04 - NATURAL FLOOD RISK MANAGEMENT IN URBAN RIVERS

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Abstract

A study of floodplain sedimentation on a recently restored floodplain is presented. This study uses a two-dimensional hydro-morphodynamic model for the prediction of flow and suspended sediment dynamics in the downstream section of Johnson Creek, the East Lents reach, where the bank of the river has been reconfigured to reconnect to a restored floodplain on a 0.28 km^2 (28-ha) site. The event based simulation scenarios (10, 50, 100, and 500 year) are considered in this study. Simulation results showed that the restored floodplain attenuates the upstream flood peak by up to 25% at the downstream. Results also indicated that ~ 20-30% of sediment from the upstream flow is deposited on the East Lents floodplain, this sediment trapping process at the East Lents flood basin considerably reduces the overall sediment loading into the main Willamette River.

Keywords: Floodplain, Green infrastructure, Grey infrastructure, Urbanisation, Sediment dynamics

1. INTRODUCTION

In recent years the impact of changes in land use and rainfall patterns on urban flood risk have been observed in many countries. This threat is likely to escalate in the light of growing population and socio economic development. A number of research studies have raised this issue and it warrants more detailed holistic approaches for urban flood risk management. Traditionally, urban storm water is managed with a single-objective and local thinking (Christine *et al*., 2005), predominately through grey infrastructure such as embankments, sewer collection system and, flood walls which keep floodwater away from vulnerable areas while shift flood problems downstream (Kendrick, 1988). Grey infrastructure generally fails to accommodate other important aspects of integrated urban water management such as water quality, amenity and biodiversity. Although, grey infrastructure as a flood protection measure is beneficial during flood conditions; it is much less useful in non-flood conditions. In addition, grey infrastructure is restricted by high capital, maintenance and upgrade costs, and cannot be raised indefinitely in response to increasing risk (Evans *et al*., 2008). When grey infrastructure fails, it causes more severe damage to a city than gradual inundation (Heine and Pinter, 2012).

Nowadays, green infrastructure such as floodplains, ponds, swales, etc is increasingly considered for urban flood risk management as a more sustainable option than traditional hard engineering infrastructures to recreate naturally oriented hydro-morphodynamic processes while adding ecological and amenity value to a river corridor (Palmer et al., 2015). It is essential to have an optimum blend of green and grey infrastructures to face current pressing urban flooding challenges. Natural Flood Management (NFM) using green infrastructure enables sewer and stormwater pipe infrastructure to work more efficiently by reducing their operational load and the need for more expensive pipe solutions. In order to promote sustainable urban drainage system, the European Union Water Framework Directive (EC/2000/60) puts emphasis on sustainable urban drainage in the design stage as a precondition for new development across the EU member states. In addition to flood resilience, NFM provides some treatments of diffuse pollution, urban cooling and biodiversity in the urban environment. However there is relatively little academic work exploring the hydraulic performance of the environmentally oriented NFM strategies with regards to its flood alleviation and sediment trapping characteristics. In contrast, there are adequate guidelines on hard engineering measures. They are generally regarded as mathematically more robust and predictable. It is important to develop an evidence based research methods and tools to realistically evaluate NFM performance in the urban rivers. This will promote implementation of the NFM approaches and integrate them with grey infrastructures to face current and future urban flood management challenges.

The aim of this research is to investigate the effects of floodplain restoration on the flood resilience and sediment dynamics of Johnson Creek, Portland, USA., a highly urbanised stream known for frequent flooding and which contains sections that do not meet water quality standards under the U.S. Federal Clean Water Act. The study area is focused on the downstream section of Johnson Creek, the East Lents reach, where the bank of the creek has been reconfigured to reconnect the river to a restored floodplain on a $0.28km^2$ (28 ha) site to provide more space for the river to flow and be stored. This restored floodplain can have considerable influence on catchment sediment dynamics in two ways. Firstly, nutrients and contaminants attached to sediments can accumulate in the flood basin over a period of time. This can lead to a serious problem both in terms of enhanced levels of contamination in the flood basin and the potential for future remobilisation back into the creek. Secondly, overbank floodplain sedimentation could result in a reduction of the nutrient or contaminant flux at the catchment outlet which influences sediment flux measurement at the outlet. This study investigates whether sediments from the watershed accumulate in the restored floodplain over a period of time or flush out to the main Willamette River. A layer-based morphodynamic model is used in this study to model suspended load sediment dynamics between the main channel and the floodplain.

