WATER RESEARCH 47 (2013) 339–350

Available online at www.sciencedirect.com

SciVerse ScienceDirect

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

Sediment contamination assessment in urban areas based on total suspended solids

Luca Rossi [a,*], Nathalie Chèvre [b], Rolf Fankhauser [c], Jonas Margot [a], Romuald Curdy [a], Marc Babut [d], D. Andrew Barry [a]

[a] Laboratoire de technologie écologique, Institut d'ingénierie de l'environnement, Faculté de l'environnement naturel, architectural et construit (ENAC), Station 2, Ecole Polytechnique Fédérale de Lausanne (EPFL), 1015 Lausanne, Switzerland
[b] Faculty of Earth Sciences and Environment, University of Lausanne, Geopolis 3630, 1015 Lausanne, Switzerland
[c] GEP Data Consulting, Hegenheimerstr. 129, 4055 Basel, Switzerland
[d] Irstea, UR MALY, 3 bis quai Chauveau, 69336 Lyon, France

ARTICLE INFO

Article history:
Received 26 January 2012
Received in revised form
13 June 2012
Accepted 5 October 2012
Available online 13 October 2012

Keywords:
Stormwater
Combined sewer overflow
Risk assessment
TSS
Sediments
Stochastic model

ABSTRACT

Sediment represents an important compartment in surface waters. It constitutes a habitat or spawning site for many organisms and is an essential trophic resource for higher level organisms. It can be impacted by anthropogenic activities, particularly through urban wet-weather discharges like stormwater and combined sewer overflows. An approach was presented for assessing the risks caused by urban wet-weather discharges to the sediment compartment based on total suspended solids (TSS). TSS is routinely measured in field surveys and can be considered as a tracer for urban wet-weather contamination. Three assessment endpoints linked with TSS were proposed: a) siltation of the riverbed, b) oxygen demand due to organic matter degradation and c) accumulation of ecotoxic contaminants on the riverbed (heavy metals, PAHs). These criteria were translated in terms of the maximal TSS accumulation load and exposure time (percentage of time exceeding the accumulation criteria) to account for sediment accumulation dynamics and resuspension in streams impacted by urban wet-weather discharges. These assessment endpoints were implemented in a stochastic model that calculates TSS behavior in receiving waters and allows therefore an assessment of potential impacts. The approach was applied to three Swiss case studies. For each, good agreement was found between the risk predictions and the field measurements confirming the reliability of the approach.

1. Introduction

Anthropogenic activities in urban areas have been shown to impact both receiving waters and streambeds (Power and Chapman, 1992; Burton and Pitt, 2002; Wildi et al., 2004; Taylor and Owens, 2009). In particular, sediments accumulated in rivers or estuaries in urban areas have been shown to be hazardous to organisms either directly (by contact, ingestion) or through bioaccumulation (Borchardt and Sperling, 1997; Faulkner et al., 2000; Heath et al., 2002; Marsalek et al., 2002; Kabelkova et al., 2005; Taylor and Owens, 2009). Despite the general improvement in European water quality over decades, many urban rivers still possess low sediment quality (Taylor and Owens, 2009). This is a long-term concern as the residence time of sediments in rivers is far greater than that of water.

* Corresponding author. Tel.: +41 21 693 57 80; fax: +41 21 693 80 35.
E-mail addresses: luca.rossi@epfl.ch (L. Rossi), nathalie.chevre@unil.ch (N. Chèvre), rolf.fankhauser@gepdata.ch (R. Fankhauser), jonas.margot@epfl.ch (J. Margot), romuald.curdy@gmail.com (R. Curdy), marc.babut@irstea.fr (M. Babut), andrew.barry@epfl.ch (D.A. Barry).
0043-1354/$ – see front matter
http://dx.doi.org/10.1016/j.watres.2012.10.011

The legacy of polluted sediments is a major problem for urban catchments. There is, therefore, a need to reduce the impact of such sediments on urban regions. Among others, urban wet-weather discharges can provoke displacement of contaminated sediments and lead to ecological disruptions of riverbed sediments downstream of urban areas. Indeed, total suspended solids (TSS) transported by rain runoff water are recognized as one important source of polluted sediments from urban areas (Chebbo, 1992; Gromaire-Mertz, 1998; Rossi et al., 2005). Many pollutants in urban wet-weather discharges are attached to particles transported in suspension, with diameters ranging from a few micrometers to 1–2 mm, and a median diameter between 30 and 40 μm (Chebbo, 1992; Ashley et al., 2004; Torres and Bertrand-Krajewski, 2008). These suspended solids can also be defined as fine sediment carried in suspension that may settle on the riverbed (Krishnappan and Marsalek, 2002). A large majority of harmful substances (trace metals, polyaromatic hydrocarbons (PAHs), etc.), as well as organic matter, are adsorbed onto sediments, and so TSS is a proxy for pollutant load (Seidl et al., 1998; Rochefort et al., 2000; Becouze-Lareure, 2010). TSS is also considered to cause habitat deterioration for the benthic zone (Alabaster and Lloyd, 1980; DFO, 2000; Henley et al., 2000; Paul and Meyer, 2008). They can, for instance, blanket the bottom of riverbeds inhibiting exchange processes in the hyporheic zone, or block gravel spawning beds (EIFAC, 1969; Edberg and Hofsten, 1973; Burton and Pitt, 2002; Ibisch and Borchardt, 2003). This siltation process is also described in the literature as "embeddedness", i.e., the proportion of coarse bed covered by fine sediment, <2 mm, essentially TSS (Waters, 1995). TSS from combined sewer overflow (CSO) discharges that are deposited in rivers and receiving waters can represent also an important source of problems for sediments due to the associated organic matter (Ciffroy et al., 2000; Borchardt and Reichert, 2001; Watts et al., 2003; Even et al., 2004). The degradation of this organic content in the hyporheic zone can cause anaerobic conditions, which are detrimental for many sensitive species (Kodama and Horiguchi, 2011), and allow the remobilization of various chemical compounds (Vink, 2002). Evaluating the risk of TSS is therefore of crucial importance to decrease the impact of urban areas on sediment (EU, 2003).

Risk assessment is generally conducted by comparing environmental contamination with quality criteria related to protection of organisms (EU, 2003). For wet-weather discharges, information on both parameters (environmental contamination and quality criteria) for TSS is therefore needed. We propose to link the risk assessment approach for sediments with TSS. Here, we (i) determine the TSS concentration in urban wet-weather discharges, (ii) propose quality criteria (assessment endpoints) for TSS and (iii) evaluate the risk for streambeds impacted by wet-weather discharges. This approach is illustrated and validated with three different examples from Switzerland.

2. Methodology

The methodology (Fig. 1) is derived from the classical USEPA approach for ecological risk assessment (USEPA, 1998) and is divided into three phases: problem formulation, analysis and risk characterization. As proposed in the USEPA formulation, the conceptual model and the assessment endpoints are the products of the problem formulation step. The analysis step can be conducted based on this information, leading to the risk characterization step.

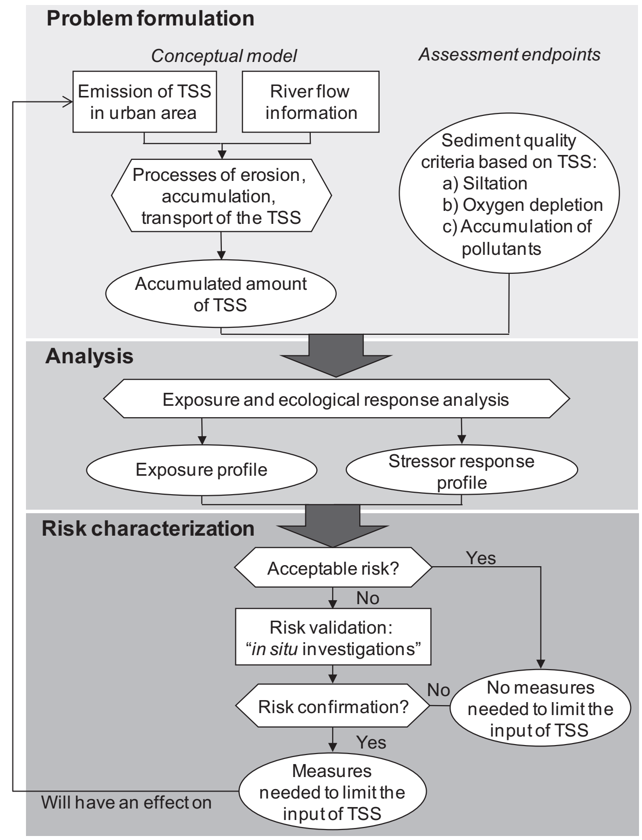

Fig. 1 – Framework of risk assessment and management for wet-weather discharges (from USEPA (1998) and EU (2003)). Within each phase, rectangles designate inputs, hexagons represent actions and circles represent outputs.

