Simulating Pollution from Urban Stormwater in Project Twin Streams Catchment, Auckland, New Zealand

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Abstract

A system dynamics simulation is presented that models the accumulation of the urban non-point source pollutant zinc from stormwater run-off into an estuary in West Auckland, New Zealand. The boundary and resolution of the model is restricted by available data to a simple structure containing combined inflows and one stock, with no outflow. This is a realistic approximation of system behaviour and mirrors results from other studies in principle. We question the usefulness of such a simulation in its lack to address any socio-ecological processes and concerns. Qualitative modelling is deemed more useful for systemic understanding mandated as part of the transition towards sustainable urban environments.

Keywords: urban stormwater management, water quality, system dynamics simulation, contaminant load model

1 Introduction

Complex socio-ecological systems exhibit uncertainty, non-linearities and potentially chaos, a multitude of feedback processes that interact at different scales and create thresholds of ecosystem functionality and quality (Grinde & Khare 2008). These characteristics easily win out over human cognitive abilities. Computer models offer possibilities to expand mental capacity to better understand complex processes and the implication of decisions and actions in these systems. Critically, the more realistically a computer model portrays the *important* interactions between the social and the ecological, the more suitable and easier to implement the policy recommendation will be.

Slowly increasing environmental degradation of water bodies from human activities concentrating in urban areas is a complex socio-ecological system. While much of the waste generated in urban areas - from production processes as well as simply from the way and at the scale at which we live - is transported outside the city, the remaining, often very small, waste substances are transported by rainwater run-off into streams and eventually accumulate in estuaries and harbours. This dispersed, or non-point source pollution, is not associated with a specific location and presents a unique challenge for its control and abatement.

Despite the fact that sources, transport processes and fate of contaminants have been well understood among researchers for the past decades, public policy responses have been nearly absent. Policy makers seem to be paralysed by the extent of the problem while the public at large is still fairly ignorant about it. Policy suggestions focus mainly on improving and extending existing infrastructure, or recently on applying innovative infrastructure to combat pollution at a local scale.

This paper presents a typical model of a waste accumulation process in an urban catchment in New Zealand. Hydrological models commonly used in stormwater management do not use system dynamics methodology (SDM). We provide a simple system dynamics model and simulation results that mirrors results of standard hydrological models in principle. We use the model as an example to show that physically-based models result in strategies that reinforce technocratic solutions and neglect the sustainability agenda. We argue that models are required that include social variables particularly if these variables influence the implementation of solutions. Finally, we discuss some of the implications of our findings.

2 Stormwater Management in Project Twin Streams Catchment

Stormwater - General Problem Situation

Stormwater, the flow of water that results from rainfall events, is a disruptive natural force impacting on urban populations as well as local and regional environments. General problems caused by stormwater are the *flow volume* (low flows and high flows/flooding), deteriorating *water quality*, and *infiltration* of stormwater into the wastewater system which can lead to overflow events. These problems are exacerbated in an urban setting. Urban development results in an increase in impervious surface areas, e.g. roofs, roads and other paved areas, a change in vegetation cover, and the compaction of top soil. This greatly reduces infiltration of stormwater and increases run-off, substantially altering the natural water cycle (Figure 1) (Wolman 1967; Arnold & Gibbons 1996). Urban pollutants that accumulate on impervious areas are then carried to receiving environments, i.e. streams, rivers, estuaries and harbours. Associated negative impacts include direct toxic effects, reductions in habitat quality and availability, amenity values, ecosystem services, among others (Paul & Meyer 2001; Bunn & Arthington 2002).

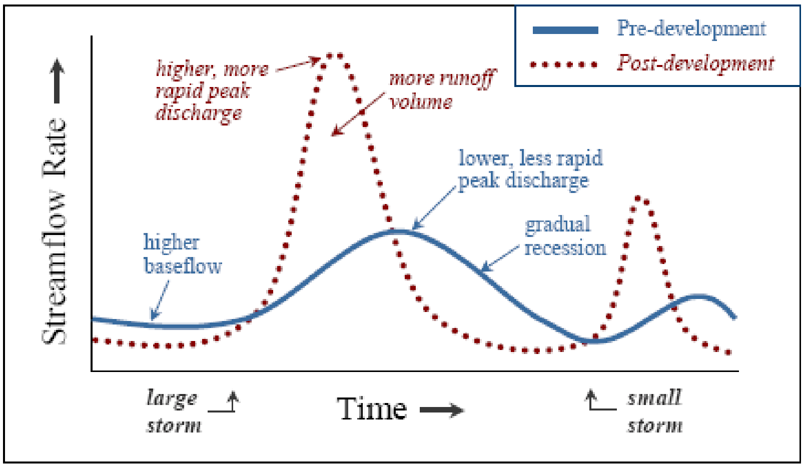

Figure 1: A hydrograph comparing streamflow over time in pre- and post-development situations. Reproduced from Glasgoe and Christy (2004)(2004).

Three stormwater management strategies can be distinguished: conventional, low impact development and community development (Table 1). These are based on substantially different mental models (Winz & Brierley 2009).

Traditionally, stormwater was piped with minimal treatment and disposed of in receiving environments as quickly as possible. Existing pipe infrastructure is inadequate in filtering the type and amount of pollutants that exist in urban areas, and insufficient given most urban growth rates. Overall, this strategy has lead to deteriorating receiving environments, a necessity to expensively upgrade existing infrastructure, and disconnection of citizens with their local streams and other receiving environments (Peters & Meybeck 2000; Hatt *et al.* 2004).

	Conventional	**Low Impact Development**	**Community Development**
Key Focus	Water quantity	Water quality	Stream health as a mirror of community health
Priorities of management goals	Public health and safety, safeguard built structures	Public health and safety, safeguard built structures, Provide ecosystem function	Behaviour change, community buy-in and development, stream restoration
Solution drivers	Capacity, reticulation infrastructure, centralisation	Permeable surfaces, maintenance, decentralisation	Behaviour change, public ownership of local waterways and their management
Solutions	Pipe infrastructure, large downstream stormwater ponds	Infiltration (rain-gardens, wetlands), detention (in rain-tanks and ponds), source control (painting roofs)	Community-driven stream restoration projects
Spatial focus	Focus on the stream as well as all drainage connections to the streams, city scale	Off-stream, lot-scale with a catchment wide integration	Local stream environment, neighbourhood scale
Use of available knowledge	Scientific knowledge (hydrology, civil engineering, public health)	Scientific knowledge (hydrology, geomorphology, environmental engineering, ecology)	Local and community knowledge, social marketing, social development
Ownership of the problem	Local authority	Local authority	Public (to a large extent) and local authority in a supporting role
Responsibility for implementing solutions	Regional and local authority	Local authority and public particularly with respect to maintenance	Public
Adverse effects	Deterioration of receiving environments; Cost of extension, maintenance and upgrades; Disconnection of public with stream environment	Cost of maintenance; Lack of behaviour change and public ownership	High cost; Limited ecological benefit; Substantive delays and long-term implementation

Table 1: Summary of the differences between main stormwater management strategies

In a system with no or minimal anthropogenic influences, natural processes keep stormwater receiving environments intact by allowing for infiltration of rainwater into the soil, thereby slowing and detaining flows as well as improving water quality. Modern, water sensitive or low impact urban stormwater management[1] aims to mimic these processes. Wide-spread uptake of water sensitive strategies has been insufficient and below expectations (Brown 2005), despite evidence of their effectiveness (Coombes *et al.* 2002; Walsh 2004; Tang *et al.* 2005; Matteo *et al.* 2006; Sudduth & Meyer 2006; Dietz 2007; Dietz & Clausen 2008).

