influenced region is not captured precisely for all vertical sections. Nonetheless, overall, the profiles are considered to be in good agreement with the trend of the measured data.

4.2 | Hydrodynamic parameters

Employing the calibrated and validated hydrodynamic model, the four study cases laid out in Section 3.3 were simulated. Representative for these results, Figure 1 shows modelled water surface elevations (Figure 1b), depth-averaged flow velocities (Figure 1c), and bed shear stresses (Figure 1d) for mean flow conditions. The steeper sections feature larger gradients of the water surface elevation, lower water depths, and thus substantially higher flow velocities of up to 5 m s$^{-1}$, whereas in the small-sloped lower subreach depth-averaged flow velocities reach around 2.5 m s$^{-1}$. Near the banks, the flow velocities are substantially lower, and particularly upstream of the sharp right bend, a large low-velocity recirculation zone develops at the left bank.

For all study cases investigated, the Froude number in the steeper regions is close to 1 or, in the case of the sharp right bend, even larger than unity, indicating supercritical flow conditions, which become manifest in the presence of surface waves and associated local velocity maxima upon retransition to a subcritical flow regime. This is also visible in the bed shear stress patterns: This parameter exhibits modest values of slightly over 25 N m$^{-2}$ in most of the reach; however, in the steeper sections and transition zones between supercritical and subcritical flow regime, bed shear stresses reach 100 N m$^{-2}$, and within the fast-velocity transition zones, maxima of over 200 N m$^{-2}$ are predicted by the numerical model. These values indicate strong forces acting upon the riverbed, which in turn lead to the bed sediment distribution as presented in Section 2, with armouring effects as only large rocky sediments are capable of resisting the forces occurring in these areas, whereas finer bed sediments are washed out and deposited downstream.
4.3 | Spatio-temporal variability of SSC

Even for a constant sediment influx, such as in Study cases I, II, and IV, the model results indicate a large spatial variability of SSC. For an unsteady sediment influx (Study case III), an additional temporal variability is encountered. Figure 5 shows contour maps of SSC in cross-sections CS1 and CS2 for both the calibration and the validation discharge, $Q = 141 \text{ m}^3 \text{ s}^{-1}$ and $Q = 347 \text{ m}^3 \text{ s}^{-1}$, respectively. In cross-section CS1, located in the lower subreach with small bed slopes and finer bed sediments, the maximum concentrations occur near the bed in the centre of the river, with values around 400 mg L$^{-1}$ for $Q = 141 \text{ m}^3 \text{ s}^{-1}$ and around 1,400 mg L$^{-1}$ for $Q = 347 \text{ m}^3 \text{ s}^{-1}$. From this zone, where the highest interaction between suspension and the riverbed takes place, the concentrations exhibit a nonlinear decrease towards the surface and the banks. Near the surface, the values range between 1/3 to 1/2 of the maxima, and near the banks, even smaller concentrations are encountered. This general pattern is predominant in the study reach. In the steep river sections or flow regime transition zones characterized by large sediment sizes at the bed, the location of maximum concentrations depends on the river discharge, such as encountered in CS2 (Figure 5c,d). The lack of fine sediments in the bed substrate leads the model to predict lower SSC in the small near-bed layer; however, this can be considered a model effect due to the implementation of the bed exchange boundary condition.

FIGURE 4  Comparison of measured (dashed line) and modelled (continuous line) SSC profiles for different locations $y$ expressed as fraction of the river width $B$ within Cross-section 1: left column, river discharge $Q = 141 \text{ m}^3 \text{ s}^{-1}$; right column, $Q = 347 \text{ m}^3 \text{ s}^{-1}$; (a,e) $y = 0.2 B$; (b,f) $y = 0.4 B$; (c, g) $y = 0.6 B$; (d,h) $y = 0.8 B$
Again, a decrease of concentrations in regions of smaller flow velocities next to the banks is visible in cross-section CS2.