2.1. *Conceptual model*

Two processes were considered for the exposure model: The emission of TSS from urban sources during rain events and the behavior of TSS in receiving waters (deposition, transport, erosion). A probabilistic approach was applied to determine the exposure in order to account for uncertainties linked to the various processes and variability in climatic conditions (Rossi et al., 2005).

For TSS emission, we used the REBEKA II stochastic model of Rauch et al. (2002) as modified by Fankhauser et al. (2004) and Rossi et al. (2005). This model predicts TSS concentrations from combined sewer overflows (CSOs) in combined sewer systems and from stormwater in separate sewer systems. A long period (10 y) of historical rain information was considered to account for rain variability. A Monte Carlo approach was used to account for parameter uncertainty. The UNCSIM package proposed by Reichert (2001) was used to generate random values of a given multivariate distribution. In this package, various random sampling techniques (random, Latin hypercube, etc.) can be selected to produce output samples for the simulation. As implemented, the model estimates the TSS concentration and probability density function at a given discharge point for a 10-min time interval. For further information see Rossi et al. (2005).

For the TSS behavior in receiving waters, we extended the existing TSS model with a simplified stream model. TSS accumulation and re-suspension processes in receiving waters vary with changing hydraulic conditions. The model considers a homogeneous stream section, in which sediment deposition/resuspension is modeled as being uniform. At a given point in the receiving water, the probability that the hydraulic conditions, defined by the relationship between the shear stress τ and a critical shear stress constraint τ_{crit}, allow deposition (F_d) or erosion (F_e) of TSS (Krone, 1962; Ciffroy et al., 2000) is calculated from:

$$F_d = CW_C\left(1-\frac{\tau}{\tau_{crit}}\right)\tau < \tau_{crit}$$
$$F_e = e\left(\frac{\tau}{\tau_{crit}}-1\right)\tau \geq \tau_{crit} \quad (1)$$

where F_d is the flux of TSS to the riverbed (g m^{-2} s^{-1}), C is the initial TSS concentration in the stream after complete mixing (g m^{-3}), W_c is the settling velocity of particles in the receiving water (m s^{-1}), τ and τ_{crit} are the shear stress and critical shear stress (N m^{-2}), respectively, F_e is the eroded flux of TSS (g m^{-2} s^{-1}) and e the erosion flux, taken as constant (g m^{-2} s^{-1}) (Ariathurai and Arulanandan, 1978). Indicative values for the different parameters are given in Table 1. The shear stress τ (N m^{-2}) is calculated using (Graf, 1971):

$$\tau = \rho_w g \frac{V^2}{K_s^2 R_h^{1/3}} 0 \quad (2)$$

where ρ_w is the water density (kg m^3), g is the magnitude of gravitational acceleration (m s^{-2}), K_s is the Strickler roughness coefficient (m$^{1/3}$ s^{-1}), V is the mean flow velocity (m s^{-1}) and R_h is the hydraulic radius (m).

Whether TSS accumulates on the riverbed depends on the definition of the critical shear stress, which is specific for each stream. The value of τ_{crit} can be estimated as (Schälchli, 1993):

$$\tau_{crit} = \Theta g(\rho_s - \rho_w)d_m, \quad (3)$$

where Θ is the non-dimensional Shield stress constraint, ρ_s the density of the riverbed material (kg m^{-3}) and d_m the average diameter of the sediment particles (m).

In Equation (3), a relatively high value for d_m is proposed (4.5–7.8 mm), which takes into account an "armor effect" (Vericat et al., 2006). This phenomenon corresponds to trapping of the fine particles on the riverbed in the interstices formed by the coarser elements. Only bedload events can dislodge these particles.

2.2. Assessment endpoints

Three TSS-based assessment endpoints were defined to characterize the risk of urban wet-weather impact on sediments:

a) *Siltation of the riverbed* (C_{max}). The release of TSS through wet-weather discharges should not impair fish reproduction and maintenance of benthic organisms by clogging the riverbed;
b) *Oxygen depletion* (O_{max}). TSS discharges, especially from CSOs, should not lead to anaerobic processes in the riverbed due to an excess of organic matter;
c) *Accumulation of persistent pollutants* (E_{max}). After TSS deposition on the riverbed, the concentration of toxic substances in riverbed sediments (e.g., heavy metals, PAHs) should remain below the levels sustainable for benthic organisms and fish fry.

Exceedance of the assessment endpoints is defined as the proportion of measurements that exceed critical exposure values, calculated over an annual cycle. In terms of stream morphology, the proposed values (Table 2) are defined for central European conditions, and may differ as a function of

Table 1 – Default value for parameters in the different equations. A uniform distribution between the min-max values is proposed for the various parameters.

Parameter		Units	Mean value and range (min – max)	References
Settling velocity in stream	W_c	cm s^{-1}	0.024 0.012 – 0.063	(Chebbo et al., 2003; Minshall et al., 2000; Gromaire-Mertz et al., 2008)
Erosion velocity	e	g m^{-2} s^{-1}	1.36 0.678 – 2.03	(Ariathurai and Arulanandan, 1978)
Shear stress constraint	Θ	–	0.072 0.047 – 0.078	(Schälchli, 1993)
Organic content of TSS for CSOs	OC_{cso}	g O_2 g TSS^{-1}	0.47 0.23 – 0.65	(Gromaire-Mertz, 1998)
Organic content of TSS for stormwater	OC_{storm}	g O_2 g TSS^{-1}	0.15 0.10 – 0.19	(Gromaire-Mertz, 1998)
Degradation rate of organic matter linked with TSS	D_R	g O_2 m^{-2} d^{-1}	2.4	(Gujer, 1999; Ibisch and Borchardt, 2003)
Inter-event degradation rate	k	d^{-1}	0.24 0.12 – 0.3	(Gujer, 1999)

Table 2 – Proposed threshold values for a tolerable TSS level in streambeds near urban wet-weather discharges. The values are given in grams of TSS per square meter and year or in grams of TSS per square meter and day.

Assessment endpoint	Maximum accumulation value for TSS	Maximum annual duration in which the accumulation could be exceeded
C_{max}: Colmation of the riverbed	625 g m^{-2} y^{-1}	20%
O_{max}: Oxygen deficit on the riverbed		
Combined sewer overflows:	5 g m^{-2} d^{-1}	10%
Stormwater discharges:	16 g m^{-2} d^{-1}	10%
E_{max}: Accumulation of persistent pollutants	25 g m^{-2} y^{-1}	5%

the characteristics of the riverbed. Numerical values for the assessment endpoints are defined below.

2.2.1. *Siltation of the riverbed* (C_{max})

Fine particles are deposited on the riverbed or are incorporated into its top layer so that the pore space is reduced, i.e., the riverbed is progressively clogged (Schälchli, 1993). This can reduce water exchange and is especially critical for spawning sites where there is a risk of limiting the reproduction of sensitive fish like salmonidae. The siltation criterion is therefore based on this clogging process. Following different regulations, the percentage of fine particles input (less than 2 mm) in the streambed substrate composition must not exceed 10% at salmonidae spawning sites (EIFAC, 1969; CCME, 1995), especially during the spawning period (2–3 months in spring). The maximum acceptable input of TSS following this criterion is calculated with:

$$C_{max} = V\rho P(C_{crit} - C_{nat}), \quad (4)$$

where C_{max} is the maximum tolerable amount of TSS (kg m^{-2}), V the specific volume of streambed considered (m^3 m^{-2}), ρ the TSS density (kg m^{-3}), P the volumetric porosity of the streambed (–). C_{crit} is the defined criterion (less than 10% of fine sediment) and C_{nat} the natural volume fraction of fine sediments (<2 mm), both dimensionless.