Recent emphasis on stakeholder involvement and social learning has promoted the establishment of local community stream restoration projects that aim to prevent flooding and erosion of urban streams while improving environmental values, raising awareness and facilitating behaviour change (Kellert *et al.* 2000; Bernhardt & Palmer 2007; Rosenberg & Margerum 2008). Project Twin Streams is an example of an urban stream restoration project based on a community development model (Waitakere City Council 2007). Stream restoration projects are surrounded by much controversy because the costs are high and ecological effects in the streams are limited (Kellert *et al.* 2000; Palmer *et al.* 2005; Alexander & Allan 2007; Rumps *et al.* 2007). Moreover, it is often assumed that reconnecting the public with their local environment results in behaviour change or that this behaviour change will form the basis for the development of long-term community ownership, without being able to ground these assumptions in data. While more research is clearly needed, evidence is emerging to substantiate claims on biological effectiveness and social change (Kellert *et al.* 2000; Middleton 2001; Purcell *et al.* 2002; Pahl-Wostl 2006; Alexander & Allan 2007; Rumps *et al.* 2007).

Stormwater and its Management in Project Twin Streams Catchment

Project Twin Streams (PTS) catchment in Waitakere City is situated between the Manukau and Waitemata harbours on the western side of the Auckland region, New Zealand. The Waitakere Ranges border the catchment in the southwest and most streams' headwaters originate there. Streams flow from the foothills of the ranges through the city's urban areas and into the Waitemata Harbour via Henderson Creek. Figure 1 shows the geographic location of the catchment as well as the three main streams: Swanson, Opanuku and Oratia. Total catchment area is 10,200 ha (Waitakere City Council 2007). Gregory *et al.* (2008), Reid *et al.* (2008a; 2008b) and Trowsdale (2006) describe present and historical geomorphic and bio-physical characteristics of this catchment in detail.

There is a clear distinction within the catchment in terms of land-use. While the headwater and most of the foothills are covered in native bush or have semi-pastoral use, the lower catchment is fully urbanised. Historically, the lower catchment featured many orchards, wineries and rural living. Today, orchards have been largely replaced by infill housing and industrial areas.

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[1] Common acronyms are LID - Low Impact Development (US), WSUD - Water Sensitive Urban Design (AUS), SUDS – Sustainable Urban Drainage Systems (UK), LIUDD - Low Impact Urban Design and Development (NZ). This manuscript uses LID.

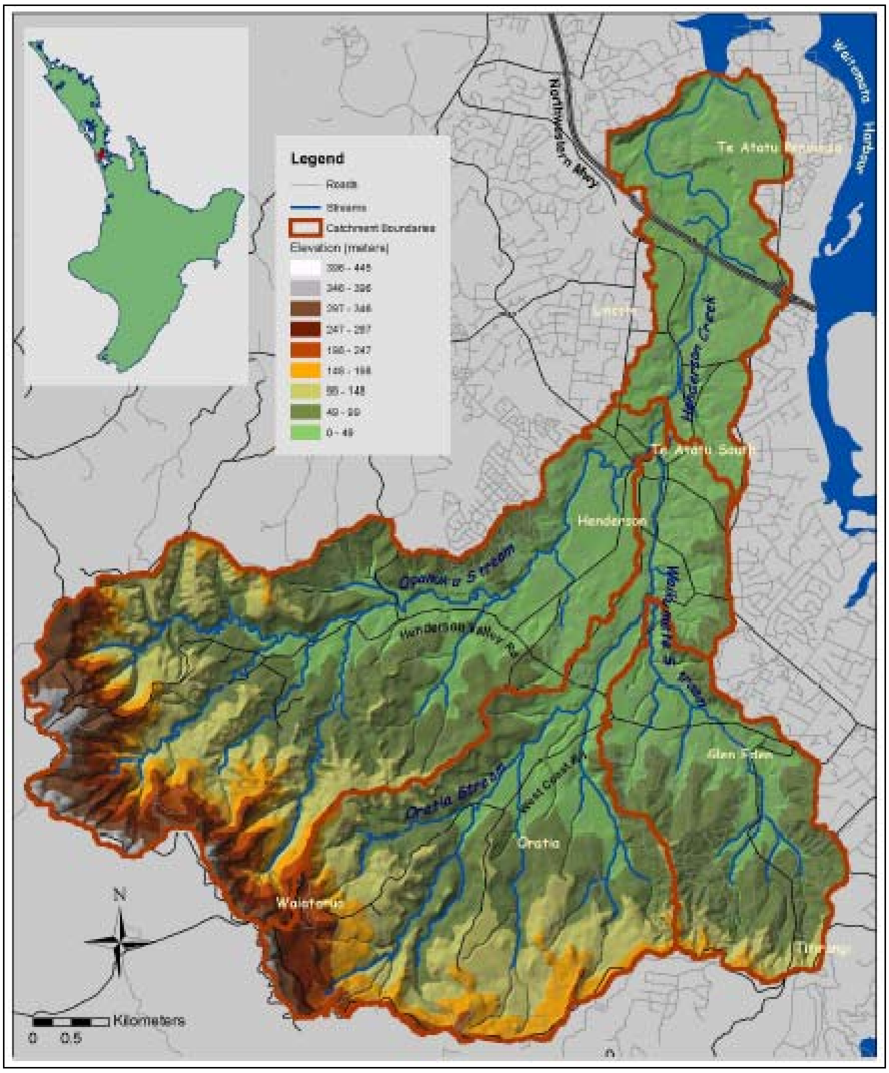

Figure 2: Map of PTS catchment showing the subcatchments Opanuku, Oratia, Waikumete and Henderson Creek. Reproduced from Reid *et al.* (2008b).

Due to the pervious character of the upper catchment, the overall volume problem is assumed to be largely unchanged from the pre-development situation (S Moore 2007, pers. comm. 7 July). The catchment is very steep and hence, the stream areas and floodplains in the lower catchment would have historically been fairly large to accommodate large and rapid peak discharges (S Flynn 2007, pers. comm. 9 July). Over the last 200 years, floodplains have been built on and stream corridors artificially narrowed with many urban streams channelled and piped. This has led to problems of downstream flooding experienced today (S Flynn 2007, pers. comm. 4 July).

