PHYSICS-BASED BASIN-SCALE MODELLING OF WATER QUANTITY AND SEDIMENT DYNAMICS USING WFLOW

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ABSTRACT

Sediment dynamics, from the mountains to the sea, play a key role in inland water systems for water resources and disaster management in general, river morphodynamics, ecology and water quality in particular. To better understand and assert these issues, a good quantification of the sediment budget on the catchment to reach scale and at a relevant temporal scale, is therefore needed.

The wflow_sediment model was developed to address basin-scale geomorphological processes and problems. It is a distributed physics-based model that uses the results of the wflow_sbm hydrological model in order to estimate soil erosion, delivery to the river, transport and deposition. Both the hydrologic and sediment dynamics wflow models are open-source and use openly available global datasets and parameter estimation in order to limit calibration and be applicable even in data scarce environments. Terrestrial processes include splash and overland flow erosion, as well as transport over the grid using either a total flow transport capacity or a transport capacity with particle differentiation. In-stream routing and erosion/deposition processes are adapted from the semi-distributed SWAT model. The wflow_sediment model was first tested in the Rhine basin (Western Europe) at a daily resolution and on a 1 km (0.008333°) grid. Both the inland and instream parts of the model gave promising results, showing the potential of this new tool for a very diverse range of applications.

Keywords: Sediment, soil loss, distributed modelling, basin-scale, global dataset

1. INTRODUCTION

When considering land and river basin management, both water and sediment dynamics have their significance. Being able to estimate and model sediment budgets from catchment to deltas can strengthen management policies and plans in the fields of sediment, land and disaster risk reduction. But it can also give insights and open the doors to a wide other range of applications linked to water quality and health, ecology and ecosystem services but also to resilience and climate adaptation plans, including the safety and sustainability of water infrastructures. To enable the quantification of sediment budgets for these different domains, there is therefore a need of a good understanding and modelling of sediment dynamics from the land to the deltas and oceans.

There are multiple ways of modelling sediment dynamics at the basin-scale and many different existing models. In a recent review, Karydas et al. (2014) compared up to 82 water erosion models (including different model versions). In order to decide which model to use, it is therefore necessary to precisely define the objectives, the desired applications and understand the different generation, deposition and transport processes that the desired sediment model should be able to handle (de Vente et al., 2013). For a small-scale model, only land surface erosion is enough to have a good estimate of sediment dynamics. However, for larger catchments, sediment dynamics need to be separated into land and in-stream processes. The main drivers of sediment dynamics, erosion, deposition and transport, are listed in Figure 1.

Over the land, soil erosion, also called soil loss, is closely linked to the water cycle. The main processes governing sediment generation are splash erosion from rain droplets (Torri et al., 1987), and sheet and rill erosion from the shear stress caused by overland flow (Merritt et al., 2003). The intensity of soil erosion by rain or flow depends on the land and soil characteristics such as slope, land use or soil type (de Vente and Poesen, 2005). Once soil is eroded, the detached particles can be transported downslope by overland flow. Along the transport pathways, soil particles can also be deposited due to a low flow velocity, a change of topography in depressions, footslopes or valley bottoms (de Vente et al., 2008), and/or can be filtered and stopped by a change in vegetation such as field boundaries.

Sediment dynamics in the river can again be described by the three same processes than on the land: erosion, deposition and transport. The difference is that channel flow is much higher, deeper and permanent compared to overland flow. In channels, erosion is the direct removal of sediments from the river bed or bank (lateral erosion) (Merritt et al., 2003). Sediments are transported in the river either by rolling, sliding and silting (bed load transport) or via turbulent flow in the higher water column (suspended load transport) (van Rijn, 1984). The type of transport is determined by the river bed shear stress. As sediment particles have a higher density than water, they can also be deposited on the river bed according to their settling velocity compared to flow velocity. In addition to regular deposition in the river, lakes, reservoirs and floodplains represents additional major sediment settling pools.