The first 5 cm of the streambed is relevant for the siltation assessment criterion. This means that the input of TSS from the urban watershed must not exceed the available porosity of the first 5 cm of the riverbed in the event of adequate granulometry for egg-laying (2–5 cm; (Ottaway et al., 1981; Crisp and Carling, 1989)). Higher inputs of TSS over that depth could block exchanges between the water column and the streambed. In order to avoid long-term diminution of gas exchanges between the stream and the riverbed, the value C_{max} must not be exceeded more than 20% of the time. This figure was defined on the basis of professional judgment after discussions with hydro-biologists and was approved by the Swiss authorities (VSA, 2007).

For example (Table 2), for 1 m^2 of streambed ($\rho = 2500$ kg m^{-3}, porosity of 10%, with 5% of "natural" fine sediments less than 2 mm), the acceptable supplementary amount of TSS from wet-weather discharges (C_{max}), in the first 5 cm ($V = 0.05$ m^3), is 0.625 kg m^{-2}.

2.2.2. *Oxygen depletion* (O_{max})

In order to avoid anaerobic processes in the sediment compartment, the input of organic matter (expressed as equivalent TSS) must not exceed the degradation capacity of the riverbed. The criterion is based on a general correlation between TSS and organic substances (expressed as grams of O_2 per gram of TSS):

$$O_{max} = \frac{D_R}{O_C}, \quad (5)$$

where O_{max} is the maximum input of TSS in (g TSS m^{-2} d^{-1}), D_R is the degradation rate (g O_2 m^{-2} d^{-1}) and O_C the quantity of O_2 required for the degradation of organic matter linked with TSS (g O_2 per g TSS). Values for the degradation rates D_R and organic content O_C are given in Table 1. These values, derived from different experiments, allow the calculation of O_{max} for CSO (5 g TSS m^{-2} d^{-1}, range: 3.7–10.4) and stormwater discharges (16 g TSS m^{-2} d^{-1}, range: 12.6–24).

2.2.3. *Accumulation of persistent pollutants* (E_{max})

The concentrations of contaminants adsorbed on TSS in stormwater and CSO discharges are often above the effect concentrations defined for sediment (MacDonald et al., 2000). PEC concentrations (Probable Effect Concentrations values, i.e., above which harmful effects are likely to be observed) are frequently exceeded, for example, in stormwater discharges (Rossi, 1998). This indicates that particles settling on the riverbed could affect organisms living there. The definition of the assessment criterion, E_{max}, is based on experiments that show acute effects (EC_{50}) on different trophic levels with sediment accumulation of up to 1 cm m^{-2} y^{-1} (Institut Forel, 1996; Marsalek et al., 1999). The maximum accumulation rate of TSS is therefore defined, per square meter of riverbed, as:

$$E_{max} = \frac{h\rho}{SF_{sed}}, \quad (6)$$

where E_{max} is the maximum tolerated amount of contaminated TSS in contact with the riverbed per year (kg m^{-2} y^{-1}), h is the critical height of accumulated sediments from wet-weather sources that can generate ecotoxicological effects (m y^{-1}), for instance 1 cm y^{-1}, ρ is the density of TSS in wet-weather discharges (median value: 2500 kg m^{-3}) and SF_{sed} is a risk assessment factor, here taken as 1000. SF_{sed} accounts for extrapolation from acute to chronic data and from laboratory tests with single organisms to aquatic ecosystems. It was adapted from the Technical Guidance for Risk Assessment from the European Union (EU, 2003).

Taking into account a value of $h = 0.01$ m y^{-1}, the value of E_{max} is 25 g m^{-2} y^{-1}. A potential risk results if more than 25 g m^{-2} of wet-weather sediments remain in contact with the riverbed during more than 95% of the time (exposure time defined by professional judgment, VSA (2007)).

2.3. Analysis

Risk assessment is based on a comparison of the TSS exposure and the assessment endpoints. The exposure time (T_{acc}) during which a criterion is violated is given by:

$$A_{tot}(t_i) = A(t_{i-1}) + [F_d(t_i) - F_e(t_i)]\Delta t \quad \begin{cases} < C_{max} \rightarrow T_{acc}(t_i) = T_{acc}(t_{i-1}) \\ \geq C_{max} \rightarrow T_{acc}(t_i) = T_{acc}(t_{i-1}) + \Delta t \end{cases}, \tag{7}$$

where A_{tot} is the total amount of TSS accumulated on the riverbed at a time t_i (g m^{-2}), $A(t_{i-1})$ is the amount at the previous time step (g m^{-2}), F_d and F_e the accumulation and erosion fluxes (g m^{-2} s^{-1}), respectively, Δt the time step in seconds (10 min in our case), C_{max} is one of the three criteria (computed from $A(t_i)$), and T_{acc} is the cumulative time for which the relevant criterion is violated. For the oxygen criterion, O_{max}, we also take into account the degradation rate of the organic matter linked to TSS between two rain events. This is expressed as a first-order kinetic rate:

$$\frac{dO_2}{dt} = -kO_2 \rightarrow O_2 = O_{2\,ini}\exp(-k\,t), \tag{8}$$

where O_2 is the oxygen demand on the riverbed linked to TSS (g m^{-2}), k (d^{-1}) is the degradation rate constant (Gujer, 1999) considering the riverbed as a bioreactor (indicative values in Table 1) and $O_{2\,ini}$ is the initial oxygen demand on the riverbed linked to TSS (g m^{-2}).

2.4. Risk characterization: Application to different case studies

The methodology proposed in this paper was applied to the Allaine, Urtenen and Sion-Riddes watersheds, located in Switzerland (Fig. 2), which cover different topographic and climatic conditions. This part represents the third part of the methodology expressed in Fig. 1. The global characteristics of the watersheds and receiving waters are given in Table 3. More details on the catchments can be found in Margot (2008) and Curdy (2010).

At each location, sediment samples were collected upstream (relative reference site) and downstream of the wet-weather or CSO discharges using a PONAR grab sampler, which consists of two opposing semi-circular jaws. This device sampled a surface area of 340 cm^2 to a depth of approximately 10 cm. The upper layer (1–5 cm depending on the site) was collected at different locations within each site. Individual site samples were mixed to form a single sample. Visual inspections, based on Schälchli (2002), were conducted at each site to assess if siltation processes were evident. The presence of anoxic conditions (odor, color) was also reported. The sediment samples were transported to the laboratory within 24 h. There, extractions were conducted for heavy metal and PAH analyses. The samples were dried at 40 °C during 2–4 d and passed through a 2-mm sieve. For heavy metal analysis (Pb, Cu, Cd, Zn, Ni, Cr, Co), 1 g of dry sediment was mixed with 7.5 ml HCl (30%) and 2.5 ml HNO_3 (65%) and heated for 2 h after one night (minimum 12 h) of digestion. The analyses were performed on the mixture filtrate, diluted five times, on a Perkin–Elmer ICP-OES (Optima 3300 DV). For PAH analyses, 10 g of sediment were extracted with a 75:25 (v/v) mixture of hexane and acetone in a soxhlet extractor for 12 h. The organic extract was then concentrated by evaporation under low pressure (Rotavapor, 40 °C, 330 mbar). Purification and separation steps were conducted on a chromatographic column (40 cm long, Ø 10 mm, filled with 8 g of silica gel and 40 g of deactivated alumina). The samples were eluted three times with respectively 20 ml n-hexane, 20 ml 90:10 n-hexane:dichloromethane and 40 ml 80:20 n-hexane:dichloromethane. Only the last fraction was used for PAH analysis, and was reduced in a Rotavapor before injection into a HPLC-FLD (Agilent 1050) equipped with a Vydac 201tp54 column. Following Chapman et al. (1982), 16 priority PAHs were quantified: naphthalene (Naph), acenaphthene (Ace), fluorene (Flu), phenanthrene (Phe), anthracene (Anth), fluoranthene (Fluo), pyrene (Pyr), benzo[a]anthracene (BaAn), chrysene (Chr), benzo[e]pyrene (BeP), benzo[b]fluoranthene (BbFl), benzo[k]fluoranthene (BkFl), benzo[a]pyrene (BaPy), dibenzo[a,h]anthracene (DiAn), benzo[g,h,i]perylene (BePe), and indeno[1,2,3-cd]pyrene (InPy). Total PAH concentrations were obtained by multiplying the sum of the 10 main PAHs by a factor two (Van Metre and Mahler, 2003). The laboratory regularly participated in ring tests to check the validity of the analytical values. The PEC (Probable Effect Concentrations) and TEC (Threshold Effect Concentrations) values from MacDonald et al. (2000) were used as comparisons for risk evaluation.