Downstream urban development resulted in dramatically increased pollutant load. Mean contaminant concentrations in the settling zone of Henderson Creek of heavy metals copper, zinc and lead have, for the past few years, consistently been above recommended guidelines which has impacted on the ecology in this environment (Williamson & Kelly 2003).

Simulation of Stormwater Processes

Computer models that simulate urban stormwater flow and quality are relied on extensively for the development of local and regional policy. The first models of aquatic processes were developed in the 1960's with increasing uptake over the years (Winz *et al.* 2009). Table 2 presents a typology of models relevant for stormwater management.

Model Type	**Definition**	**Other Observations**
Stochastic	One or more variables in the model have an associated probability distribution.	Uncertainty is part of the model but limited by probability distribution. Use of stochastic variables not practical for large models.
Deterministic	No probability distributions used.	Identical results for the same inputs.
Conceptual	Model is based on physical laws.	
Empirical	Model established from observation.	
Distributed	Model includes spatial variability of inputs.	Most urban run-off models are deterministic and distributed.
Lumped	Model takes no account of spatial variability of inputs.	
Event	Model simulates individual storm events.	Short time horizon. Suitable for the design of stormwater infrastructure and as operational models.
Continuous	Model simulates a catchment's overall water balance over a long period of time.	Long time horizon. Form the basis of planning models for water resources.
Operational	Model controls, operates or allocates water resources in real time.	
Planning	Model calculates the costs associated with different infrastructure configurations over its working life.	Long time horizon.
Design	Model simulates in detail stormwater flows through infrastructure.	

Table 2: A typology of models; adapted from Zoppou (2001)

A conventional urban storm water model consists of a rainfall-runoff part which calculates runoff from rainfall and a transport part which calculates water and pollutant flows through the infrastructure (Zoppou 2001). There are literally hundreds of urban stormwater models capable of simulating flows and the transport of pollutants over impervious and pervious areas, through channel and pipe networks and through storage areas. Most of these models simulate catchment responses over time and with some albeit limited spatial variability (Zoppou 2001). Because of their complexity, these models typically take years to develop.

Already in the 1970's, researchers commented on data availability as the most restricting factor for model advancement (c.f. Zoppou (2001) and references therein). There are only a few models that are deliberately kept simple in order to make them more applicable in a wide range of management situation. For example, Williamson and Morrisey (2000) developed a simple model of contaminant accumulation from stormwater in urban estuaries. The investment in data collection and analysis, time and effort spent on these sophisticated models, in addition to the uncertainties present in such a complex system, seems questionable when simpler models can provide adequate indications of the effects of management decision: *"There is enough understanding to make decisions. I am not convinced that we need to penetrate what we know further and further. We know something about the pathways of* *contaminants; just knowing that in more detail doesn't necessarily take us much further"* (I Boothroyd 2007, pers. comm. 2 August).

3 Simulating Pollutant Flows and Accumulation

Purpose

Present work is a direct response to the identified need to better understand the long-term impact of land use change/urbanisation on water quality in urban receiving environments and the effectiveness of remedial action, particularly low impact design solutions (Auckland Regional Council 2004b). Also Wong *et al.* (2006, p. 58):

To protect receiving waters from stormwater pollution, stormwater managers need to be able to predict the performance of proposed stormwater treatment measures, under variable operating conditions.

In addition, I acknowledge existing natural variability as well as uncertainties regarding environmental effects and the effectiveness of LID solutions. Therefore, a case can be made that simple conceptualisations are useful approximations of long-term system behaviour. As Williamson and Morrissey (2000, p. 56) note:

Not only are […] sophisticated models often unrealistic in terms of the resources needed to develop and run them, but they are also an inefficient use of those resources if simpler models can provide adequate information.

While statistical validity of simpler approaches may be reduced, they are resource efficient in that they fulfil research opportunities provided by existing data, and are also effective in that they can provide a general understanding of system trajectories. The model presented here is a deterministic, lumped, continuous planning model. System dynamics methodology was chosen as the model approach for its numerous advantages (Winz *et al.* 2009).

In summary, the purpose of the model is:

To develop a system dynamics model for PTS catchment that:

- *is simple, transparent and requires minimal data input,*
- *helps to increase knowledge about the long-term impact of urbanisation,*
- *allows to design, test and evaluate the effectiveness of low impact design strategies,*
- *and to determine effective strategies that lead to long-term reductions in annual zinc loads carried by urban streams.*

Description of the Model

The model simulates zinc pollutant flows in PTS catchment over a 50 year time horizon (years 2001-2050) with yearly time steps. The pollutant zinc was chosen as a heavy metal that is currently of primary concern for water managers due to its toxic effect on aquatic life (Auckland Regional Council 2004a,b). Common sources of zinc in the study area are vehicle wear (from tyres and braking pads), vehicle exhaust fumes and galvanization of roofs. Zinc concentrations in the Auckland harbour have exceeded thresholds of ecological health guidelines for the past 20 years and Timperley and Green (2005) have predicted further increase (Figure 3).

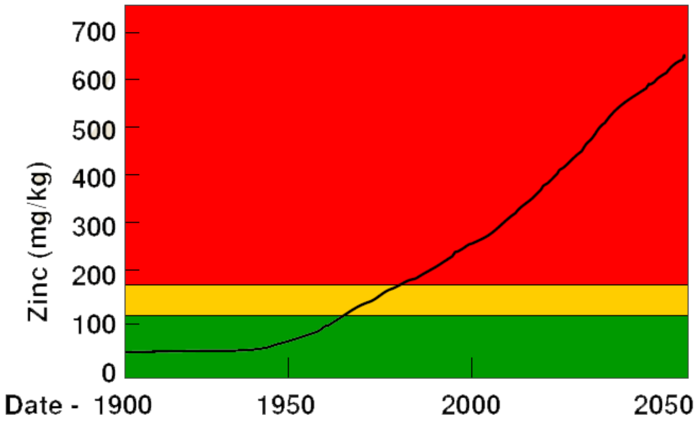

Figure 3: Historic zinc concentration and future predicted increase in the Waitemata harbour. Reproduced from Reid and Irving (undated).

Dynamic Hypothesis

The dynamics hypothesis (Figure 4) shows the inflows (sources, black) and the zinc stock (boxed) in the receiving environment. Solution strategies (green) are aimed at reducing zinc input by painting roofs, at controlling pollutant flows by filtering sediment out of streams in settling ponds and at reducing zinc input by installing rain gardens, i.e. planted areas where stormwater permeates the soil and is thus filtered and detained to a degree. In theory, it is possible to dredge the estuary, i.e. clean out the sediment. However, this strategy is not only costly but remobilises polluted sediment which can get washed out to the harbour and open sea. Dredged sediment is often heavily polluted requiring Class A landfill disposal (Trowsdale & Simcock 2008). The main feedback to behaviour is weak due to the long time delays associated with behaviour change.