2. DATA AND METHODS

2.1 Study region

Johnson creek is a 42km (26-mile) long tributary of the Willamette River in the east of Portland metropolitan area of the US state of Oregon as shown in Figure 1. Its watershed consists of $140km^2$ (54 square miles) with a mixture of land uses, forest and agriculture dominating the upper watershed and urban areas in the lower watershed. Over 50% of the watershed is urbanized development consisting primarily of buildings and structures, stormwater and sanitary systems, roadways, bridges, pipes, outfalls, and culvers. The creek and its tributaries run through Gresham, Damascus, Portland, and Milwaukie before emptying into the Willamette River. The shape of the watershed (i.e., long relatively short tributaries) and impervious urban areas of the watershed cause a quick response to storms and rapid fluctuations in the flow (Clark, 1999). Johnson creek has experienced a long history of flooding, water quality, and ecological problems attributable to rural and urban development of the watershed.

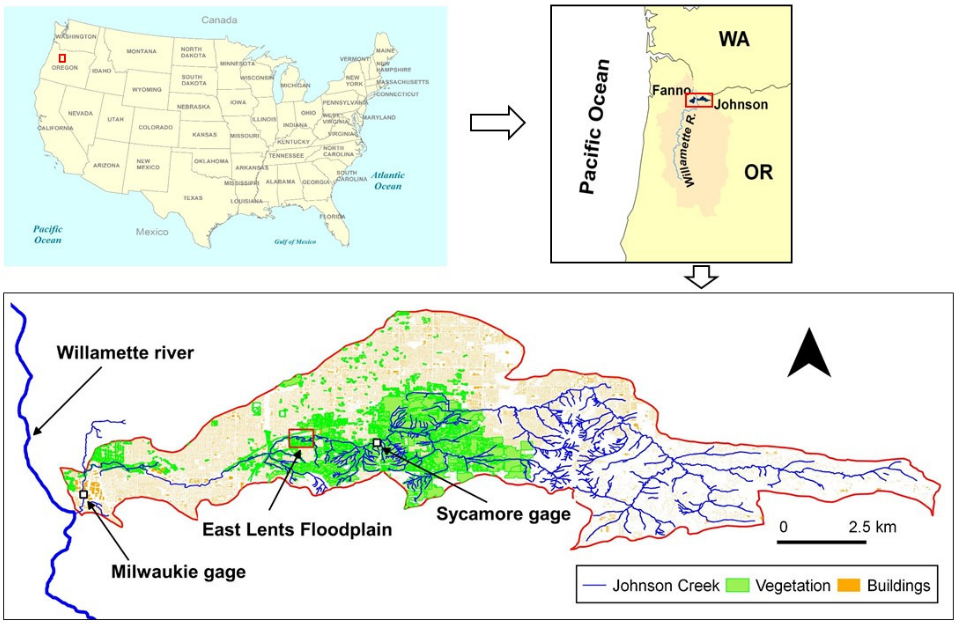


Figure 1: *Johnson Creek watershed*

Precipitation patterns in the Johnson Creek watershed are heavily influenced by Pacific storm systems which contribute to high flow events during the late autumn and winter. Due to the relatively small drainage area, flood peaks can occur within hours of significant rainfall, with storm runoff hydrographs generally lasting from about one to two days. Over the past 80 years there were large scale attempts by the City of Portland's Bureau of Environmental Services (BES) using grey infrastructure to improve flood resilience and water quality of the Johnson creek watershed. Nevertheless, they were not as effective as expected, as flooding water quality and other environmental issues continue to be significant problems in the watershed. These experiences reflect that working against a creek's natural tendency is often more costly and ineffective for a long term solution.