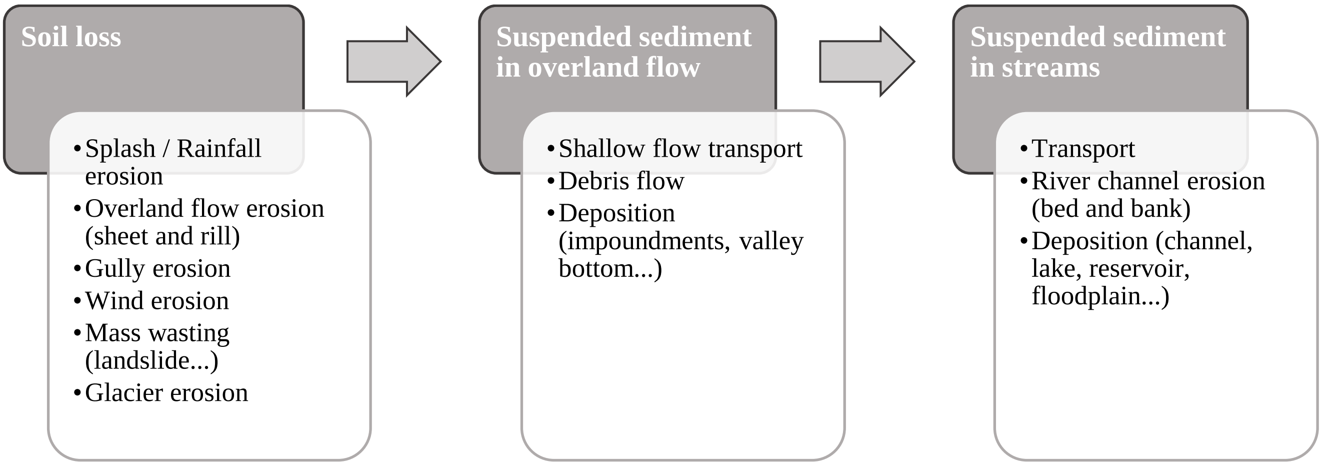

Figure 1. Processes governing basin to reach-scale sediment dynamics.

The wflow_sediment model was developed to address basin-scale geomorphological processes and problems. In order to quantify the sediment budget and linked processes in large systems, two different modelling parts were considered. The first part is the modelling and estimation of soil loss and sediment yield to the river network by land erosion. The second part is the transport and processes of the sediment in the river network. The two parts together constitute the wflow_sediment model.

The choice of a sediment dynamics model relied on the following constraints and objectives:

1. As soil loss is dependent on very local characteristics, such as slope gradient or vegetation, the model needed a **fine space resolution**.
2. The model was also designed for local to global applications and should then be able to handle both **small and very large catchments**.
3. The sediment budget should finally be linked to future other applications including water quality modelling, and the model should then work on a **fine temporal resolution** (daily to sub-daily timestep).

For all these reasons, it was decided to couple the sediment model to a fully **distributed** hydrologic model. The wflow_sbm hydrologic model from Deltares was chosen as it contains some very interesting features. It is an open source, **physics-based** model for which a global version is in development, meaning that the model works only with **global available datasets** and **parameter estimation** (van Verseveld et al., 2020). As these properties were thought very promising, they were as well added to the objectives that the final chosen sediment model should respect. Equations and concepts for the development of wflow_sediment were therefore chosen in order to fit best these different objectives.

2. METHODS AND MODEL DEVELOPMENT

2.1 Inland sediment model

To quantify the different processes of sediment dynamics, there are many soil loss and inland sediment yield models available in the literature and reviews of those models are regularly published. Choosing a model then depends on the objectives of the model's applications and defining the type of model that fits best these objectives: spatial scale and spatial units, time-scale or duration, processes and features to be included and type of model algorithm (empirical or physics-based). Figure 2 presents the different processes and equations implemented in the inland part of wflow_sediment.

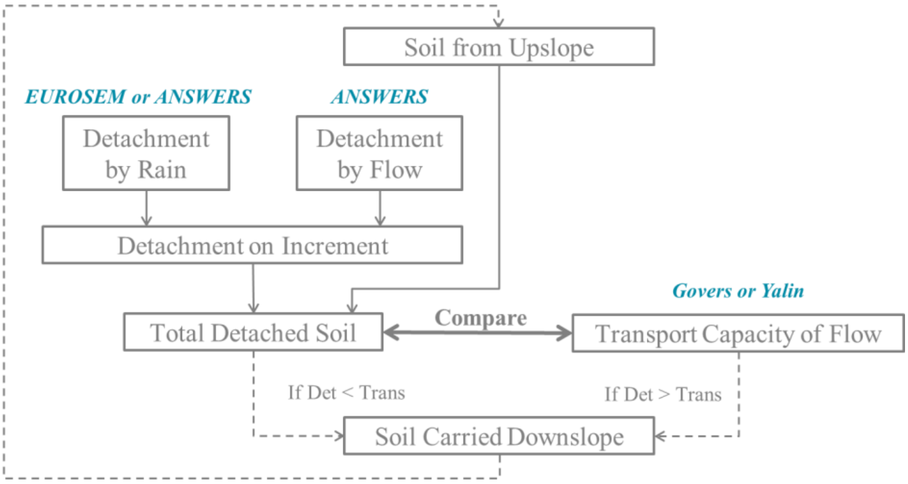

Figure 2. Overview of the different processes for a land cell in wflow_sediment

2.1.1 Sediment generation

One of the first and most well-known soil loss model is the empirical Universal Soil Loss Equation (USLE) by Wischmeier and Smith (1978) which links soil detachment A to rainfall intensity R and several factors considering the positive or negative impact of terrain topography LS, soil erodibility K, crop/vegetation C and support practices P (Eq. 1):

$$A = R \cdot K \cdot LS \cdot C \cdot P \tag{1}$$

The USLE equation used to estimate yearly or monthly soil loss at the field scale was later modified by Renard et al. (1997) to get the RUSLE and rainfall intensity was linked to surface runoff in the MUSLE by Williams et al. (1985) to get event-based estimations at the watershed scale. Most models, either empirical or more physics-based such as WATEM-SEDEM, ANSWERS or LISEM, still base their soil loss equation on one of the USLE model family or on its factors. Fewer entirely physics-based model, such as EUROSEM, WEPP or PESERA developed equations based on rainfall kinetic energy or shear stress of overland flow.