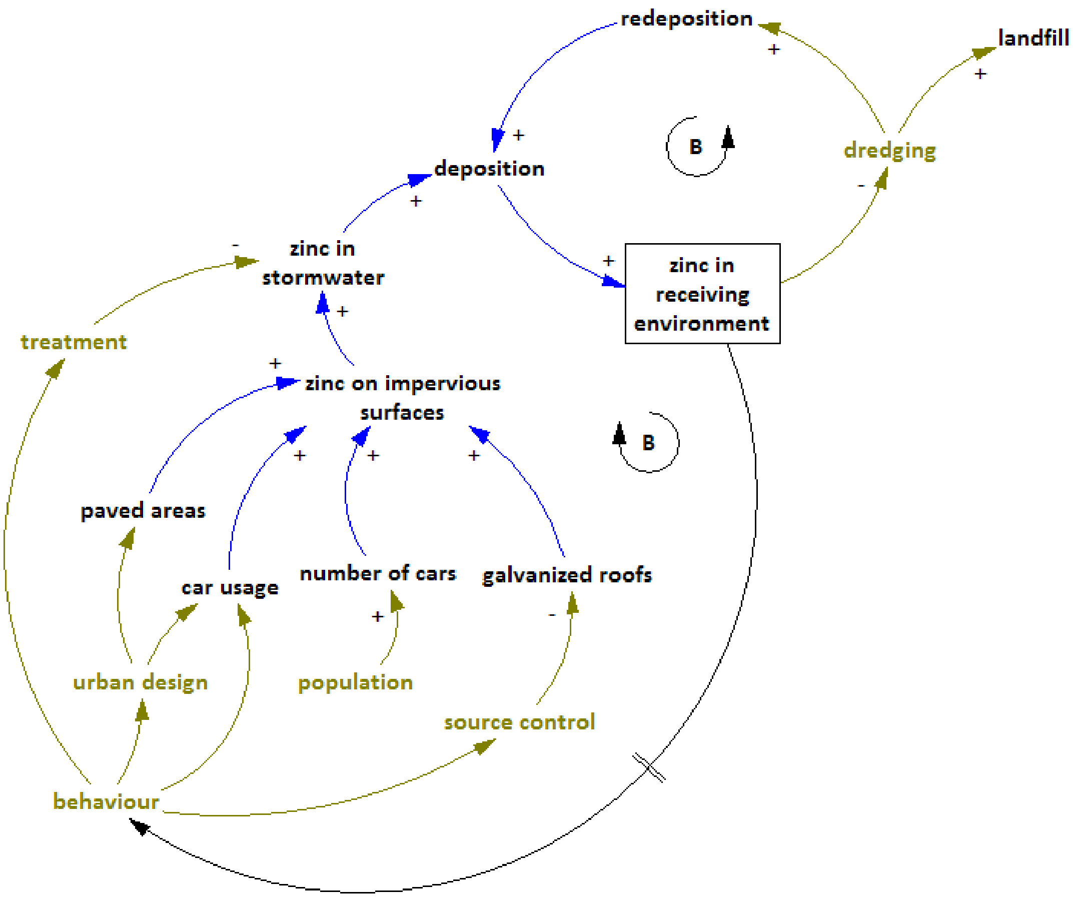

Figure 4: Dynamic hypothesis

Overview of Key Variables

Table 3 lists key endogenous, exogenous and excluded variables of the stock and flow model. The main interest of water managers has been on the *annual* load of zinc contaminated sediment. In its dissolved form (zinc oxide in solution), zinc is highly reactive and easily adsorbs onto dust or sand particles (Auckland Regional Council 2004a). In streams these particles cluster into polluted sediment which gets partially buried and partially washed downstream during times of high flows from stormwater. Eventually layer upon layer of sediment gets deposited in the estuary settling zones. Sediment cores, similarly to ice cores, can give testimony to historic urban pollutant loads (Abrahim & Parker 2007). While a minimal amount of polluted sediment gets taken up by sediment-dwelling animals or remobilised in estuarine wave action and carried out into the harbour, for most polluted sediment this environment is the final resting place with no outflow[2]. The impact on particulate zinc depends on its bioavailability. Animals, e.g. invertebrates, are affected by dissolved zinc and by ingesting small-sized zinc-contaminated silt particles (Auckland Regional Council 2004b).

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[2] As Pål Davidsen liked to say a “sink for the zinc”. This phenomenon is not universal and due to the type of estuary, known as sheltered estuaries, which are common in New Zealand (Williamson and Morrisey 2000).

	Endogenous	**Exogenous**	**Excluded**
Input	Impervious surface area (split into roofs, roads and paved areas)	Initial roof, road, and paved areas	Spatial characteristics including soil types, stream geomorphology, rainfall distribution and intensity, topography, vegetation cover of land and in-stream/stream banks
	Zinc loads from source areas	Growth factors for built surfaces from urban development	Any erosion including sheet erosion from land, bank and in-stream erosion
		Load reduction factors from management strategies	Sedimentation and remobilisation of sediment in-stream and in estuary, as well as existing sediment stock in-stream and in estuary, and any sediment outflow from estuary into harbour
		Stream Area	Change in size of estuary
		Sediment Yield	pH of water
			Influence of other pollutants
			Rainfall, run-off, water quantity
			Existing zinc load in the estuary
			Natural degradation of impervious areas[3]
Output	Combined annual zinc load and cumulative deposition in estuary		

Table 3: Input and output variables of the PTS stormwater stock and flow model.

Stock and Flow Model

Figure 5 shows the stock and flow model of the PTS stormwater model. In this model, zinc is *independent* of flow and sediment volumes. This is a reasonable generalisation as almost all zinc is adsorbed on to particles while it is carried through the drainage network (Auckland Regional Council 2004a, p. 10f.). This fact, together with the steepness of the catchment and the lack of floodplains results in rapid run-off which will transport virtually all contaminated sediment to the estuary (Zoppou 2001; Auckland Regional Council 2004b). As a result, a simple model of zinc inflows into one stock of accumulated zinc in the estuary is sufficient to provide an indication of zinc accumulation particularly when using large time steps and long time horizons. This simulation is an extension of the Urban Stormwater Contaminant Load Model (CLM Version March 2008) spreadsheet developed by Mike Timperley at Auckland Regional Council, which calculates annual contaminant loadings in catchments as follows (Timperley *et al.* 2009):

Annual load (kg/year) = source area x source yield x load reduction factor for management options x proportion of source area draining to the management options.

Where

Source area = area (m^2) of a contaminant source;

Source yield = quantity of contaminant produced by the source in g/m^2/year;

Load reduction factor (LRF) = the proportional reduction of the source load achieved by either a stormwater treatment or a source control management option;

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[3] This is a reasonable assumption for this time horizon. Even if some roads and other paved areas deteriorate, their base course is so compacted that permeability is near zero.

Area proportion = proportion of the whole site area draining into the management option.

Through the use of arrays, the model takes into account that different types of roofs, roads and paved areas contribute different amounts of zinc. A listing of differential equations is provided in the Appendix.