Figure 2*: East Lents Floodplain*

In 2001 BES developed a detailed Johnson Creek Restoration Plan (JCRP) to improve the watershed situation for both people and the natural environment. This plan gives more emphasis on working with creek natural dynamics. In recent years BES is carrying out a number of river restoration projects at the locations shown in Figure 1 along the creek which include floodplain reconnection, riparian restoration, wetland restoration, etc.

To improve conditions for both resident and anadromous fish species at the downstream of the Johnson Creek, East Lents reach, the bank of the creek has been reconfigured to reconnect the river to a restored floodplain on a 0.28km^2 site as shown in Figure 2. Since 1990, BES has acquired all of the property necessary for this floodplain restoration project through the Willing Seller Land Acquisition program. This program helps move people and property out of areas that frequently flood. The East Lents floodplain provides more space for the river to flow and be stored and in turn reduces the costs and damage incurred during flood events. This restoration also helps to improve fish and wildlife habitat by increasing stream complexity, and creates passive recreational activities for city residents. The Johnson creek's sediment dynamics is primarily characterised by washload transport, the major proportion of the sediment supplied to the reach is fine material (silt/clays and find sands) that mostly remains in suspension and does not interact with channel morphology. Relatively low stream power is needed to transport the fine sediment fraction; thus sediment transport through the reach will most likely be determined by the upstream sediment supply and local erosion process in the reach in the form of bank failures.

2.2 Flow and sediment data

The annual maximum flow data sets of the Johnson Creek at Sycamore (USGS – 14211500) gage that is located about 4km upstream of the East Lents floodplain as shown in Figure 1 is incorporated in this study. The drainage area at the gage is 70km^2 and represents a majority of the contributing area to the East Lents floodplain. The U.S. Army Corps of Engineers (USACE) developed the flood frequency estimates using a log-Pearson Type III probability distribution at Sycamore gage (USACE, 1999, FEMA, 2004) that are is used in this study. In the first part of the study the 10 year, 50 year, 100 year, and 500 year flood hydrographs were used in the event based sediment simulations as shown in Figure 3.

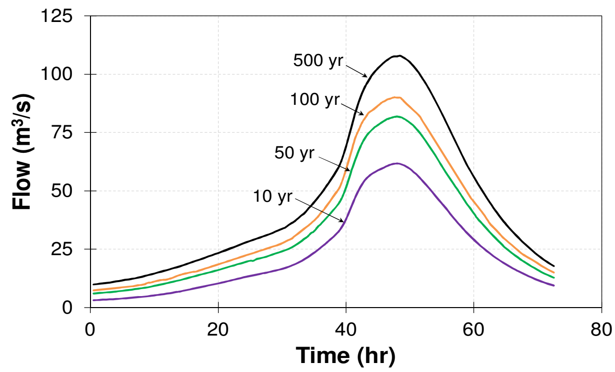


Figure 3: *Derived flood events for the Sycamore gage*

The U.S. Geological Survey (USGS) flow and turbidity measurements at the Milwaukie gauging station from Dec 2005 to Jan 2009 are used in this study. These samples were collected primarily during large storm events, when suspended sediment concentrations (*SSC*) were highest. This data set is used to establish the relationship between turbidity and discharge; where; *Q* is stream flow, in cubic feet per second; T, turbidity in Formazin Nephelometric Units (FNU).

$$\log_{10} T = 0.455 \log_{10} Q + 0.947 \quad [1]$$

As part of the USGS investigation on suspended-sediment characteristics of the Johnson Creek basin, Stonewall & Bragg (2012) established the following relationship amongst SSC, T and Q, at the Milwaukie gauging station.