The recurring issue of most soil loss models is that many of their controlling factors (slope, vegetation, soil cohesion, hydrology) vary greatly over space and time and are often difficult to assess (de Vente and Poesen, 2005). Because of this space and time dependence of soil loss, it was decided that wflow_sediment should be a distributed model, be linked to a hydrologic model to estimate the runoff (which best explain soil loss with a fine time scale compared to precipitation), and therefore use a physics-based model for soil loss generation. As underligned by many reviews, the main issue with distributed physics-based models is that they are often too data and computationally intensive (Merritt et al., 2003; de Vente et al., 2013; Aksoy et al., 2005). However, by choosing to use wflow_sbm for the hydrologic simulations, data requirements are intensely reduced as the model is built on detailed global datasets and parameter estimation. That is why in the end, a combination between EUROSEM and ANSWERS model, such as used in the hourly version of SWAT (Jeong et al., 2011), was implemented in wflow_sediment to estimate soil loss.

Soil detached by rainfall D_R can either be computed using EUROSEM equation (Eq 2.) or ANSWERS (Eq. 3). And soil detachment by overland flow D_F is modelled using ANSWERS (Eq. 4). As in rainfall erosion, the effect of the overland flow shear stress on the soil can be reduced by the vegetation or by the soil properties.

$$D_R = k_{erod} \cdot KE \cdot e^{-\varphi h} \tag{2}$$

where D_R is in g.J^{-1}, k is the soil detachability in g.J^{-1}, KE is the total rainfall kinetic energy (sum of direct throughfall and leaf drainage kinetic energies) in J.m^{-2}, h is the surface runoff depth on the soil in m and φ is an exponent varying between 0.9 and 3.1 used to reduce rainfall impact.

$$D_{R,rate} = 0.108 \cdot C_{USLE} \cdot K_{USLE} \cdot A_i \cdot {R_i}^2 \tag{3}$$

$$D_{F,rate} = 0.90 \cdot C_{USLE} \cdot K_{USLE} \cdot A_i \cdot S \cdot q \tag{4}$$

where $D_{R,rate}$ and $D_{F,rate}$ are in kg.min^{-1}, C_{USLE} is the soil cover-management factor from the USLE equation, K_{USLE} is the soil erodibility factor from the USLE equation, A_i is the area of the cell (m^2), S is the slope gradient, R_i is the rainfall intensity (mm min^{-1}), and q is the overland flow rate per unit width (m^2.min^{-1}).

2.1.2 Transport and deposition

The second part in land sediment dynamics after soil erosion is the transport of the detached soil to the river network or catchment outlet. In almost all models it is done by using either a sediment delivery ratio or a transport capacity equation for the flow (Merritt et al., 2003). Transport capacity is the maximum amount of sediment that the flow can transport, thus if the detached sediment exceeds the transport capacity, the excess is deposited. Hessel and Jetten (2007) reviewed the different transport equations used to simulate transport of sediment in shallow flows. The equation from Govers (1990), based on the unit stream power and developed specifically for overland flow (Eq. 5), is the most used one (e.g in LISEM and EUROSEM) and the one that gives best results for a wide range of slope (including steep ones).

$$TC = c_{Govers} \cdot (\omega - \omega_{cr})^{\eta_{Govers}} \tag{5}$$

where TC is the transport capacity of the flow, ω is the unit stream power ($cm.s^{-1}$), ω_{cr} is the critical unit stream power threshold for movement (taken to 0.4 $cm.s^{-1}$) and c_{Govers} and η_{Govers} are coefficients calculated from the median grain size of the detached sediment. This median grain size is estimated using soil texture data and the fraction of fine and very fine sand based on the equation from Fooladmand and Sepaskhah (2006). Another frequently used equation (e.g in WEPP and ANSWERS 2000) is the Yalin equation modified by Foster et al. (1980) in order to consider different particle sizes (Eq. 6). Both equations where retained in wflow_sediment depending on if only the total sediment load is needed or also loads for different particle sizes.

$$TC_i = (P_e)_i \cdot (S_g)_i \cdot \rho_w \cdot g \cdot d_i \cdot V_* \tag{6}$$

where TC_i is the transport capacity of the flow for the particle class i, $(P_e)_i$ is the effective number of particles of class i, $(S_g)_i$ is the specific density for the particle class i ($kg.m^{-3}$), ρ_w is the mass density of the fluid ($kg.m^{-3}$), g is the acceleration due to gravity ($m.s^{-2}$), d_i is the diameter of the particle of class i (m) and $V_* = (g \cdot R \cdot S)^{0.5}$ is the shear velocity of the flow ($m.s^{-1}$) with S the slope gradient and R the hydraulic radius of the flow (m).