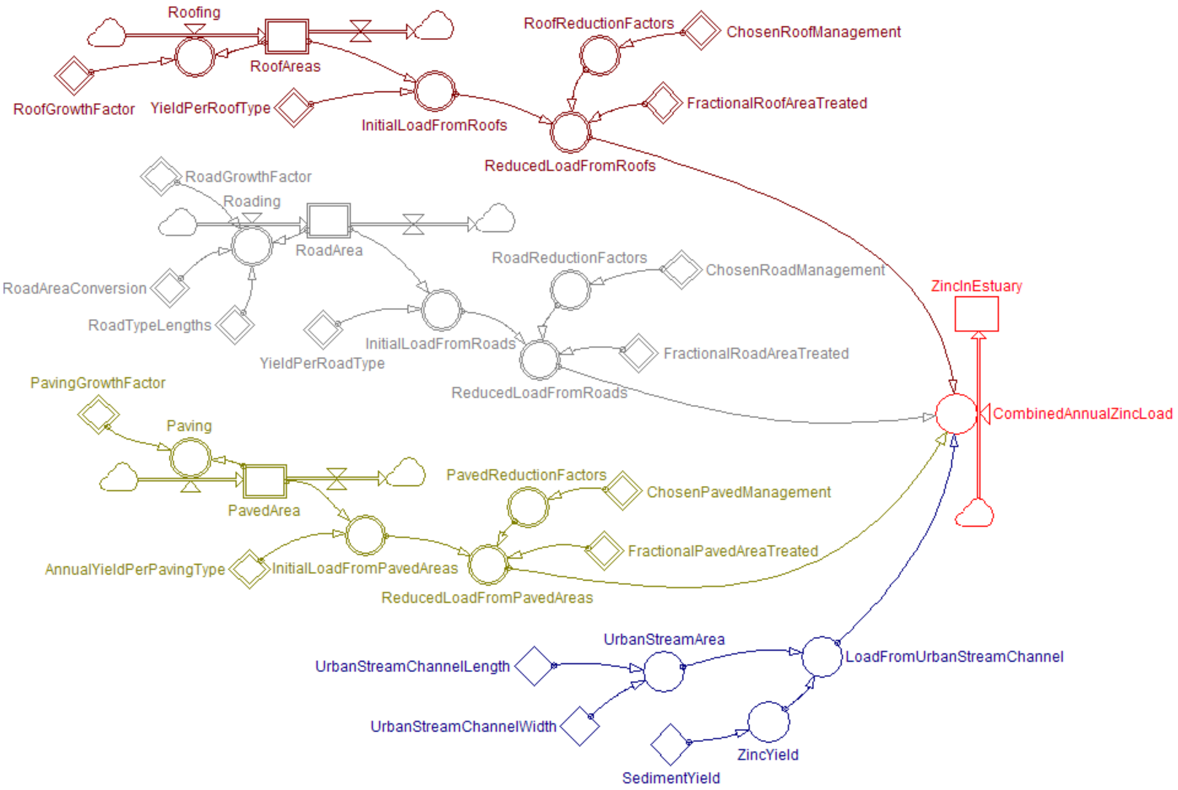
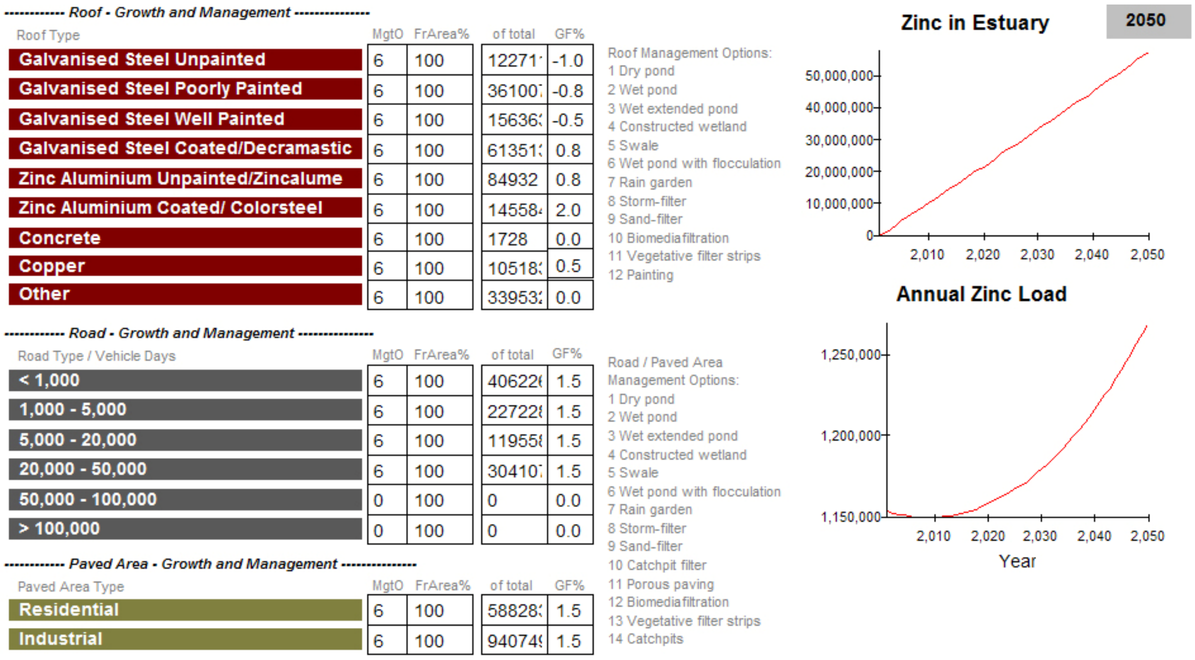


Figure 5: Stock and Flow model of the PTS stormwater simulation

In Figure 5, the brown structure represents zinc input from roofs, the grey structure zinc input from roads, the green structure zinc inputs from paved areas, and the blue structure zinc inputs from soil. The red structure combines all inflows and calculates the zinc stock in the estuary.

Graphical User Interface

The graphical user interface (GUI) is designed to allow any user to set values for management options, fractional area treated and growth factors for all sources. Two graphs are provided which show the annual zinc load and the accumulated zinc in the estuary over the time horizon of the simulation. The GUI is presented in Figure 6.