$$\log_{10} \mathrm{SSC} = 1.024 \log_{10} \mathrm{T} + 0.143 \log_{10} \mathrm{Q} - 0.419 \quad [2]$$

The stream slope varies considerably over its length, from 7 m/km in the upper basin, to 3.4 m/km in the mid-basin, and 15.2 m/km in the lowest 10 km reach. The study region is located in the mid basin as shown in Figure 1. The distribution of stream bottom-material particle sizes correlates with the channel slope and adjacent land use. As part of this study a sample was taken at the upstream of the study region and particle size analysis was undertaken. The following particle sizes (D10=15.11 µm (fine silt), D50=59.98 µm (silt), D90=283.82 µm (fine sand)) is equally distributed as an input in the upstream boundary.

2.3 Model setup

A layer-based hydro-morphodynamic model developed by Guan et al., (2014, 2015) is used to model suspended sediment dynamics between the main channel and the floodplain. The model has three modules: a hydrodynamic module governed by the two-dimensional shallow water equations, a sediment transport module, and a morphological evolution module for updating the bed elevation due to erosion and deposition. Because sediment transport in the Johnson Creek is predominately characterised by wash load transport the suspended sediment module is considered in this study. This study primarily focuses on the amount of suspended sediment trapped in the floodplain instead of the internal bed modifications in the East Lents flood basin. As shown in Figure 2, the East Lents flood basin is densely covered by long grass, therefore it is assumed that the original floodplain is immobile in this situation.

2.3.1 Hydrodynamic model

The hydrodynamic model is based on the two-dimensional shallow water equations with the exchange of sediment transport and water. Following Guan et al. (2014), the governing equations can be expressed in details by:

$$\frac{\partial \eta}{\partial t}+\frac{\partial hu}{\partial x}+\frac{\partial hv}{\partial y}=0 \quad [3]$$

$$\frac{\partial hu}{\partial t}+\frac{\partial}{\partial x}\left(hu^2+\frac{1}{2}gh^2\right)+\frac{\partial huv}{\partial y}=gh\left(S_{ox}-S_{fx}\right)+hv_t\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)+\frac{(\rho_0-\rho)u}{\rho}\frac{\partial z_b}{\partial t}-\frac{\Delta\rho g h^2}{2\rho}\frac{\partial C}{\partial x} \quad [4]$$

$$\frac{\partial hv}{\partial t}+\frac{\partial huv}{\partial x}+\frac{\partial}{\partial y}\left(hv^2+\frac{1}{2}gh^2\right)=gh\left(S_{oy}-S_{fy}\right)+hv_t\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)+\frac{(\rho_0-\rho)v}{\rho}\frac{\partial z_b}{\partial t}-\frac{\Delta\rho g h^2}{2\rho}\frac{\partial C}{\partial y} \quad [5]$$

where t, time, in second; g, gravitational acceleration in m/s^2; η, water surface in m; z_b, bed level in m; $h = \eta - z_b$ = flow depth in m; u, v, depth-averaged flow velocities in x and y direction in m/s; v_t = turbulent viscosity coefficient; C = total volumetric sediment concentration $C=\sum_{i=1}^{N} C_i$, where C_i = volumetric concentration of the i^{th} class by suspended load; $\Delta\rho = \rho s-\rho w$, ρs, ρw, density of sediment and water flow respectively (m^{3}s^{-1}); ρ, density of sediment and flow mixture in m^{3}s^{-1}; $S_{ox}=-\partial z_b/\partial x$, $S_{oy}=-\partial z_b/\partial y$, bed slopes in the x and y direction respectively; S_{fx}, S_{fy} are frictional slopes in the x and y components which are calculated based on Manning's roughness coefficient n.