This spatial variability is also evident in the plan view visualization as shown in Figure 6a (near bed), Figure 6b (midlayer), and Figure 6c (near surface) for the peak discharge and sediment influx \( Q = 109 \text{ m}^3 \text{ s}^{-1}, c = 903 \text{ mg L}^{-1} \) of the unsteady rainfall-induced hydrograph investigated as Study case III. Also, in this case, the SSCs generally exhibit their respective maxima near the bed and decrease towards the surface. However, due to the sharp rise of the sediment influx hydrograph, the sediment concentrations in the transport zone in the upper part of the water column rise faster before mixing with the low-level, bed-influenced regions characterized by smaller flow velocities. Therefore, the time instant of the peak discharge shows a temporary partial inversion of the usual suspended sediment distribution pattern, with lower near-bed concentrations particularly in the small-sloped downstream section. In the transport zone in the upper part of the water column, comparably homogenous suspended sediment distributions are visible, whereas near the bed and the banks, a higher variability is present. A decrease towards the banks is particularly apparent in nearly all vertical layers.

### 4.4 Severity of ill indices

SEV indices were calculated in the novel modelling approach as aggregates over the complete duration of all study cases. Figure 6d–f shows the variability of SEV throughout three depth layers for the rainfall-induced event (Study case III). In general, maxima of SEV are found in the centre section of the river with a decrease towards the banks, where values of SEV 6–7 are present in all subreaches. The straight subreach exhibits a relatively homogeneous pattern with values of SEV 8 in the centre zone throughout all depth layers. In contrast, the winding subreach shows a higher variability with SEV 7–8 and even a small patch of the paralthal class SEV 9 in the supercritical flow zone of the second right bend. The variability is also present over the extent of the water column in this part of the study reach.

The results of all study cases are aggregated in Figure 7, where a middepth layer was selected to compare the SEV patterns. Study case I, with a constant discharge \( Q = 141 \text{ m}^3 \text{ s}^{-1} \) and associated sediment influx, leads to SEV values ranging from 6 to 7 in the upper subreach, with bank zones exhibiting patches of smaller values. In the lower subreach, this study case shows a homogenous value of SEV 7. For Study case II, with a constant discharge \( Q = 347 \text{ m}^3 \text{ s}^{-1} \) and associated sediment influx, this pattern is essentially repeated but with SEV values generally one index point higher than in Study case I. The rainfall event studied in Case III yields similar SEV patterns as in Study case II; however, due to the lower discharges, bank zones with reduced SEV values are smaller in extent. Finally, Study case IV, with a constant discharge \( Q = 141 \text{ m}^3 \text{ s}^{-1} \) but high sediment influx of \( c = 1000 \text{ mg L}^{-1} \), leads to SEV 8 throughout the study reach. Reduced SEV values in bank zones primarily exist in the winding subreach.

For all study cases, the percentage of the total water volume in the reach associated with the various SEV classes is shown in Figure 8 along with a subclassification into flow velocity classes. In general, for all study cases, a fraction of 2% to 5% of the entire water volume corresponds to SEV ≤ 3. Around half of these regions are located in slow-flow zones with flow velocities \( U < 1.0 \text{ m s}^{-1} \). For Study case I, approximately 95% of the water volume corresponds to SEV 6 or 7; a negligible
fraction of less than 0.5%, located in fast-velocity zones, is classified as SEV 8. Higher SEV values do not occur. In Study case II, the result is identical, except that all SEV values are higher by one index point, that is, around 30% SEV 7 and 65% SEV 8. These zones, however, are almost exclusively in the faster regions of \( U \geq 1.0 \text{ m s}^{-1} \), and of those, more than three quarters lie in the range of \( U \geq 2.0 \text{ m s}^{-1} \). A total of 0.35% is classified as SEV 9. For the rainfall event investigated in Study case III, 1% of the total volume identifies as SEV 6, 22% as SEV 7, and 73% as SEV 8. Because the rainfall event leads to high SSC at comparably low discharges, the distribution into velocity classes is different than for the other study cases, with between half (SEV 7) and one quarter (SEV 8) of these volumes falling into the velocity classes of \( U < 1.0 \text{ m s}^{-1} \). Again, only a small fraction of 0.6% identifies as SEV 9. Study case IV finally exhibits a pronounced peak at the SEV 8 class, with 90% of all volumes associated with this severity class; 5.5% identify as SEV 7 and <0.1% as SEV 9, the latter exclusively located in the faster velocity regions of \( U \geq 1.0 \text{ m s}^{-1} \). Also, in the class of SEV 8, only 5% associate with velocities of \( U < 1.0 \text{ m s}^{-1} \) and nearly half is in the range of \( U \geq 2.0 \text{ m s}^{-1} \). SEV 7 is found in an approximate even distribution over all velocity class ranges.