2.2 In-stream sediment model

Complete models of sediment dynamics based on hydrology and not hydraulic or hydrodynamic are much rarer than for soil loss and inland dynamics. The simpler models such as the SWAT default sediment river model uses again the transport capacity of the flow to determine if there is erosion or deposition (Neitsch et al., 2011). A more physics-based approach (Partheniades, 1965) to determine river erosion is used by Liu et al. (2018) and in the new SWAT's approach developed by Narasimhan et al. (2017). For wflow_sediment, the new physics-based model of SWAT was chosen for transport and erosion as it enables the use of parameter estimation for erosion of bed and bank of the channel and separates the suspended from the bed loads. The different processes included in the river part of wflow_sediment are summarized in Figure 3.

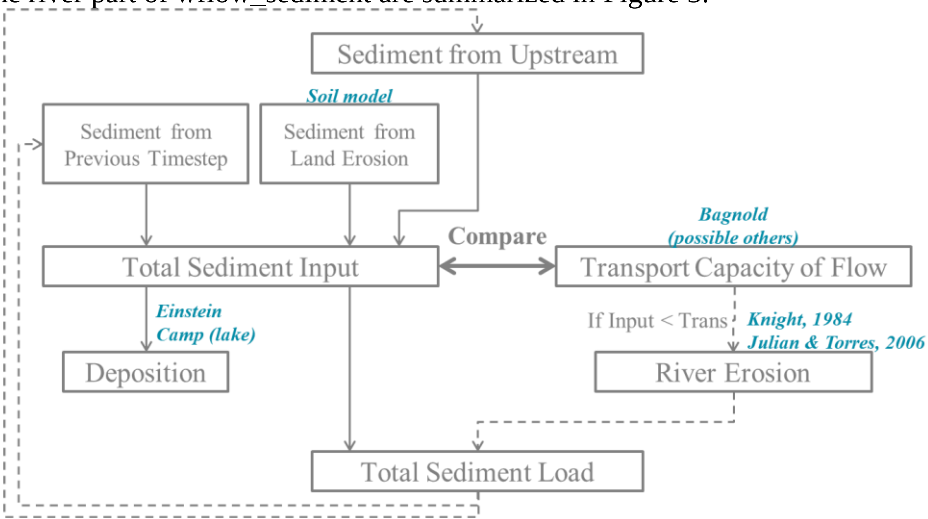

Figure 3. Overview of the different processes for a river cell in wflow_sediment.

2.2.1 River transport

Concerning sediment transport in streams, there are many equations available to describe either bed, suspended or total sediment load, that are usually valid for only specific ranges of flow and sediment characteristics. Table 1 adapted from Richardson et al. (2001) shows the river transport capacity formulas included in wflow_sediment and the type of rivers in which they can be applied.

Table 1.Selected river transport equations and applicability

NAME	APPLICABILITY			MAIN EQUATION*
	GRAVEL	SAND	VERY FINE SAND AND SILT	
BAGNOLD		x	x	$C_{max} = c_{sp} \left(\frac{prf \cdot Q}{h \cdot W}\right)^{sp_{exp}}$

ENGELUND & HANSEN		x		$C_w = 0.05\left(\frac{\rho_S}{\rho_S-\rho}\right)\left(\frac{u \cdot S}{\sqrt{\left(\frac{\rho_s}{\rho_s-\rho}\right) \cdot g \cdot d_{50}}}\right)\theta^{0.5}$
KODATIE (POWER)	x	x	x	$C_{max} = \left(\frac{a \cdot u^b \cdot h^c \cdot S^d}{V_{in}}\right) \cdot W$
MOLINAS & WU		x		$C_w = \frac{1430 \cdot (0.86 \cdot \sqrt{\psi}) \cdot \psi^{1.5}}{0.016+\psi} \cdot 10^{-6}$
YANG	x	x		$\log(C_{ppm}) = I + J \cdot log\left(\frac{u \cdot S - u_{cr} \cdot S}{\omega_{s,50}}\right)$

* where C_{max}, C_w and C_{ppm} are respectively the sediment concentration in ton.m^{-3} or by weight or in parts per million by weight, Q is the surface runoff (m^3.s^{-1}), h is the water level (m), W is the river width (m), u is the flow velocity (m.s^{-1}), ρ and ρ_S are the fluid and sediment density (g.m^{-3}), g is the acceleration due to gravity (m.s^{-1}), d_{50} is the particle mean diameter (m), $\omega_{S,50}$ is settling velocity of a particle with the median riverbed diameter estimated with Stokes (m.s^{-1}), V_{in} is the water inflow during timestep (m^3), ψ is the universal stream power and θ is the Shields parameter. C_{sp}, prf and sp_{exp} are calibration coefficients from Bagnold; a, b, c and d are coefficients from Kodatie for which values depend on the river d_{50}; and u_{cr}, I and J are coefficients computed from Yang's sand or gravel equations.