2.3.2 Suspended sediment load model

The suspended load transport is governed by the advection-diffusion equation. For non-uniform graded sediment mixtures, it is necessary to divide the graded sediments into fractions due to the difference in behaviour of different sized grains and the resulting differences in parameterisations. For the suspended transport of each fraction, the governing equation is described by

$$\frac{\partial hC_i}{\partial t}+\frac{\partial huC_i}{\partial x}+\frac{\partial hvC_i}{\partial y}=\frac{\partial}{\partial x}\left(\varepsilon_x h\frac{\partial C_i}{\partial x}\right)+\frac{\partial}{\partial y}\left(\varepsilon_y h\frac{\partial C_i}{\partial y}\right)+\left(S_{E,i}-S_{D,i}\right) \quad [6]$$

where ε_x, ε_y, diffusion coefficients of sediment in the x and y directions, respectively; $S_{E,i}$, entrainment flux of sediment for the i^{th} fraction; $S_{D,i}$ deposition flux of sediment of the i^{th} fraction. As there is no universal theoretical expression for the vital entrainment flux and deposition flux of sediments, both variables are calculated by the following widely-used function.

$$S_{E,i} = F_i \omega_{f,i} C_{ae,i}; \; S_{D,i} = F_i \omega_{f,i} C_{a,i} \qquad [7]$$

where F_i, percentage of the i^{th} grain fraction; $\omega_{f,i}$, effective settling velocity for the i^{th} grain fraction; $C_{a,i} = \delta C_i$ is the near-bed concentration for the i^{th} grain fraction at the reference level a; the definition of the coefficient δ is: $\delta = \min\{2.0, (1.p)/C\}$; $C_{ae,i}$ is the near bed equilibrium concentration at the reference level that is calculated by using the van Rijin's formula (van Rijin, 1984; Guan *et al*., 2015).

2.3.3 Morphological evolution model

Morphological evolution is determined by the difference between sediment entrainment and deposition that is calculated per grid cell at each time step. The equation used to calculate morphological change is written by

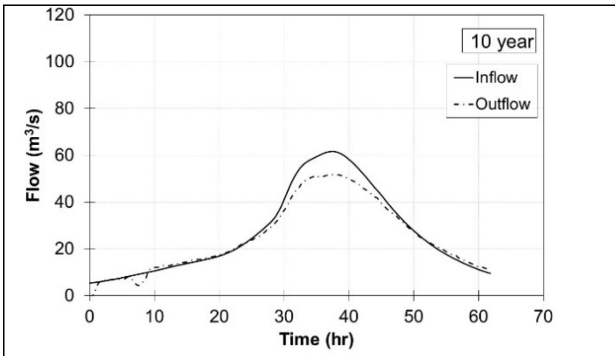
$$\frac{\partial z_b}{\partial t} = \sum_{i=1}^{N} \left(\frac{\partial z_b}{\partial t}\right)_i = \frac{1}{1-p} \sum_{i=1}^{N} (S_{D,i} - S_{E,i}) \qquad [8]$$

where N is the number of grain size fractions, here N = 3.

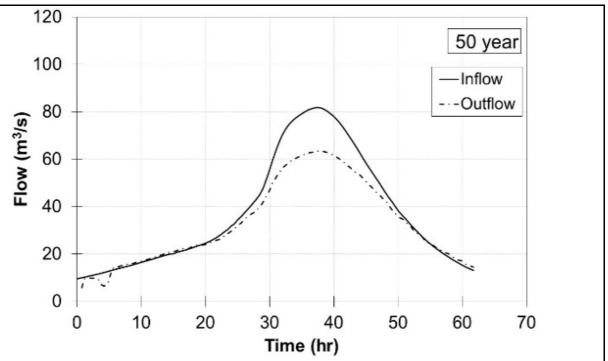
3. Results and Discussions

3.1 Hydrodynamic model simulations

Figure 4 displays the inflow and outflow hydrographs of the 10, 50, 100 and 500 year flood events.