------------ *Roof - Growth and Management* ---------------

Roof Type	MgtO	FrArea%	of total	GF%
Galvanised Steel Unpainted	6	100	12271	-1.0
Galvanised Steel Poorly Painted	6	100	36100	-0.8
Galvanised Steel Well Painted	6	100	15636	-0.5
Galvanised Steel Coated/Decramastic	6	100	61351	0.8
Zinc Aluminium Unpainted/Zincalume	6	100	84932	0.8
Zinc Aluminium Coated/ Colorsteel	6	100	14558	2.0
Concrete	6	100	1728	0.0
Copper	6	100	10518	0.5
Other	6	100	33953	0.0

Roof Management Options:
1 Dry pond
2 Wet pond
3 Wet extended pond
4 Constructed wetland
5 Swale
6 Wet pond with flocculation
7 Rain garden
8 Storm-filter
9 Sand-filter
10 Biomediafiltration
11 Vegetative filter strips
12 Painting

------------ *Road - Growth and Management* ---------------

Road Type / Vehicle Days	MgtO	FrArea%	of total	GF%
< 1,000	6	100	40622	1.5
1,000 - 5,000	6	100	22722	1.5
5,000 - 20,000	6	100	11955	1.5
20,000 - 50,000	6	100	30410	1.5
50,000 - 100,000	0	100	0	0.0
> 100,000	0	100	0	0.0

------------ *Paved Area - Growth and Management* ---------------

Paved Area Type	MgtO	FrArea%	of total	GF%
Residential	6	100	58828	1.5
Industrial	6	100	94074	1.5

Road / Paved Area Management Options:
1 Dry pond
2 Wet pond
3 Wet extended pond
4 Constructed wetland
5 Swale
6 Wet pond with flocculation
7 Rain garden
8 Storm-filter
9 Sand-filter
10 Catchpit filter
11 Porous paving
12 Biomediafiltration
13 Vegetative filter strips
14 Catchpits

Figure 6: The graphical user interface with Scenario 3 results

Data Sources and Initial Values

The CLM breaks down geographic areas into contaminant source areas and divides residential, commercial and industrial areas into roofs, roads, paved surfaces (other than footpaths which are included in the road area) and pervious areas (Timperley & Reed 2008; Timperley *et al.* 2009). A similar area division in three stages was performed in this model (Figure 7).

In a *first area division* the catchment was divided into residential, commercial and industrial areas. The size of these areas was estimated using WCC GIS of digitised land use from aerial photographs from the most recent records available (2005). Therefore, the residential area is 55% the catchment area, the commercial area is 3% and the industrial area is 1%. The remaining 41% of the catchment area (Waitakere Ranges, open areas and water bodies) are assumed not to contribute zinc.

In a *second area division*, residential, commercial and industrial areas are divided into roof, road and paved surface areas. Estimates for these impervious areas are provided in Timperley and Reed (2008) based on surveys of impervious areas in Auckland City. However, a calculation of total roof area from GIS provided by WCC confirms that these estimates are overly conservative – PTS catchment has overall less impervious area as the widely more urbanised Auckland City. Therefore, the GIS roof data was used.

The total road length in PTS catchment was available from GIS. Assuming an average road width of 15m (from CLM) results in a road area of 3,766,422 m^2. Comparing estimates with available data, actual roof area is 50% of the estimate and road area is 75% of the estimate. Therefore, the paved area has been set at 75% of the estimate. It was decided to use the adjusted data as model input but perform sensitivity tests with the original estimated roof, road and paved areas (results not included here).

In a *final area division*, roof areas are divided into material types, road areas are divided according to road usage and paved areas are divided into commercial and industrial paved areas. Each of these subclasses has different zinc contributions associated with it and these values were taken straight from the CLM, Version March 2008.

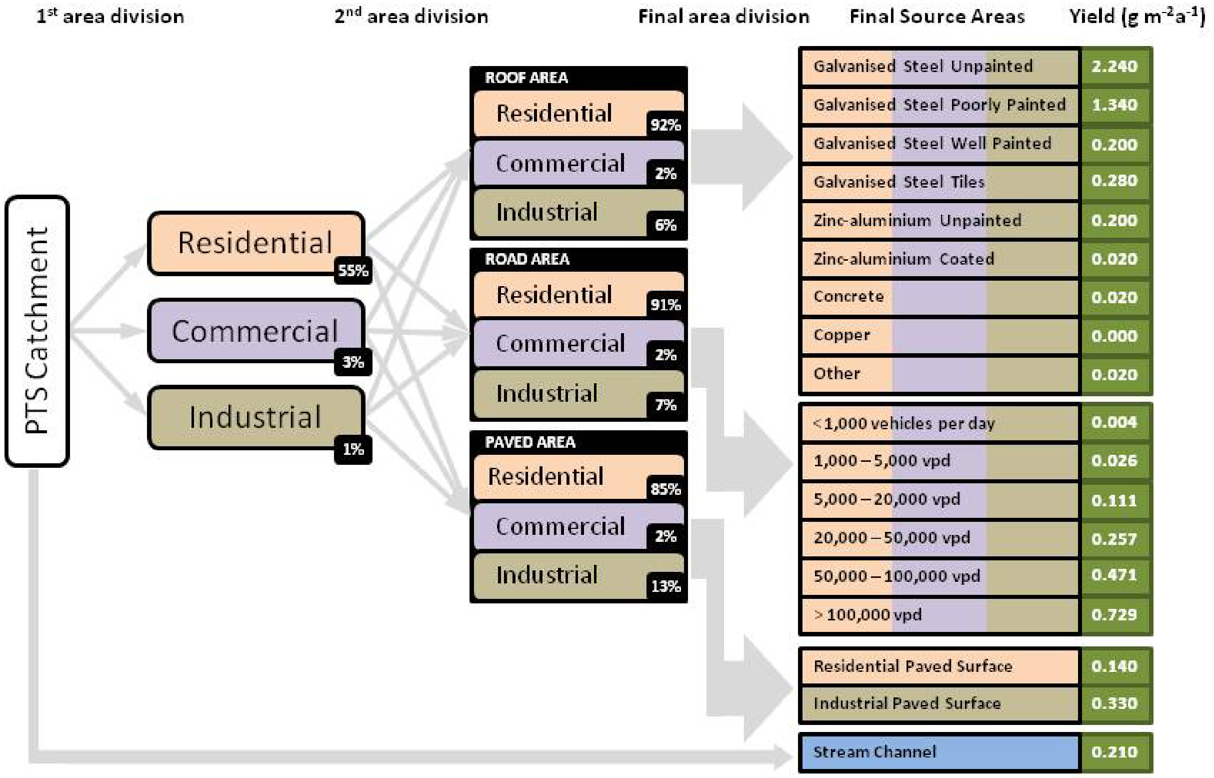


Figure 7: Area divisions, final source areas and CLM yields

Roof material estimates were provided by Timperley and Reed (2008), based on a survey by Kingett Mitchell (2003). Again, adjustments of these source areas were required since the estimates are based on Auckland City data which was developed much earlier than large parts of Waitakere City. Older developments have a higher proportion of galvanised steel roofs while newer developments use more zinc-aluminium (Timperley & Reed 2008). Therefore, unpainted galvanised steel was adjusted downwards and zinc-aluminium roof types adjusted upwards proportionately.

Timperley and Reed (2008) estimate that 91% of all roads are residential roads, and the remainder commercial and industrial. They provide further estimates for traffic loads in these areas. The CLM prescribes different zinc contributions according to road usage measured in *vpd* (vehicles per day). WCC has some traffic count data available but it is uncertain whether these cover a balanced view of road usage within the catchment or focus on high priority roads only. Therefore, Timperley and Reed (2008) estimates were used.