2.2.2 Erosion

As in the land part of the model, erosion of the river bed and bank occurs only if the amount of sediment is lower than the transport capacity. If this is the case, the eroded sediments are computed using an erosion potential of the bed and bank of the river computed from the physics-based approach of Knight et al. (1984). For a rectangular channel, assuming it is meandering and thus only one bank is prone to erosion, they are calculated from Eq. 7.

$$E_{R,bed/bank} = k_{d,bed/bank} \cdot (\tau_{e,bed/bank} - \tau_{cr,bed/bank}) \cdot 10^{-6} \cdot A_{i,bed/bank} \cdot \rho_{b,bed/bank} \cdot \Delta t \tag{7}$$

where E_R is the potential bed/bank erosion rates (tons), k_d is the erodibility of the bed/bank material (cm^3.N^{-1}.s^{-1}), τ_e is the effective shear stress from the flow on the bed/bank (N.m^{-2}), τ_{cr} is the critical shear stress for erosion (N.m^{-2}), A_i is the area where the shear is applied (L·W for the bed and L·h for the bank, where L,W and h are the channel length, width and water height in m), ρ_b is the bulk density of the bed/bank of the river (g.cm^{-3}) and Δt is the model timestep (s). In wflow_sediment, the erodibilities k_d of the bed and bank are approximated from the critical shear stress using the approach from Hanson and Simon (2001). The critical shear stress τ_{cr} is evaluated differently for the bed and bank: the common formula from Shields initiation of movement is used for the bed, and the equation of Julian and Torres (2006) for the bank. Then, the repartition of the flow shear stress is refined into the effective shear stress on the bed (Eq. 8) and bank (Eq. 9) of the river using the equations developed by Knight and Hanson (1984) for a rectangular channel:

$$\tau_{e,bed} = \rho \cdot g \cdot R_H \cdot S \cdot \left(1 - \frac{SF_{bank}}{100}\right) \cdot \left(1 + \frac{2h}{W}\right) \tag{8}$$

$$\tau_{e,bank} = \rho \cdot g \cdot R_H \cdot S \cdot (SF_{bank}) \cdot \left(1 + \frac{W}{2h}\right) \tag{9}$$

where ρ_g is the fluid specific weight (9800 N.m^{-3} for water), R_H is the hydraulic radius of the channel (m), h and W are the water level and river width (m), and SF_{bank} is the proportion of shear stress acting on the bank compared to the bed (%) estimated from Knight and Hanson (1984).

2.2.3 Deposition and mass balance

In most models, deposition in the river is generally estimated using either Krone's formula or Einstein's. Simple deposition formulas for a 1D reservoir or lake have been reviewed by Verstraeten and Poesen (2000). Einstein's formula (Eq. 10) and a simple Camp reservoir deposition equation (Eq. 11) were chosen for deposition in the channel and in lakes in wflow_sediment. As the hydrologic model wflow_sbm doesn't model floodplains, no floodplain deposition was implemented.

$$P_{dep} = \left(1 - \frac{1}{\exp\left(\frac{1.055 \cdot L \cdot \omega_S}{u \cdot h}\right)}\right) \cdot 100 \tag{10}$$

$$P_{dep} = \left(\frac{A_{lake}}{Q_{out,lake}} \cdot \omega_S\right) \cdot 100 \tag{11}$$

where P_{dep} is the percentage of sediments that is deposited respectively on the river bed or in the lake, L and h are channel length and water height (m), ω_S is the particle settling velocity calculated with Stokes formula (m.s^{-1}), u is the mean flow velocity (m.s^{-1}), A_{res} is the surface area of the lake (m^2) and $Q_{out,res}$ is the outflow of the lake (m^3.s^{-1}).

Finally, after estimating inputs, deposition and erosion with the transport capacity of the flow, the amount of sediment leaving each river cell to go downstream is estimated using Eq. 12:

$$sed_{out} = \left(sed_{in} + sed_{erod} - sed_{dep}\right) \cdot \frac{V_{out}}{V} \tag{12}$$

where sed_{out} is the amount of sediment leaving the river cell (tons), sed_{in} is the amount of sediment coming into the river cell (storage from previous timestep, land erosion and sediment flux from upstream river cells in tons), sed_{erod} is the amount of sediment coming from river erosion (tons), sed_{dep} is the amount of deposited sediments (tons), V_{out} is the volume of water leaving the river cell (m^3) and V is the volume of water in the river cell (m^3). A mass balance is then used to calculate the amount of sediment remaining in the cell at the end of the timestep t, $(sed_{riv})_t$ (Eq. 13). For wflow river cells where the length is less than the length that the flow can travel in the model timestep, the river processes are iterated over smaller sub-timesteps.

$$(sed_{riv})_t = (sed_{riv})_{t-1} + (sed_{in})_t + (sed_{erod})_t - \left(sed_{dep}\right)_t - (sed_{out})_t \tag{13}$$