3. Results

Fig. 3 illustrates the exposure of TSS in the riverbed of the Urtenen case study. The TSS accumulation on the riverbed is presented for one run of the Monte Carlo simulation for a sub-period of 1 y. The results of the entire Monte Carlo procedure consider a period of 10 y and multiple runs (typically 2000). Therefore, the results illustrated in Fig. 3 can vary, depending on the set of parameters selected randomly from their respective distributions.

For this example, rain intensities and the resulting flows in the stream did not allow significant TSS accumulation on the riverbed during the summer months (June to September). The horizontal lines correspond to the TSS accumulated on the riverbed between two rain events. This means that the shear stress is too low to mobilize previously accumulated sediments. Some high values (peaks) deal with accumulation at the beginning of the rain event itself and remobilization with increased flow in the stream.

From these results, it is possible to calculate the duration for which the accumulated TSS mass exceeds a given threshold (such as 25 g m^{-2}, left axis of Fig. 3). The accumulated time of exceedance during 1 y is plotted as a probability (Fig. 4). The horizontal axis represents the percentage of a year that a given criterion is exceeded. For example, a value of 20% represents a criterion violation for 73 d annually. The probability of non-exceedance is presented on the vertical axis. In fact, all the results of the Monte Carlo simulation are ranked and normalized from the smallest to the largest value.

The probability is relatively high that the accumulation of TSS (C_{max} criterion) does not exceed the defined quality

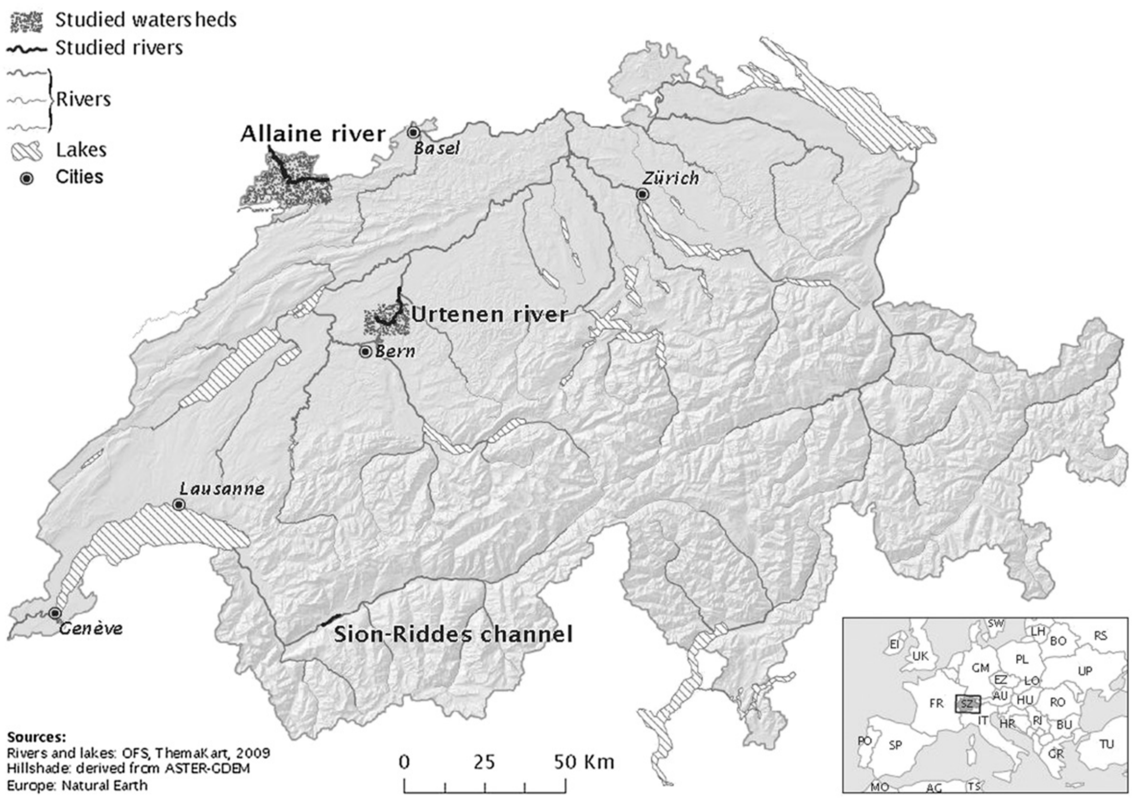

Fig. 2 – Locations of the three investigated case studies in Switzerland. Detailed information is given in Table 3.

Table 3 – Characteristics of the studied streams and catchments. Average values and min-max values used in the Monte Carlo simulations are shown. Rain information was extracted for a 10–y period from the nearest meteorological station from the Swiss federal office of meteorology and climatology network (www.meteossuisse.ch).

Watershed	Allaine stream	Urtenen stream	Sion-Riddes channel
Urban watershed area (ha)	950[a]	126	928
	700–1000	–	–
Inhabitants on the watershed (–)	24,000	18,500[b]	50,000[c]
	15,000–27,000	8600–23,500	50,000–65,000
Upstream watershed (km^2)	130[a]	18	0.07
	127–133	–	–
Base Flow ($Q_{95\%}$) (m^3 s^{-1})	1	0.15	0.19
	0.3–1.5	0.1–0.2	0.18–0.25
Stream width (m)	11.5	1.5	3.7
	7–15	1.2–2	2.6–4
Slope (%)	0.34	0.24	0.06
	0.17–0.51	0.05–0.3	0.05–0.7
Strickler coefficient ($m^{1/3}$ s^{-1})	30	40	40
	20–35	25–45	20–45
Average particle size on the riverbed d_m (cm) [d]	2	0.7	1.7
	1–3	0.5 - 1	1.5–2.5
90% particle size on the riverbed d_{90} (cm) [d]	4.5	1.7	3.8
	3.5–5.5	1.5–2.5	3.5–4.5
Local rain information [mm y^{-1}]	1037	1077	573
	700–1500	739–1318	429–892

a The size of the catchment is not fully defined due to a karstic geological context.
b The number of habitants varies considerably due to industrial activities on the watershed.
c The number of habitants fluctuates due to influxes of tourists.
d In-situ measurements based on Fehr (1987).

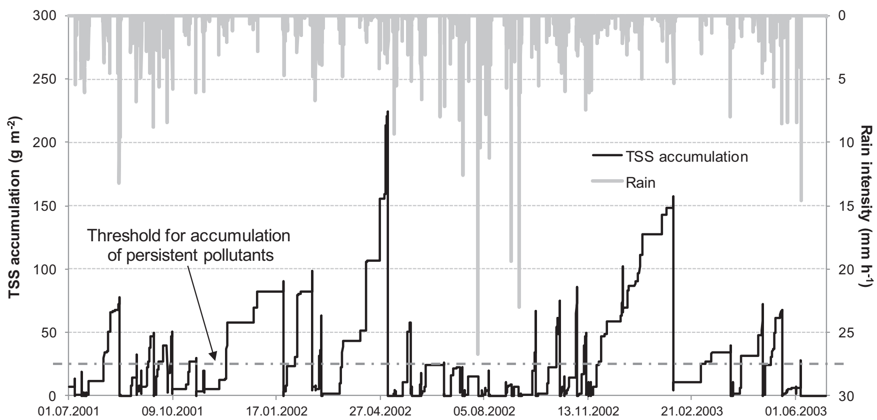

Fig. 3 – Example of calculation of TSS accumulation on the riverbed over one year in the developed software. TSS accumulation on the riverbed (left axis) is expressed in g m^{-2}. The rain intensity (right axis) is expressed in mm h^{-1}. The threshold for accumulation of persistent pollutants (25 g m^{-2}) is illustrated.

criterion for the Allaine (84%) and the Sion (69%) case studies. The probability is lower for the Urtenen (46%). This reflects field observations. Siltation processes were not observed in the Allaine and Sion watersheds. In contrast, the riverbed was covered by a fine deposit on the whole section downstream of the wet-weather discharges for the Urtenen. The general aspects of the curves in Fig. 4, with an initial rapid increase and a relatively large flat zone, indicate that the percentage of time annually (horizontal axis) does not have a significant impact on the results. In fact, changing the reference value of annual time from 20% to 40% or 60% does not change the interpretation of the results. Generally, the results for other Swiss watersheds showed that the siltation criterion was never exceeded (results not presented). Siltation processes were observed near urban areas, but were mainly due to wash-off from construction sites, cement spills or erosion of non-stabilized riverbanks and agricultural fields.