(a)



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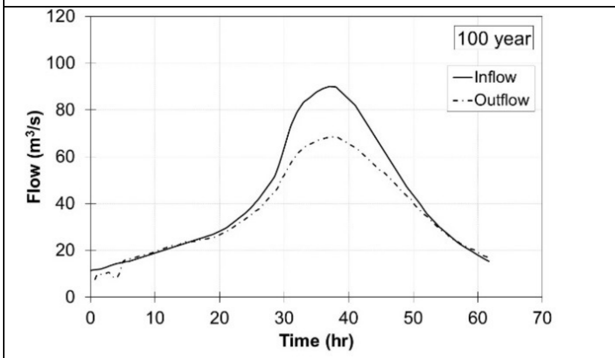

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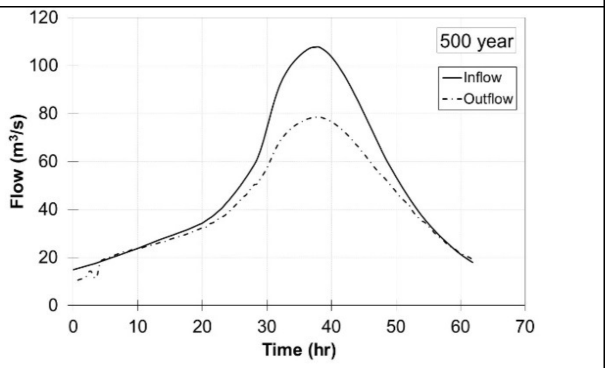

(d)

Figure 4: *Inflow and attenuated outflow hydrographs of the 10year, 50year, 100year and 500year flood events*

Figure 4 indicates that the off-channel storage of flood waters in the East Lents flood basin has a significant attenuation effect on upstream hydrographs. Simulation results show that the basin provides flood storage of (4.4×10^5) m^3 and (1.9×10^6) m^3 for 10 and 500 year flood events, respectively. The difference in the peak flow of the upstream and downstream hydrographs is expressed in terms of % relative attenuation:

$$\%\ \text{Relative attenuation} = \frac{Q_{P1} - Q_{P2}}{Q_{P1}} \times 100 \qquad [9]$$

where Q_{P1} and Q_{P2} are the peaks of the inflow and outflow hydrographs in Figure 4. This offline storage provides reduction in flood peak of 16% and 27% for 10 year and 500 year flood events, respectively. Further, the peak flow of 500 year flood hydrograph was reduced to approximately 80 m^3s^{-1}, which is equivalent to peak flow of 50 year flood. This demonstrates the significant benefit of the floodplain storage on flood peak attenuation.

3.2 Morphodynamic model simulations

The spatial variation of simulated sediment deposition for different flood events is shown in Figure 5.