3. RESULTS AND DISCUSSIONS

3.1 Study case: Rhine basin

At the beginning of the development of the wflow_sediment model, only the Rhine was successfully tested by the global version of wflow_sbm and was therefore chosen as a development and test case of the sediment dynamics model. The Rhine is one of the largest catchments in Europe connecting Switzerland, western Germany and eastern France to the Netherlands and the North Sea (Figure 4). Its upstream area at the Dutch-German border (Lobith station on the map) is 160,000 km^2 (Asselman et al., 2003) and possesses very heterogeneous climate, hydrology, geology, geomorphology and land use characteristics from the Alpine area to the lowland area. Hydrology and sediment dynamics for the Rhine were modelled on an approximately 1 x 1 km grid (5 arc-minute), at a daily timestep and for the period 2010-2014.

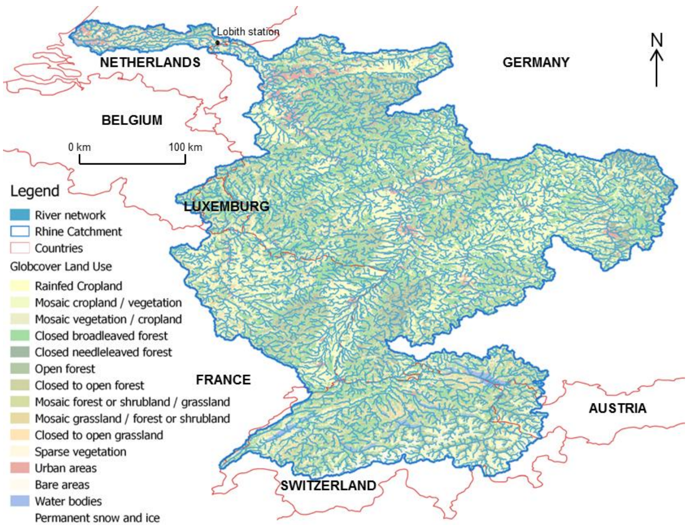

Figure 4. Rhine basin: land use and river network

To test model capabilities in more data scarce regions, only global datasets were used to setup and run the models, and preferentially from the same source for both hydrology and sediment. These datasets are SRTM for the elevation (Farr et al., 2007), GlobCover for landuse (Arino et al., 2012), SoilGrids250m for soil properties (Hengl et al., 2017), HydroSHEDS (Lehner et al., 2008) and HydroLAKES (Messager et al., 2016) for catchment, river delineation and lake properties, GRanD for reservoirs and dams location (Lehner et al., 2011), and ERA5 Reanalysis (C3S, 2017) for climate information (precipitation, temperature and radiations).

As the hydrological and sediment model are physics-based, model parameters for the hydrology were estimated using the approach from Imhoff et al. (2019). In a similar way, model parameters were estimated using either pedo-transfer functions or literature values linked to the soil and landuse datasets.

3.2 Results of the inland part of the model

To model soil loss, the EUROSEM equation was chosen for rainfall erosion and soil detachability values were defined based on soil texture (Morgan et al., 1998). For overland flow erosion with ANSWERS, the USLE C factor was linked to GlobCover landuse and the USLE K factor was computed using the formulation from Renard et al. (1997). Results (without calibration) showed that soil loss was more dependent on surface runoff compared to precipitation and thus soil loss patterns follow the overland flow patterns resulting from the hydrological model (Figure 5).

Validation of soil erosion models are rather difficult as actual observed values and samplings on soil plots are very scarce. Even when requesting soil loss data from European institute for the EIONET-SOIL database, Panagos et al. (2014) found that the received values were actually model results from USLE/RUSLE. A few studies such as Cerdan et al. (2010) and Maetens et al. (2012), gathered existing field values for Europe via extensive literature studies and personal communications. While detailed amounts, locations and date of sampling are not available, derived statistics either by countries or land use type can be used to validate the range of predicted erosion amounts from the wflow_sediment model.

Another source of validation of soil erosion is then to compare the results produced by the wflow_sediment model with other model maps such as the ones from Panagos et al. (2015) for the year 2010 with the RUSLE2015 model and by Kirkby et al. (2008) for the year 2003 with the PESERA model (Figure 6), which are the most used for Europe. RUSLE2015 is based on the RUSLE equation and consists of a set of published high resolution maps of all the RUSLE factors for the European Union states. As this equation is entirely based on rainfall, soil loss patterns are less distinctive than a physics/runoff based model and RUSLE2015 results in high erosion amounts over the Rhine basin compared to results with the wflow_sediment model. The PESERA model on the contrary is entirely based on surface runoff erosion and does not include direct splash erosion.