For the accumulation of ecotoxic TSS (E_{max} criterion), the most problematic location identified was again the Urtenen stream, with a probability of only 7% to not exceed the defined criteria (i.e., probability of 93% to exceed the defined goal). For the other sites, Allaine and Sion, the probability was higher (about 45%). These results are also in agreement with the concentrations of organic compounds measured in the sediments (Table 4). The highest contamination was observed in the Urtenen stream, with the trace metals Cd, Pb, Cu and Zn concentrations between TEC and PEC values (MacDonald et al., 2000). At this location, PAH values for Phe, Anth, Fluo, Pyr, Chr and BaPy were the highest measured over the three case studies; concentrations were also between TEC and PEC values. The value for BaAn even reaches the PEC value, indicating a potential impact for organisms. In the reference site for the Urtenen, all sediment concentrations were below the TEC values. This highlights the impact of wet-weather discharges on the riverbed.

For the Allaine case study, the reference site was already contaminated by Cd. A geogenic source of Cd seems to be the reason for this result (Vasquez, 1999). Below the CSO discharge, heavy metal concentrations of Cd, Ni and Cu are above the TEC value. The situation is identical for five PAHs (Pyr, BaAn, ChrBaPy and DiAn). Contamination of the riverbed through stormwater and CSO discharges were confirmed for this site. However, concentrations are lower than for the Urtenen. Observed concentrations never reached PEC values. For the Sion case study, concentrations in sediment were already high upstream of the CSO discharge. This can be attributed to Sion's numerous stormwater discharge pipes upstream of this channel. Copper concentrations were higher than at the other sites, due probably to the presence of large vineyards in the watershed. Downstream of the CSO, discharge concentrations increased, especially for Cu, Zn, Phe, Anth, Fluo, Pyr, BaAn, Chr and BaPy. Again, the effect of the CSO on the sediment compartment is confirmed and well predicted by the model (probability of 46% to not exceed the criterion). Globally, for the E_{max} criterion, the shape of the probability curves indicates relatively robust results, as changing the reference value for the percentage of average annual time does change them significantly.

For the risk assessment of accumulated organic matter linked with TSS on the riverbed (O_{max} criterion), the Urtenen stream was estimated as the most problematic, with a probability of only 30% to not exceed the criterion. This was confirmed by in situ observations during the sampling phase. The sediment profile was brown on the upper part and black just below with a strong smell of sewage. The texture was sticky, while the presence of red worms and leeches confirmed the anoxic conditions. For the Allaine stream, visual and olfactory in situ analysis of the sampled sediment revealed a brown sediment with little organic matter and a low odor level, consistent with aerobic conditions. Biotic organisms *Gammarus* and *Tubifex* were observed, indicating the presence of organic matter but in limited quantities. This observation is in accordance with the results of the model, which calculated a 53% probability of not exceeding the criterion. Nearly the same probability was estimated for the Sion case study (56%). In this case also, in situ investigations were in accordance with the model. The sediment was separated into two regions, with a brown oxic upper layer without odor and a dark-colored anoxic lower layer due to the degradation of organic substances. For the O_{max} criterion, the shape

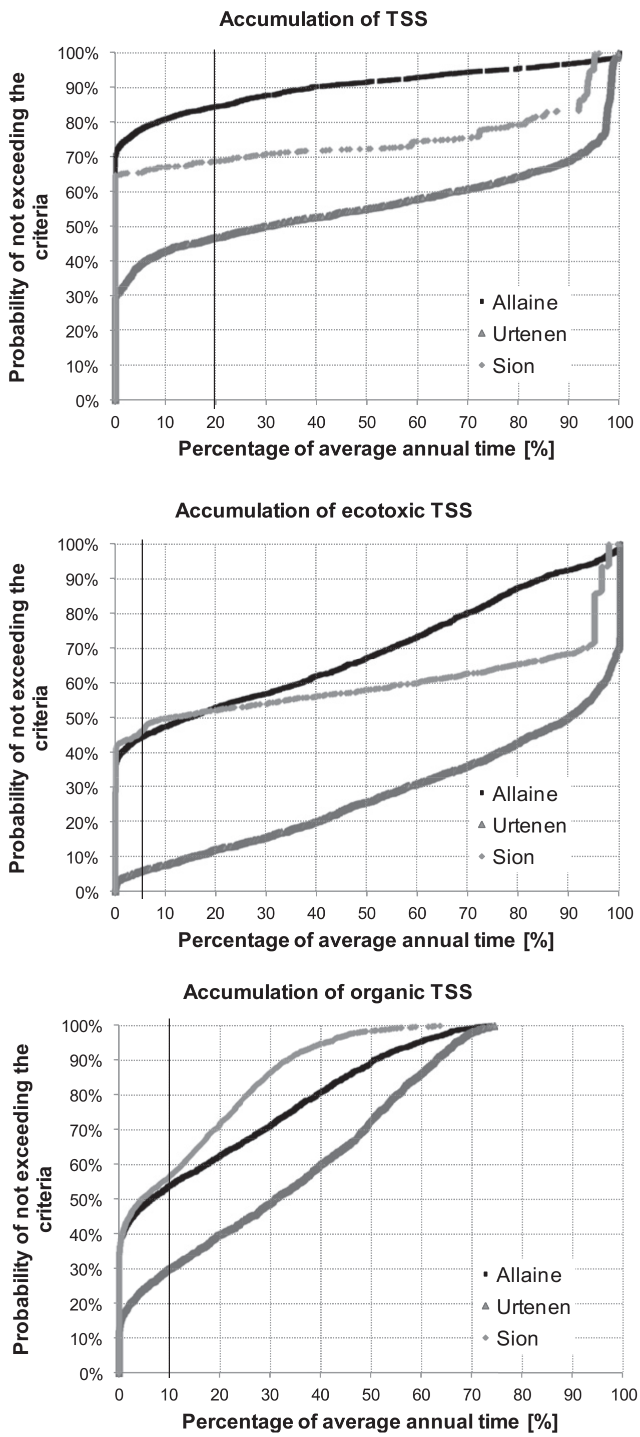

Fig. 4 – Calculation results for the three different criteria (2000 Monte Carlo repetitions). The horizontal axis represents the percentage of the annual time during which the criterion is exceeded. The vertical axis gives the probability of achieving this goal.

of the probability curve is sharp around the critical percentage of annual time (10%). As anoxic conditions are critical during the egg-laying period (typically in early spring for *salmonidae*), a more refined analysis of the results would be necessary for the identification of potential problems. Results of the model, however, are in agreement with site observations.

A sensitivity analysis is also integrated in the approach, in order to identify the most important parameters in the different processes. Not surprisingly, parameters like roughness, slope and particle size of the riverbed are the most sensitive for the Allaine case study. They are directly linked with the dynamics of TSS on the riverbed, i.e., erosion or accumulation processes. To improve the modeling approach, priority should be given to the acquisition of these parameters. The heterogeneity of the ecomorphological stream criteria are accounted for in the probabilistic approach as they are defined in a given range of variation. This allows the model to reflect the reality of in situ conditions.

For the Urtenen case study, the same parameters were identified as important, with the addition of the critical shear stress value (τ_{crit}), which affects evaluation of the E_{max} impact. This parameter is also linked directly with sediment dynamics. Similar results were found for the Sion case study. Overall, the range of values proposed for the different TSS processes gives estimates consistent with real situations.

4. Discussion

The proposed strategy allows an assessment of the risk for receiving waters linked to the accumulation of TSS from urban wet-weather discharges. In the illustrated examples, the model estimates a potential risk for the streambed. To reduce this risk, TSS control measures (for example with CSO or stormwater detention tanks) can be simulated with the model and the beneficial effects of such installations estimated. After validation, this TSS model provides a tool to estimate the necessary investments for protection of receiving waters. This approach also allows for actions to be prioritized based on ecological risk assessment. Such approaches for sediments fit well with the EU Water Framework Directive philosophy (Apitz, 2008; Brils, 2008). Similar approaches for prioritization of contaminated sites are, for example, applied to historical contaminated sediments in Germany (Heise and Förstner, 2006) and in the USA (Suter, 2008).