Urban stream areas contribute sediment which are contaminated with zinc from natural sources, for example volcanic activity (Timperley & Green 2005). Stream channel length in PTS catchment has been calculated from GIS data at approximately 75km (N Trahan 2008, pers. comm. 30 September). Stream channel width is estimated to average 4m, which is the same average used by Timperley and Reed (2008). Each square meter of stream provides an annual load of 0.21g of zinc (values from CLM).

Changes in Source Areas over Time

In general, the model assumes an increase of zinc contributing areas over time according to population growth estimates provided by WCC of 25-35% population growth over 20 years (B Osborne 2008, pers. comm. 22 August). Therefore, average annual growth is set at 1.5%. Roof composition will likely change over time with a trend towards replacing galvanized steel roofs with zinc-aluminium roofs. This change has already been observed (Timperley & Reed 2008).

Road areas are estimated to grow by the average annual growth rate of 1.5% with the exception of roads carrying more than 50,000vpd which have zero growth. Paved industrial and residential areas are assumed to grow by the average annual growth rate of 1.5%.

Model Testing

Extreme condition tests were performed with high negative growth factors of -20% and -50%. Negative growth factors create negative inflows which reduce the stock level over time. This test is important to show that the stocks do not become negative during a full simulation run as this would represent an error in the model. The results are presented in Table 4/Figure 8.

	Combined Annual Zinc Loads	**Cumulative Zinc Deposition**
Growth Factor -20%	Decreases from 2,087 kg/year to 63.036 kg/year	Increases from 0 kg to 13,206 kg
Growth Factor -50%	Decreases from 2,087 kg/year to 63.000 kg/year	Increases from 0 kg to 7,135 kg

Table 4: Extreme condition tests with high negative growth factors

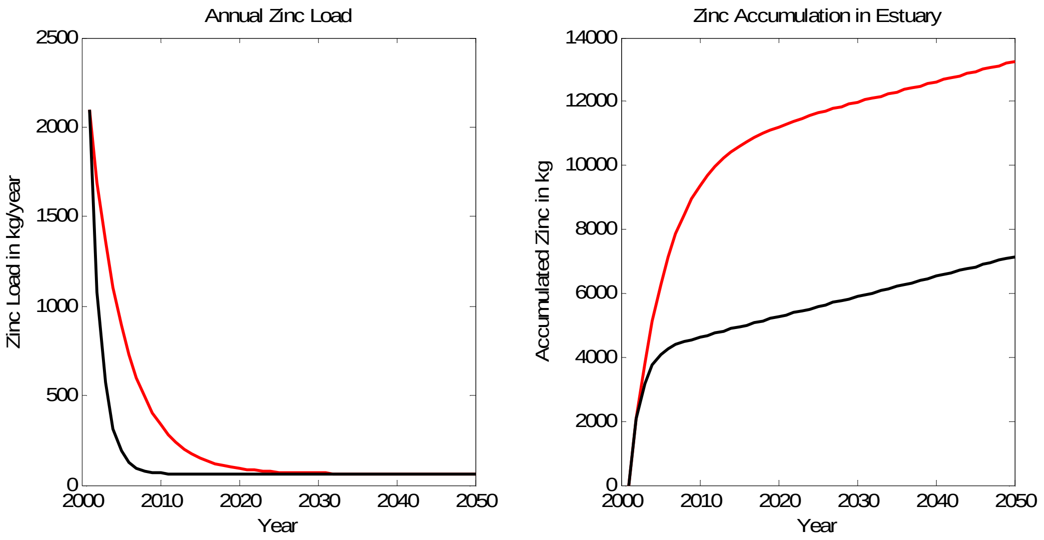
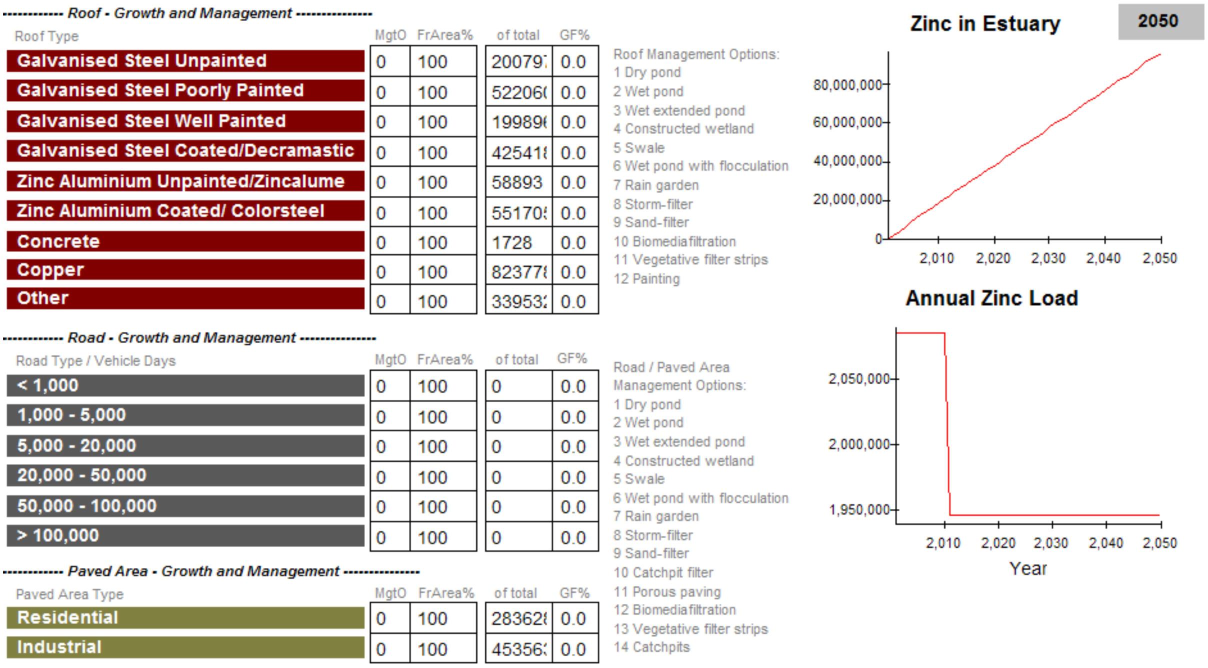


Figure 8: Comparison between results of negative growth test (red 20% decline, black 50% decline)

Indeed, the area stocks approach a zero value asymptotically but are never negative. This is due to the fact that the inflows are calculated as a percentage of the existing stock level. Therefore, the remaining 63kg/year annual zinc load must be from the urban stream channel, i.e. a natural load or background contribution. A closer examination of the data shows this to be true. This natural zinc load is constant throughout the simulated time as the stream area is assumed not to change in size.