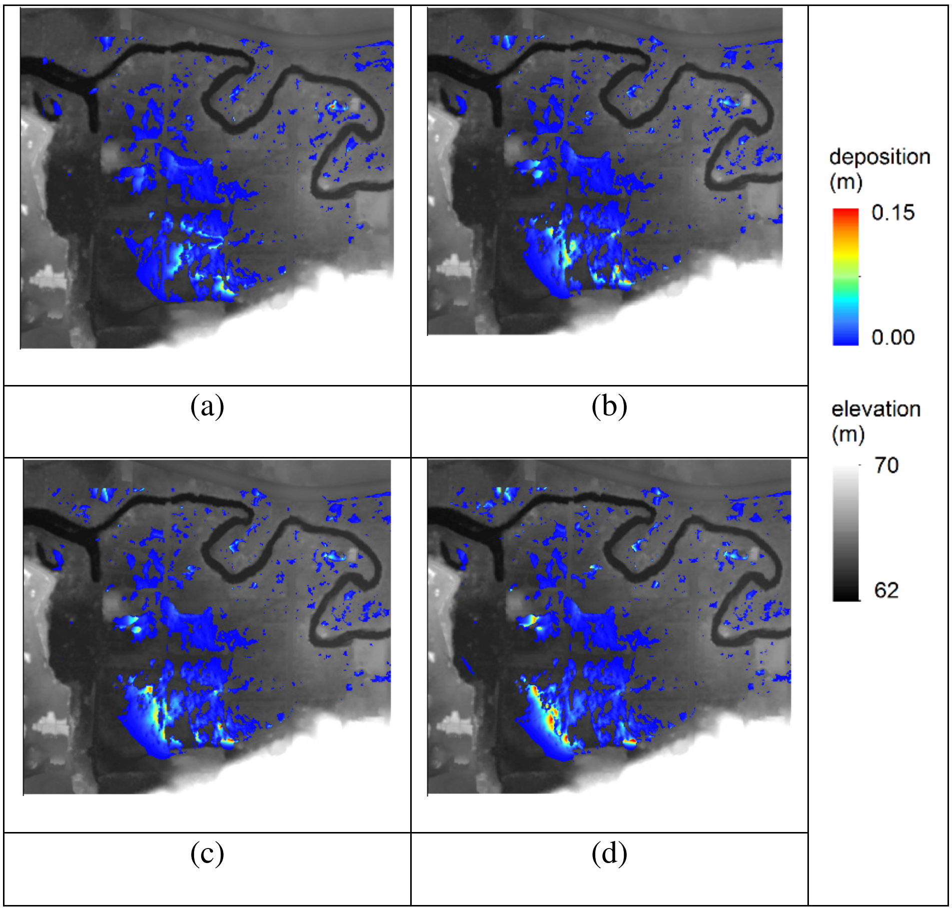

Figure 5: *Sediment depositions for (a) 10, (b) 50, (c) 100 and (d) 500 year flood events*

As expected, scale of sediment deposition in the floodplain increases with flood magnitude. The larger events bring higher overbank flow and sediments into the flood basin. Figure 5 also shows sediment deposition moves towards the lower elevation of the floodplain in the downstream direction with flood magnitude as it has low energy environment. Table 1 compares cumulative amount of sediment deposited into the basin with the total suspended sediment load (SSL) input into the upstream.

***Table 1** Sediment mass balance for different flood events*

	10 Year	50 Year	100 Year	500 Year
Input (SSL m³)	630.74	1040.32	1241.35	1687.62
Deposited in the floodplain (SSL m³)	203.24	300.67	379.62	490.51
% SSL deposit	29.06	30.58	28.90	32.22

As shown in the Table 1, circa. 30% of the suspended sediment that comes from the upstream is deposited in the East Lents flood basin over the four modelled flood events. The amount of sediment deposition increases with flood magnitude but the percentage of the sediment trapped in the floodplain remains constant when compared with total suspended sediment input. Figure 6 (a) shows the temporal variation of input suspended sediment concentration (SSC) at the upstream and the cumulative deposition volume in the floodplain during the flooding. As SSC is derived from the discharge (Q) through regression relationships, Figure 6 (a) offsets the discharge curve (Figure 3).