Different problems were identified during the modeling and sampling steps of our approach. The hydrological model was unable to estimate correctly the measured flow upstream of the CSO discharge for the Allaine case study. Here, the upstream watershed is situated in a karstic region where the hydrological processes do not follow classical behavior. For that case, one recommendation is to use a detailed deterministic model for the simulation of the upstream part of the watershed, and to use its outputs as the input time series for the stochastic simulation (Margot, 2008). The simplified description of the urban watershed (the model considers only one global catchment) was also a difficulty for modeling the three case studies, even if results were in accordance with measured flow data. For the field evaluation step, it was difficult to find a deposit of fine sediment for the Sion case study. As illustrated in Fig. 3, the accumulation of TSS on the riverbed is related directly to the past rain conditions. If sampling occurs after an intense rain event, most of the TSS from urban sources would have already been transported

Table 4 – Concentrations measured in the sediments at the different locations, and TEC/PEC values for comparison. Values upstream (up) and downstream of the wet-weather discharges are presented, except for the Allaine (upstream concentrations were measured near the source of the stream). Values exceeding the TEC values are in bold, values equal or bigger than the PEC in gray.

	Parameter	$Allaine_{up}$	$Allaine_{down}$	$Urtenen_{up}$	$Urtenen_{down}$	$Sion_{up}$	$Sion_{down}$	TEC	PEC
Metals	Cd	**2.7**	**2.4**	0.6	**1.1**	**1.5**	**1.6**	0.99	4.98
[mg kg^{-1} DW]	Co	7.0	8.9	2.5	3.3	5.9	5.3	–	–
	Ni	21.8	**32.2**	15.6	16.0	**32.7**	**31.2**	22.7	48.6
	Cr	29.2	40.6	13.1	27.8	31.3	35.7	43.4	111
	Pb	4.7	26.8	17.9	**50.2**	**43.2**	34.3	35.8	128
	Cu	8.9	**34.0**	14.4	**65.2**	**85.1**	**100.8**	31.6	149
	Zn	67.0	117.3	51.2	**355.5**	**131.3**	**150.0**	121	459
PAHs	Naph	10	10	4	16.1	12.9	8	176	561
[μg kg^{-1} DW]	Ace	LD	3.5	LD	11.4	LD	8	–	–
	Flu	LD	7.6	1.7	27	6.5	17	77	536
	Phe	25	134	34	**581**	92	**351**	204	1170
	Anth	2.4	21	6	**98**	34.0	**95**	57	845
	Fluo	81	386	51	**1673**	194	**873**	423	2230
	Pyr	69	**327**	73	**1345**	189	**760**	195	1520
	BaAn	24	**189**	45	**653**	**124**	**394**	108	653
	Chr	28	**206**	44	**840**	137	**390**	166	1290
	BeP	LD	236	LD	972	162	LD	–	–
	BbFl	LD	194	39	731	113	300	–	–
	BkFl	12	131	27	451	70	207	–	–
	BaPy	21	**261**	59	**762**	138	**368**	150	1450
	DiAn	LD	**36**	8	LD	LD	LD	33	–
	BePe	LD	245	43	811	150	316	–	–
	InPy	24	339	59	893	154	420	–	–
	∑ 16 PAHs	295	2726	493	9864	1577	4508	–	–
	Total PAHs	519	**3155**	649	**11990**	**1855**	**6514**	1610	22800

downstream. A careful analysis of past rainy conditions is therefore necessary before carrying out field studies. Preliminary modeling efforts could guide the definition of optimal sampling conditions.

For TSS inputs into receiving waters, in terms of concentrations and loads, we have proposed a stochastic approach. However, any model able to generate TSS concentrations from urban watersheds can be used. No global consensus for particle transport in streams exists yet and it is possible to modify our approach incorporating different processes mainly linked with armor effects, biostabilization, trapping in the hyporheic interstitials of the riverbed, consolidation of the sediments, etc. (Graf, 1971; Schälchli, 1995; Ciffroy et al., 2000; Krishnappan, 2000; Minshall et al., 2000). These more refined approaches will increase the complexity of the modeling approach and will have as consequences the incorporation of new parameters and site-specific constants. The goal here is not to be able to measure directly in the river itself downstream of the wet-weather discharge the sediment height, but rather to identify, among numerous wet-weather discharges along a river, the most problematic ones linked to TSS. The proposed model works with a limited number of variables (seven for TSS in the receiving water) and reasonable default values are provided for most of them, as demonstrated in the field studies. We use uniform distributions for these parameters in the Monte Carlo calculation, due to a lack of knowledge concerning their values. A sensitivity analysis, also incorporated in our model, can further underpin investigations on the effects of different parameter distributions. Due to its influence on the model results, the TSS settling velocity, W_C, should be chosen with care. In our case, it has been estimated from measurements made in streams using fine organic particles marked by a tracer (Minshall et al., 2000; Thomas et al., 2001) and on laboratory measurements. The average settling velocity suggested corresponds to measurements conducted on the River Seine after a CSO discharge (Even et al., 2004) and is in accordance with settling velocities observed using the French VICAS protocol (Gromaire-Mertz et al., 2008).

The entire procedure was simplified by incorporating all the steps of the risk assessment in the software tool REBEKA II (Fankhauser et al., 2004). The risk-assessment process can be conducted directly on the basis of the model outputs. The use of the model for three case studies showed that predicted problems are effectively identified in the receiving waters.

Deterministic models could be also used to calculate the various endpoints for sediment exposure. For example, a model has been developed for estimating oxygen depletion in the hyporheic zone (Borchardt and Reichert, 2001). A deterministic model for siltation has also been proposed by Schälchli (1995), while Wu (2000) presented a model to assess the effects of sediment deposition on embryo survival. However, it is very demanding to validate such models in terms of data. Moreover, the investments in time for deterministic modeling are often disproportionate in view of the large number of urban wet-weather discharges in streams.

Three ecological criteria, linked with TSS, have been proposed to assess the risk of wet-weather discharges for sediment. Based on current knowledge, they are three of the most important parameters to characterize the state of riverbed sediments. Furthermore, they have the advantage of being linked to a parameter commonly measured in all studies of urban storm drainage, namely TSS. The knowledge of the TSS exposure allows, therefore, assessment of the risk of wet-weather discharges for the riverbed. However, note that this risk is theoretical and based on modeling. The field investigations reported here represent a validation of the proposed approach. To identify the clogging problem or oxygen limitations in sediments, visual investigation of the riverbed was proposed as a screening procedure in Switzerland (Schälchli, 2002). Due to the dynamics of TSS in the receiving waters, these visual inspections have to be repeated several times. Actually, long-term integrated measuring campaigns that take into account urban wet-weather discharges and sediment assessment are very rare.

The assessment endpoints proposed in Table 2 are defined for classical Swiss situations. They can be refined and adapted to each specific situation in the receiving waters. For the siltation assessment endpoint, for example, if the amount of fine sediment is relatively high upstream of urban discharges, the additional contribution from urban discharges that can be tolerated will be reduced. In the same manner, we can consider also sediments with background contamination for the accumulation assessment endpoint, or a constant input of oxygen demand from a wastewater treatment plant for the oxygen endpoint. Regarding TSS accumulation rates on the riverbed, the proposed values are in agreement with other values measured in urban environments in the UK. Lawler et al. (2006) reported fine-grained sediment deposition of 50–100 g m^{-2} for the urbanized Upper River Tames. For the Aire and Clader Rivers (UK), Walling et al. (2003) measured values in the range 100–1450 g m^{-2}.

For simplification, we consider the three assessment criteria independently, but they are not. Riverbed siltation, for instance, will limit the oxygen transfer and thus induce oxygen depletion. Borchardt and Fischer (2000) observed that the longitudinal gradient of oxygen between down and upwelling zones was a function of the siltation process during periods of low discharges in the Lahn River with no scouring of the bed material and the surface/sub-surface biofilms. Moreover, the impacts of oxygen depletion may reinforce toxic effects linked to contaminants, allowing the remobilization of heavy metals. However, as cumulative effects of the different criteria were not studied, we did not consider them together in our assessment procedure.