5 | DISCUSSION

The results derived using the novel modelling approach contain several points of discussion: (a) The successful prediction of the three-dimensional variability of SSC in the water body is a fundamental prerequisite for the ensuing ecological assessment. In this context, the method of modelling exchange processes with the riverbed using an equilibrium SSC after Van Van Rijn (1984) is dependent on the actual grain size distribution of the riverbed material, which had to be estimated from the prevailing flow conditions in parts of the modelling domain for reasons of inaccessibility. The same modelling approach is used by Esmaeili et al. (2017), whereas in Hostache et al. (2014), the formula by Zyserman and Fredsoe (1994) is employed. Particularly for cohesive material, which is likely to be mobilized during flushing operations, Hostache et al. (2014) used the erosion/deposition flux calculation by Partheniades (1965) instead. A systematic comparison of the performance of these different approaches has the potential to further reduce uncertainties associated with the results in a future model improvement. Also, the modelled temporary partial inversion of the concentration profile at the onset of a
suspended sediment wave originating from upstream was not observed in the field because measurements are not available for these conditions. Future field measurements are planned to verify this pattern. However, despite these uncertainties, it could be shown that the results of the chosen model approach are already in good agreement with the available suspended sediment measurements, in particular also regarding the variability of this parameter over the cross-section.

(b) High SSCs have been measured (calibration and boundary condition data for modelling) and simulated for the Inn River even for natural precipitation events. Such events are very common and are exceeded in periods of glacier melting at the Inn River (Hauer et al., 2019). Thus, there should be a discussion how valuable the thresholds of the Newcombe and Jensen (1996) approach are, because even though there is a reduced fish population at the Inn River (e.g., hydropoeaking and morphological degradation; cf. Hauer, Unfer, Holzapfel, Haimann, & Habersack, 2014), multiyear fish abundance is given (Schmutz, Kaufmann, Vogel, Jungwirth, & Muhar, 2000). Considering literature, there are various numbers listed related to negative or even fatal impacts of high SSC on fish. Exemplarily, for hypoxia, a critical factor is presented if SS exceeds 30,000 mg L\(^{-1}\) leading to a DO of <2 mg L\(^{-1}\) (Staub, 2000). Similar findings concerning the DO (<2 mg L\(^{-1}\)) are described in Merle (2000). Moreover, Croswal et al. (2010) proposed that SS should be lower than 10,000 mg L\(^{-1}\) to avoid negative impacts on ecosystems in alpine streams. A 100% survival of brown trout larvae was documented for 300 to 750 mg L\(^{-1}\) for an entire period of 3 to 4 weeks with some peaks in SSC up to 2,300–6,500 mg L\(^{-1}\) (Griffin, 1938). Similarly, Slanina (1962) documented a 100 % survival of rainbow trout for SSC 5,000–300,000 mg L\(^{-1}\) for an exposure of 1 week to this increased concentration. These numbers correspond to an SEV of 9–10 for Griffin (1938) and SEV of 10–13 for Slanina (1962) according to Newcombe and Jensen (1996), and a 100% survival would not be possible. However, even though there are uncertainties given according to the thresholds defined by Newcombe and Jensen (1996), their work is of the major ones with a comprehensive overview of (a) various SSC values over (b) variable time considering (c) different life stages of fish, and thus their findings are used for evaluation in the SED-FISH model. However, future adoptions of these thresholds in the numerical code are possible and targeted.