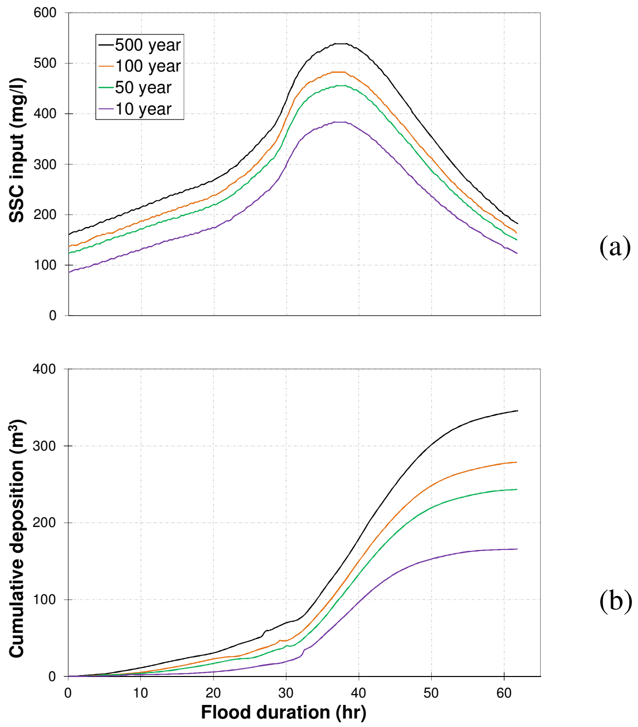

***Figure 6:** SSC input and Cumulative Sediment deposition*

The severity of impact of suspended sediment on fisheries is a function of the suspended sediment concentration and the exposure time. Based on meta-analysis of 80 published documents, Newcombe and Jensen (1996) developed an empirical 'severity-of-ill-effects' scores based on fish response to concentration and duration of exposure. As shown in the Figure 6 (a), the suspended sediment concentration increases with magnitude of the flood event, the average suspended sediment concentration for (10 - 500 year) return period events are vary from 227 mg/l to 337 mg/l. These concentrations with an exposure time of 60 hours make a severity-of-ill-effect score between 7 and 8 along a 15-point scale for juvenile salmonids (Chinook salmon, Rainbow trout, and Mountain whitefish). Although this level of score is not high enough for fish mortality, this can cause increased physiological stress on juvenile salmonids and make them to move out the location. Figure 6 (b) shows the cumulative sediment deposition in the floodplain with flood duration. The cumulative sediment deposition follows the suspended sediment concentration input and the higher rate of deposition occurred in the floodplain on the recession limb of the hydrograph as this phase provides low energy environment for sediment to settle.

Figure 6 (b) shows that high rates of sediment deposition occur during the high flow period. This is somewhat different from the fact that during the high flow period, the higher velocities will entrain and remove more sediment that is deposited in the natural floodplain. However the East Lents flood basin is designated to provide flood storage during higher flood events, in other words it acts like a form of storage reservoir. As the East Lents flood basin provides low energy environment, sedimentations occur during high flow period. The primary focus of this study is on the suspended sediment dynamics of the East Lents floodplain. Bed load sediment dynamics of the channel and the floodplain are not considered in the study.

4. CONCLUSIONS

Grey and green infrastructures are commonly used in the urban flood management. Grey infrastructure is effective in quickly move flood water out of the vulnerable region. However they generally fail to accommodate other aspects of the problem such as water quality, bio diversity and amenity. There is a growing shift from grey to green initiatives to achieve multiple benefits such as flood mitigation, biodiversity, urban cooling, etc. Nevertheless, there are number of barriers in implementing the green infrastructure in urban settings, one of the important barriers is maintenance. As flood water carries large amount of sediment, it is important to understand sediment dynamics in the green infrastructure to ensure their effective performance.

This study focuses on sediment dynamics of the Johnson creek, which is highly urbanised stream known for frequent flooding and contains section that does not meet water quality standards under U.S. Federal Act. In order to enhance flood resilience and water quality of the reach, the Bureau of Environmental services is carrying out number of restoration work along the creek. The study area is on downstream of the creek, East Lents reach where bank of the creek is reconnected to restore floodplain. The two dimensional layer based morphodynamic model is developed for this study region.

The four flood events (10, 50, 100 and 500 year) were considered in this study. The simulation results indicate that circa. 30% of the sediments from the upstream deposits in the flood basin for these flood events. This sediment trapping significantly reduce the overall sediment loading into the main Willamette River. On the other hand as urban pollutants are attached to the sediment particles, East Lents flood basin can become pollution hotspot over period of time. Regular field monitoring and maintenance is essential in order to overcome this potential health issue and to ensure the flood basin's effective hydrological performance in the long-term. In addition, sediment accumulation over longer periods of time in the flood basin can reduce the storage capacity of the flood basin and reduce its intended attenuation of flood peaks. Although datasets were collated as part of the study, there are some limitations in the available data. These include the absence of sediment measurements at the East Lents flood basin and upstream of the study location for different flood events. The conclusions of this study could be improved by the additional flow and sediment data sets at the East Lents flood basin.

5. ACKNOWLEDGEMENTS
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