For the three ecological criteria, pragmatic choices were made based, for example, on the zone where TSS will have most effect. Thus, we consider the top 5 cm of the streambed as relevant for the siltation assessment criterion. We also consider a safety factor of 1000 for the ecotoxicological effects of accumulated pollutants (EU, 2003). Such simplifications do not take into account the complexity of the processes that occur in the riverbed and that can induce toxicity, and thus risk, for the aquatic organisms. In particular, we did not consider the differences that could exist in the bioavailability of the compounds for the different species, nor the aging of compounds that can decrease their toxicity (Reid et al., 2000). Thus, they must be considered as indicative more than mandatory values and could be updated based on new data. As a screening tool, this approach will highlight risk hot spots, but the results have to be supported by further investigations considering chemical analysis, ecotoxicological testing and biological survey (e.g., the TRIAD approach of Chapman, 1990).

5. Conclusion

Sediment represents an important compartment of the receiving waters as a habitat or spawning site for organisms. The approach we propose allows assessment of the risk of wet-weather discharge for sediment based on TSS and three related assessment endpoints crucial for sediment quality. The procedure proposed is implemented in a software program, from which results can be used directly for wet-weather management. This global approach was shown to be suitable to assess the risk of the wet-weather discharge for sediment in three Swiss case studies. However, it must be considered as a screening evaluation rather than providing deterministic results.

Tools for the in situ assessment of specific urban wet-weather discharges are still needed, as the entire biological integrity of the receiving water has to be considered. A future research program must first and foremost include comprehensive, long-term monitoring of the linkages between urban wet-weather discharges, the flow regime in the receiving water and the biotic or physical response of the riverbed ecosystem. Greater interdisciplinary research is therefore needed, combining sedimentologists, hydrologists, chemists, biologists and ecotoxicologists.

Acknowledgments

The authors would like to thank the Swiss Federal Office for the Environment for financial and scientific support (STORM Project). We acknowledge also the Cantonal authorities of Cantons Jura, Bern and Valais for providing information. Many thanks also to Alexandre Hirzel, UNIL, who provided Fig. 2.

REFERENCES

Alabaster, J.S., Lloyd, R., 1980. Water Quality Criteria for Freshwater Fish. Butterworths, London (UK).

Apitz, S., 2008. Is risk-based, sustainable sediment management consistent with European policy? Journal of Soils and Sediments 8 (6), 461–466.

Ariathurai, R., Arulanandan, K., 1978. Erosion rates of cohesive soils. Journal of the Hydraulics Division 104 (2), 279–283.

Ashley, R.M., Bertrand-Krajewski, J.-L., Hvitved-Jacobsen, T., Verbanck, M., 2004. Solids in Sewers. IWA Publishing, London (UK), Scientific and Technical Report no 14.

Becouze-Lareure, C., 2010. Characterization and Estimation of Priority Substances Flows in Urban Wet-weather Discharges on Two Experimental Watersheds. INSA, Lyon, France (In French).

Borchardt, D., Reichert, P., 2001. River water quality model no.1 (RWQM1): case study I. Compartmentalisation approach applied to oxygen balances in River Lahn (Germany). Water Science and Technology 43 (5), 41–49.

Borchardt, D., Sperling, F., 1997. Urban stormwater discharges: ecological effects on receiving waters and consequences for

technical measures. Water Science and Technology 36 (8–9), 173–178.
Borchardt, D., Fischer, J., 2000. Three-dimensional patterns and processes in the River Lahn (Germany): Variability of abiotic and biotic conditions. Verhandlungen Internationale Vereinigung für Theoretische und Angewandte Limnologie 27, 393–397.
Brils, J., 2008. Sediment monitoring and the European water framework directive. Ann Ist Super Sanita 44 (3), 218–223.
Burton, G.A., Pitt, R.E., 2002. Stormwater Effects Handbook. In: A Toolbox for Watershed Managers, Scientists, and Engineers. Lewis Publishers, Boca Raton, Florida, USA.
CCME, 1995. Protocol for the Derivation of Sediment Quality Guidelines for the Protection of Aquatic Life. Environment, Canadian Council of Ministers of the Environment, Hull, QC, Canada, p. 35, Environment Canada.
Chapman, P.M., 1990. The sediment quality triad approach to determining pollution-induced degradation. Science of the Total Environment 97-98, 815–825.
Chapman, P.M., Romberg, G.P., Vigers, G.A., 1982. Design of monitoring studies for priority pollutants. Water Pollution Control Federation 54 (3), 292–297.
Chebbo, G., Gromaire-Mertz, M.-C., Lucas, E., 2003. VICAS Protocol: Measure of TSS Settling Velocities in Urban Water Discharges. Association générale des hygiénistes et techniciens municipaux, Paris, France (In French).
Chebbo, G., 1992. Solids in Urban Wet-weather Discharges: Characterisation and Potential of Treatment. École nationale des ponts et chaussées, Paris, France (In French).
Ciffroy, P., Moulin, C., Gailhard, J., 2000. A model simulating the transport of dissolved and particulate copper in the Seine River. Ecological Modelling 127 (2–3), 99–117.
Crisp, D.T., Carling, P.A., 1989. Observations on siting, dimensions and structure of salmonid redds. Journal of Fish Biology 34 (1), 119–134.
Curdy, R., 2010. Method Proposal for the Evaluation of Sediment Toxicity: Application on the Urtenen Stream. EPFL, Lausanne, Switzerland (In French).
DFO, 2000. Effects of Sediment on Fish and Their Habitat. Environment Canada. Fisheries and Oceans, West Vancouver, British Columbia, Canada.
Edberg, N., Hofsten, B.V., 1973. Oxygen uptake of bottom sediments studied in situ and in the laboratory. Water Research 7 (9), 1285–1294.
EIFAC, 1969. Water quality criteria for European freshwater fish – extreme pH values and inland fisheries. Water Research 3 (8), 593–611.
EU, 2003. Technical Guidance Document on Risk Assessment. European Chemicals Bureau. EUR 20418 EN/2.
Even, S., Poulin, M., Mouchel, J.-M., Seidl, M., Servais, P., 2004. Modelling oxygen deficits in the Seine River downstream of combined sewer overflows. Ecological Modelling 173 (2–3), 177–196.
Fankhauser, R., Kreikenbaum, S., Krejci, V., Rossi, L., Rauch, W., 2004. Rebeka II – a stochastic software tool for assessing impacts of urban drainage on receiving waters, 6th Int. Conf. on Urban Drainage Modelling (UDM), 175–184, Dresden, Germany.
Faulkner, H., Edmonds-Brown, V., Green, A., 2000. Problems of quality designation in diffusely polluted urban streams - the case of Pymme's Brook, north London. Environmental Pollution 109 (1), 91–107.
Fehr R., 1987. A Method for Sampling Very Coarse Sediments in Order to Reduce Scale Effects in Movable Bed Models. Proceedings of IAHR Symposium on Scale Effects in Modelling Sediment Transport Phenomena, Toronto, Canada, 383397.
Graf, W.H., 1971. Hydraulics of Sediment Transport. McGraw-Hill Book Company, Highlands Ranch, Colorado, USA.
Gromaire-Mertz, M.-C., 1998. Pollution of Urban Stormwater in Combined Sewer Systems: Characteristics and Origin. École nationale des ponts et chaussées (ENPC), Paris, France (In French).
Gromaire-Mertz, M.-C., Kafi-Benyahia, M., Gasperi, J., Saad, M., Moilleron, R., Chebbo, G., 2008. Settling velocity of particulate pollutants from combined sewer wet weather discharges. Water Science and Technology 58 (12), 2453–2465.
Gujer, W., 1999. Urban Water Management. Springer, Berlin, Germany (In German).
Heath, J., Vicory, A., Tennant, P., Turner, C., 2002. A Study of Impacts and Control of Wet Weather Sources of Pollution on Large Rivers. IWA, Portland, Oregon, USA.
Heise, S., Förstner, U., 2006. Risks from historical contaminated sediments in the Rhine Basin. In: Kronvang, B., Faganeli, J., Ogrinc, N. (Eds.), The Interactions Between Sediments and Water. Springer, Netherlands, pp. 261–272.
Henley, W.F., Patterson, M.A., Neves, R.J., Lemly, A.D., 2000. Effects of sedimentation and turbidity on lotic food webs: a concise review for natural resource managers. Reviews in Fisheries Science 8 (2), 125–139.
Ibisch, R.B., Borchardt, D., 2003. Effects of periphyton biomass and suspended solids on river bed permeability and hyporheic oxygen balances. Verhandlungen Internationale Vereinigung für Theoretische und Angewandte Limnologie 28 (4), 1875–1879.
Institut Forel, 1996. Clean-up of Vidy Bay: Sediment Quality, Impacts of the Vidy WWTP. Université de Genève, Institut Forel, Geneva, Switzerland (In French).
Kabelkova, I., Stastna, G., Stransky, D., Malec, L., 2005. Changes of Stream Ecology along the Urbanization Gradient, 10th International Conference on Urban Drainage, Copenhagen, Denmark.
Kodama, K., Horiguchi, T., 2011. Effects of hypoxia on benthic organisms in Tokyo Bay, Japan: a review. Marine Pollution Bulletin 63 (5–12), 215–220.
Krishnappan B.G., 2000. Modelling cohesive sediment transport in rivers. The role of erosion and sediment transport in nutrient and contaminant transfer, Proceedings of a symposium held at Waterloo, Canada, July 2000. IAHS Publication 263, 269–276.
Krishnappan, B.G., Marsalek, J., 2002. Modelling of flocculation and transport of cohesive sediment from an on-stream stormwater detention pond. Urban Water 4 (1), 3–11.
Krone, R.B. 1962. Flume studies of the transport of sediment in estuarial shoaling processes. Final Report, Hydr. Eng. San. Eng. Res. Lab., University of California, Berkeley, California, USA.
Lawler, D.M., Petts, G.E., Foster, I.D.L., Harper, S., 2006. Turbidity dynamics during spring storm events in an urban headwater river system: the Upper Tame, West Midlands, UK. Science of the Total Environment 360 (1–3), 109–126.
MacDonald, D.D., Ingersoll, C.G., Berger, T.A., 2000. Development and evaluation of consensus-based sediment quality guidelines for freshwater ecosystems. Archives of Environmental Contamination and Toxicology 39 (1), 20–31.
Margot, J., 2008. (In French) Impacts of Stormwater Discharges on Rives: Implementation of the STORM Guidelines and Validation by Ecotoxicological and Chemical Analyses. EPFL, Lausanne, Switzerland.
Marsalek, J., Anderson, B.C., Watt, W.E., 2002. Suspended Particulate in Urban Stormwater Ponds: Physical, Chemical and Toxicological Characteristics (Portland, Oregon, USA).
Marsalek, J., Rochfort, Q., Mayer, T., Servos, M., Dutka, B., Brownlee, B., 1999. Toxicity testing for controlling urban wet-weather pollution: advantages and limitations. Urban Water 1 (1), 91–103.
Minshall, G.W., Thomas, A.S., Newbold, J.D., Monaghan, M.T., Cushing, C.E., 2000. Physical factors influencing fine organic particle transport and deposition in streams. J. N. Am. Benthol. Soc. 19 (1), 1–16.
Ottaway, E.M., Carling, P.A., Clarke, A., Reader, N.A., 1981. Observations on the structure of brown trout, Salmo trutta Linnaeus, redds. Journal of Fish Biology 19 (5), 593–607.