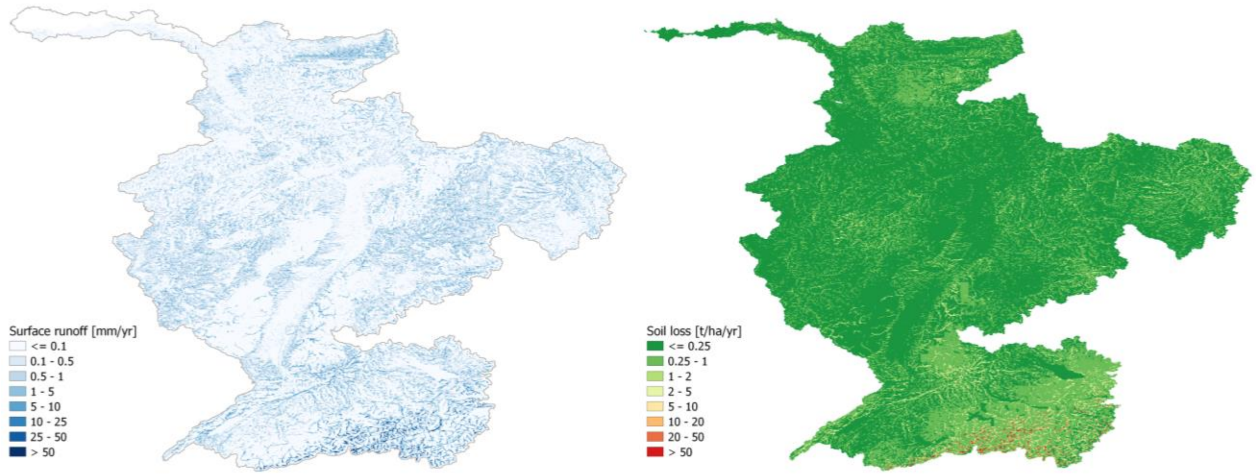

Figure 5. Simulated runoff (left) and soil loss (right) for the year 2010 in the Rhine basin with wflow_sbm and wflow_sediment

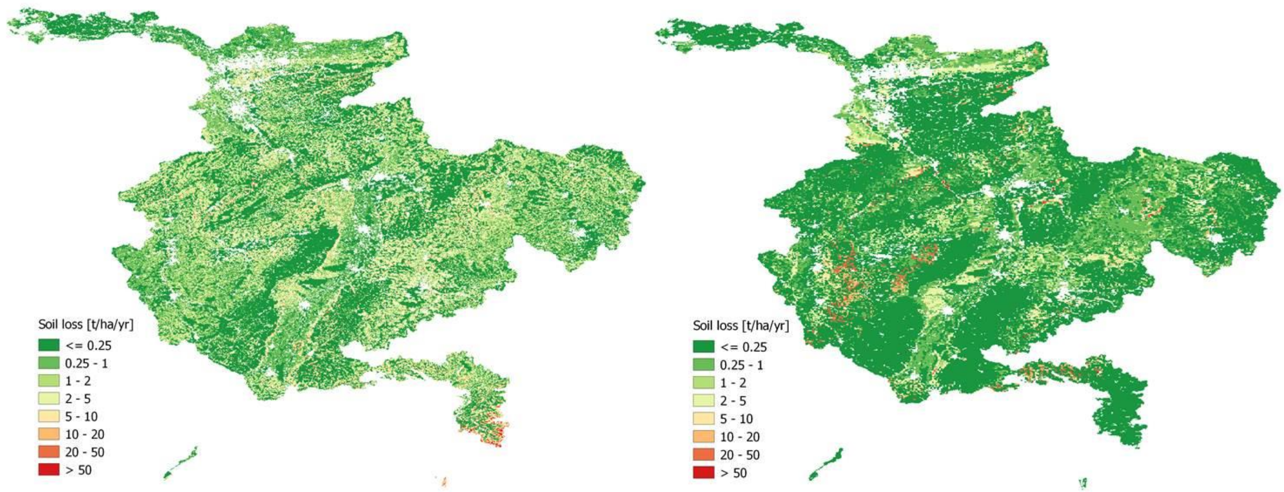

Figure 6. Simulated soil loss by RUSLE2015 for the year 2010 (left) and by PESERA for the year 2003 (right).

To get a better appreciation of the soil loss amounts simulated by wflow_sediment, results were then averaged over the entire simulation period and by different land use class (forest, cropland, and grassland), in order to allow comparison with both literature field data and other modelled data. Results, in Table 2, show that for forests, simulated results from wflow_sediment are both in the range of field data and very close to the PESERA results. For cropland, results are lower than both models and field values. The main reason is that the land use classification from Globcover only considers an irrigated cropland category, contrary to the CORINE classification used in the other models that distinguishes crop types. As different crops can have very different USLE C values,refining crop categories where possible may then improve the results. Finally, for grassland, the average value from wflow_sediment, while lower than the other modelled averages, is still in a good range with the field data.