Moreover, (c) the role of possible refugial habitats for fish to avoid negative impacts of increased SSC warrants a discussion. Fish in the river environment react to changes in turbidity and SSC (e.g., Gregory, 1993; Lloyd, 1987). However, these reactions have not been linked to spatial variability of habitat use in rivers so far. There are only minor studies that focused on the detection of spatial variability of turbidity/SSC (e.g., Hauer et al., 2019). In Hauer et al.
(2019), habitat-related turbidity measurements were examined in discrete hydromorphological units (cf. Hauer, Mandlburger, & Habersack, 2009; Hauer, Unfer, Tritthart, Formann, & Habersack, 2011) with a hand-held Solitax ts-line-type turbidity sensor from Hach-Lange. The results of Hauer et al. (2019) showed a clear heterogeneity in the distribution of the SSC in the studied river, which confirm this spatial heterogeneity of SSC with a distinct variability between various hydromorphological units (shallow water, run, riffle, and backwater). Although a clear trend for one specific habitat type with lower turbidity was not given for all measuring dates (n = 4), it turned out that in all investigated sections of the Inn River, sheltered habitats (in terms of reduced turbidity; SSC < 150 mg L$^{-1}$ according to Hauer et al., 2019) were present during a controlled reservoir drawdown in winter 2015/2016 with maximum SSC > 2000 mg L$^{-1}$ for short-time periods. On the one hand, such findings support the results of the presented study; on the other hand, they underline the need for a reach-scale assessment tool to evaluate the impacts of reservoir flushings or controlled drawdowns of reservoirs with increased SSC in downstream river sections.

However, what is needed for a final overall evaluation of possible impacts of fine sediments based on numerical modelling is to include habitat suitability data (cf. Bovee, 1986; Habersack, Tritthart, Liedermann, & Hauer, 2014) or habitat limiting data (e.g., Plaut, 2001) in the modelling framework and to validate the modelling results by fish monitoring, similar to the monitoring of a controlled reservoir drawdown (Hauer et al., 2019). In our presented case study, areas of various SSC and thus variable SEV indices have been identified. So far missing is a further evaluation whether these habitats are in a suitable range for fish to “live” (low to mean flow) or “survive” (high flows; cf. Sedell, Reeves, Hauer, Stanford, & Hawkins, 1990). Nevertheless, it could be clearly figured out that heterogeneous river morphology—in this case, a comparison of winding sections with a channelized straight one—contains larger extents of areas with the so-called “refugial habitats.” These findings go hand in hand with other studies dealing with variable anthropogenic disturbance such as hydropeaking (Hauer et al., 2014; Hauer, Holzapfel, Leitner, & Graf, 2017). In these hydropeaking studies, it could be clearly shown that heterogeneous river morphology contains improved conditions for fish to survive the negative impacts, such as reduced stranding due to limited dewatering areas downstream of bars. Thus, the presented findings underline, from the viewpoint of anthropogenically altered SSC, the need and chance of a morphological restoration of heavily disturbed river systems (cf. Stanford et al., 1996), also argued in terms of flood mitigation (Nienhuis & Leuven, 2001) and habitat improvement in general (Palmer, Menninger, & Bernhardt, 2010).

**6 | CONCLUSIONS**

The presented novel modelling framework employs field data to calibrate three-dimensional numerical models for river flow and the transport of suspended sediments. This model-based upscaling mechanism in turn allows to gain insights into the distribution of abiotic parameters...
in all regions of a river, which could otherwise not be observed, including the spatio-temporal variability of SSC. These data are then aggregated to assess the severity of illness impact on biota, in particular fish guilds. This novel assessment tool allows to identify volumetric zones inside the river continuum that can serve as retreat habitats during the passage of natural sediment waves, originating from rainfall or other types of flood events, as well as anthropogenic-induced sediment passage, for instance due to upstream reservoir flushing operations. The results of this study show clearly that habitats with lower severity of illness classification exist even for comparably high SSC in other volumetric zones of the river. Hence, the toolset can be employed to set forth concentration limits for flushing operations on a case-by-case basis, considering the existing morphology of the river rather than using a generic value. Moreover, the substantially higher variability in a naturally winding reach as compared with a channelized stretched reach in terms of concentrations as well as the severity of illness classes makes clear that the ecological impact of sediment in suspension also needs to be considered for any type of river regulation or restoration measure. The presented modelling framework can be applied to obtain the necessary information for decision making during such a process.

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DATA AVAILABILITY
The data that support the findings of this study are available from the corresponding author upon reasonable request.

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