Paul, M.J., Meyer, J.L., 2008. Streams in the urban landscape. In: Marzluff, J.M., Shulenberger, E., Endlicher, W., Alberti, M., Bradley, G., Ryan, C., Simon, U., ZumBrunnen, C. (Eds.). Springer, US, pp. 207–231.

Power, E.A., Chapman, P.M., 1992. Assessing Sediment Quality. Sediment Toxicity Assessment. Lewis Publishers, Boca Raton, Florida, USA.

Rauch, W., Krejci, V., Gujer, W., 2002. REBEKA – a software tool for planning urban drainage on the basis of predicted impacts on receiving waters. Urban Water 4 (4), 355–361.

Reichert, P., 2001. UNCSIM – A Program Package for Uncertainty Analysis and Bayesian Inference: User Manual. EAWAG, Dübendorf, Switzerland.

Reid, B.J., Jones, K.C., Semple, K.T., 2000. Bioavailability of persistent organic pollutants in soils and sediments-a perspective on mechanisms, consequences and assessment. Environmental Pollution 108 (1), 103–112.

Rochefort, Q., Grapentine, L., Marsalek, J., Brownlee, B., Reynoldson, T., Thompson, S., Milani, D., Logan, C., 2000. Using benthic assessment techniques to determine combined sewer overflow and stormwater impacts in the aquatic ecosystem. Water Qual. Res. J. Canada 35 (3), 365–397.

Rossi, L., Krejci, V., Rauch, W., Kreikenbaum, S., Fankhauser, R., Gujer, W., 2005. Stochastic modeling of total suspended solids (TSS) in urban areas during rain events. Water Research 39 (17), 4188–4196.

Rossi, L., 1998. Urban Stormwater Quality. Ecole polytechnique fédérale de Lausanne (EPFL), Lausanne, Switzerland (In French).

Schälchli, U., 1993. The Siltation of Riverbeds: Processes and Design Principles, P. 273. Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie, Eidgenössische Technische Hochschule Zürich, Zürich, Switzerland (In German).

Schälchli, U., 1995. Basic equations for siltation of riverbeds. Journal of Hydroelectric Engineering 121 (3), 274–287.

Schälchli, U., 2002. Internal Clogging: Identification and Assessment Methods, P. 27. Eawag, Dübendorf, Switzerland (In German).

Seidl, M., Servais, P., Mouchel, J.M., 1998. Organic matter transport and degradation in the river Seine (France) after a combined sewer overflow. Water Research 32 (12), 3569–3580.

Suter, G.W., 2008. Ecological risk assessment in the United States environmental protection agency: a historical overview. Integrated Environmental Assessment and Management 4 (3), 285–289.

Taylor, K., Owens, P., 2009. Sediments in urban river basins: a review of sediment–contaminant dynamics in an environmental system conditioned by human activities. Journal of Soils and Sediments 9 (4), 281–303.

Thomas, S.A., Newbold, J.D., Monaghan, M.T., Minshall, G.W., Georgian, T., Cushing, C.E., 2001. The influence of particle size on seston deposition in streams. Limnology & Oceanography 46 (6), 1415–1424.

Torres, A., Bertand-Krajewski, J.L., 2008. Evaluation of uncertainties in settling velocities of particles in urban stormwater runoff. Water Science and Technology 57 (9), 1389–1396.

USEPA, 1998. Guidelines for Ecological Risk Assessment, P. 159. U.S. Environmental Protection Agency, Washington D.C., USA.

Van Metre, P.C., Mahler, B.J., 2003. The contribution of particles washed from rooftops to contaminant loading to urban streams. Chemosphere 52 (10), 1727–1741.

Vasquez, N.B., 1999. Cadmium Speciation and Phyto-availability in Soils of the Swiss Jura: Hypothesis about Its Dynamic. Ecole polytechnique fédérale de Lausanne, Lausanne, Switzerland.

Vericat, D., Batalla, R.J., Garcia, C., 2006. Breakup and reestablishment of the armour layer in a large gravel-bed river below dams: the lower Ebro. Geomorphology 76 (1–2), 122–136.

Vink, J.P.M., 2002. Measurement of heavy metal speciation over redox gradients in natural water–sediment interfaces and implications for uptake by benthic organisms. Environmental Science & Technology 36 (23), 5130–5138.

VSA, 2007. (In French, German and Italian). Urban Wet-weather Discharges in Receiving Waters (STORM). In: Directive for the Planning of Conceptual Protection Measures. Swiss Water Association (VSA), Zürich, Switzerland.

Walling, D.E., Owens, P.N., Carter, J., Leeks, G.J.L., Lewis, S., Meharg, A.A., Wright, J., 2003. Storage of sediment-associated nutrients and contaminants in river channel and floodplain systems. Applied Geochemistry 18 (2), 195–220.

Waters, T.F., 1995. Sediment in Streams: Source, Biological Effects, and Control. American Fisheries Society, Bethesda, Maryland, USA.

Watts, C.D., Naden, P.S., Cooper, D.M., Gannon, B., 2003. Application of a regional procedure to assess the risk to fish from high sediment concentrations. Science of the Total Environment 314 (16), 551–565.

Wildi, W., Dominik, J., Loizeau, J.-L., Thomas, R.L., Favarger, P.-Y., Haller, L., Perroud, A., Peytremann, C., 2004. River, reservoir and lake sediment contamination by heavy metals downstream from urban areas of Switzerland. Lakes & Reservoirs: Research & Management 9 (1), 75–87.

Wu, F.C., 2000. Modeling embryo survival affected by sediment deposition into salmonid spawning gravels: Application to flushing flow prescriptions. Water Resources Research 36 (6), 1595–1603.