Table 2. Mean soil loss per land use type (tons.ha^{-1}.yr^{-1})

Source	Forest	Cropland	Grassland
Cerdan (Europe)	0.2	3.6	0.4
Maetens (Europe)	0.7	6.5	0.7
RUSLE2015 (Rhine, 2010)	2.61	2.16	2.53
PESERA (Rhine, 2003)	0.33	1.62	0.73
wflow_SEDIMENT (Rhine, 2010)	0.35	0.91	0.46

To test the inland sediment yield and inland transport routine, the total load coming from land erosion at Lobith station (Figure 4), was compared to the observed load for the year 2010. The measured load at Lobith was 1.62 x 10^6 tons and the simulated load by hillslope erosion was 1.01 x 10^6 tons. As sediment in the Rhine is supposed to mainly come from hillslope rather than river erosion (Asselman et al., 2003), this value was then considered accurate enough for an uncalibrated model and the parameters were kept as such for the further river part of wflow_sediment model development.

3.3 Results of the instream part of the model

For the instream part of the model, simulated daily suspended sediment load was compared to measured suspended particulate matter at Lobith station at the German-Dutch border (Figure 4). The first tested formula for transport was the equation from Engelund and Hansen which did not give satisfactory results. The reason was that in the first version of the global wflow_sbm model, surface runoff, water level and width are adjusted to the actual channel characteristics but not the slope which is still the average slope of the grid cell and not the actual slope of the river bed. For certain hilly region such as for the Rhine near Koblenz in Germany, this gave too high results for sediment transport capacity and erosion. Furthermore, as river width is calculated by an equation from Finnegan et al. (2005) that uses the slope, widths are then also underestimated for these regions.

In the end, calibration was required to work with the state of the global wflow_sbm model and the very rough river schematization and characteristics, and the simplified Bagnold transport formula that only relies on flow velocity was used. Results for surface runoff and suspended sediments for Lobith for the year 2012 (calibration year) and 2010 (validation year) are shown in Figure 7. With global data and parameter estimation, runoff at Lobith is quite well estimated with a Nash-Sutcliffe Efficiency (NSE) coefficient around 0.6. Suspended sediments are a little less accurate with a NSE of around 0.2-0.4, depending on the modelled year, which is still quite acceptable given the datasets used and the minimum calibration required. The global trend still seems to be caught by the model even if some of the peaks are underestimated mainly since only the flow in the channel is used in the simplified Bagnold's formula.

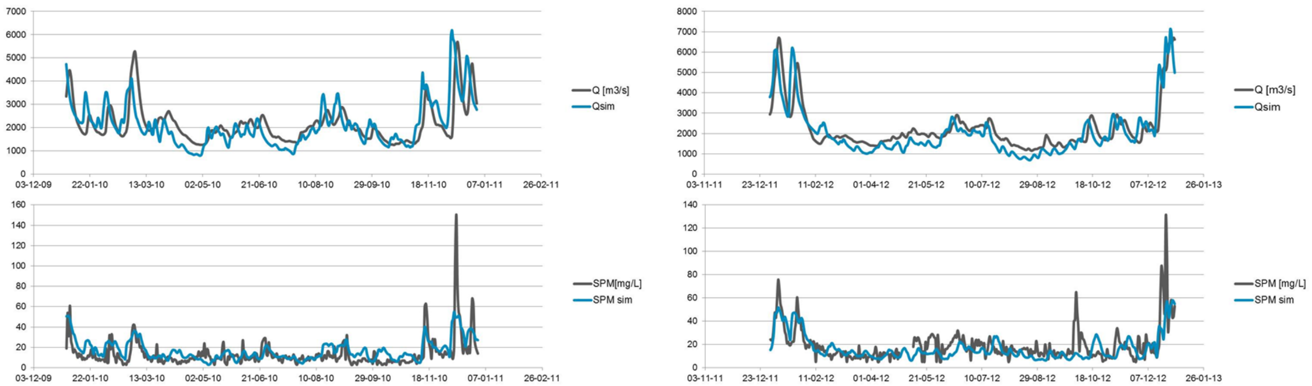

Figure 7. Measured (grey) and modelled (blue) surface runoff (m3.s-1) and suspended sediment concentration (mg/L) at Lobith station in 2010 (left) and 2012 (right)

4. CONCLUSIONS

Wflow_sediment is a new fully integrated model of the wflow framework, able to estimate basin-scale sediment dynamics using results from the hydrologic model wflow_sbm. It is a distributed model working at a fine time and space resolution that is able to model soil loss, delivery to the river network as well as in-stream transport and processes, using global available datasets, parameter estimation and minimal calibration. Wflow_sediment has been successfully tested in the Rhine basin where it gave promising predictions of soil loss and sediment loads. The foreseen next steps are improving the river hydrology and parameterization to minimize calibration and applying the model in catchments under different climate and erosion processes.

If successful, results of the model could further and easily be used in other domains such as water quality modelling where fate and transport of hydrophobic particles, such as Tyre and Road Wear Particles (TRWP) or emerging pollutants, are intricately linked to sediment dynamics (Unice et al., 2019; van Gils et al., 2020).

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