A further extreme condition test was performed where the total stock of zinc contributing road area was suddenly reduced to zero. This would correspond to a situation where everyone would stop driving their vehicle. For this test the growth factor was set to zero. The STEP function was used to initiate a total reduction of the road stock in the year 2010. As a result, in 2011 the annual zinc load reduces from a constant 2,087 kg/year to 1,948 kg/year. The zinc stock in the estuary increases from 0 kg to 96,835 kg (Figure 9). The fact that the flow value reduces only slightly, suggests that the comparatively larger roof source area has a dominating impact on the overall zinc load.



------------ Roof - Growth and Management --------------

Roof Type	MgtO	FrArea%	of total	GF%
Galvanised Steel Unpainted	0	100	20079	0.0
Galvanised Steel Poorly Painted	0	100	52206	0.0
Galvanised Steel Well Painted	0	100	19989	0.0
Galvanised Steel Coated/Decramastic	0	100	42541	0.0
Zinc Aluminium Unpainted/Zincalume	0	100	58893	0.0
Zinc Aluminium Coated/ Colorsteel	0	100	55170	0.0
Concrete	0	100	1728	0.0
Copper	0	100	82377	0.0
Other	0	100	33953	0.0

Roof Management Options:
1 Dry pond
2 Wet pond
3 Wet extended pond
4 Constructed wetland
5 Swale
6 Wet pond with flocculation
7 Rain garden
8 Storm-filter
9 Sand-filter
10 Biomediafiltration
11 Vegetative filter strips
12 Painting

------------ Road - Growth and Management --------------

Road Type / Vehicle Days	MgtO	FrArea%	of total	GF%
< 1,000	0	100	0	0.0
1,000 - 5,000	0	100	0	0.0
5,000 - 20,000	0	100	0	0.0
20,000 - 50,000	0	100	0	0.0
50,000 - 100,000	0	100	0	0.0
> 100,000	0	100	0	0.0

------------ Paved Area - Growth and Management --------------

Paved Area Type	MgtO	FrArea%	of total	GF%
Residential	0	100	28362	0.0
Industrial	0	100	45356	0.0

Road / Paved Area Management Options:
1 Dry pond
2 Wet pond
3 Wet extended pond
4 Constructed wetland
5 Swale
6 Wet pond with flocculation
7 Rain garden
8 Storm-filter
9 Sand-filter
10 Catchpit filter
11 Porous paving
12 Biomediafiltration
13 Vegetative filter strips
14 Catchpits

Figure 9: GUI and extreme condition test result

Calibration of model data (source yields and reduction factors) has been performed by Timperley and Reed and is described in their 2008 report. Overall these tests show that the model corresponds as expected to different input parameters.

Simulation Results

Parameters and results are listed in Table 5. A visual comparison between results of scenarios 1, 2 and 6 is provided in Figure 10.

	Input Parameters	Combined Annual Zinc Loads	Cumulative Zinc Deposition
Base	No urban growth	2,087 kg/year	Increase from 0 kg to 102,258 kg
1	Annual urban growth at 1.5%	Increase from 2,087 kg/year to 2,500 kg/year	Increase from 0 kg to 109,161 kg

	Input Parameters	**Combined Annual Zinc Loads**	**Cumulative Zinc Deposition**
2	Annual urban growth at 1.5% Source control – painting roofs	Increase from 882.6 kg/year to 1,587 kg/year	Increase from 0 kg to 57,895 kg
3	Annual urban growth at 1.5% Input reduction – wet ponds with flocculation	Initial decrease in zinc load from 1,154 kg/year to 1,150 kg/year in 2009 followed by steady increase to 1,269 kg/year (Figure 6)	Increase from 0 kg to 57,905 kg
4	Annual urban growth at 1.5% Input reduction – rain gardens	Initial decrease in zinc load from 777 kg/year to 772 kg/year in 2012 followed by steady increase to 839 kg/year	Increase from 0 kg to 38,648 kg
5	Annual urban growth at 1.5% Combination of painting roofs, and rain gardens for road and paved area run-off	Increase from 375 kg/year to 535 kg/year	Increase from 0 kg to 21,559 kg
6	Reduction in road usage -1% Combination of painting roofs, and rain gardens for road and paved area run-off	Increase from 375 kg/year to 474 kg/year	Increase from 0 kg to 20,229 kg

Table 5: Parameters and results for simulation runs

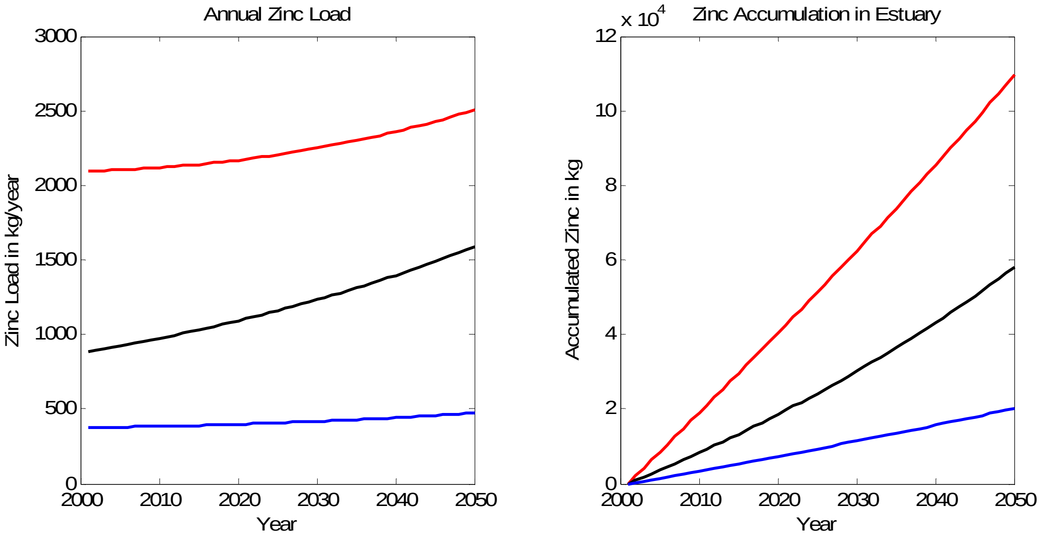


Figure 10: Comparison between results of Scenarios 1 (red), 2 (black) and 6 (blue).

Discussion of Results

As expected, the policies reduce annual loads of zinc and thus incremental zinc increases in the estuary are smaller (see also Figure 10). Independent of urban development scenarios, the most effective management strategies (roof painting and rain garden for other impervious area run-off) can only reduce but never fully internalise zinc inputs.

In Scenarios 3 and 4, annual zinc load initially decreases and then increases again. The decrease is due to the fact that the decrease in galvanized steel roofs reduces zinc loads more than what is contributed from urban development. Later, this incremental annual decrease is overtaken by annual growth of other source areas. This shows that even if galvanized steel roofs are eliminated over time, the wins in annual zinc load reduction will eventually disappear and become outpaced by load increases associated with urban development.

The natural or background zinc load introduced with Figure 8, is only a marginal part of the total zinc contribution. Considering a current annual load of 2,087 kg/year, the natural contribution of 63kg/year is only 3% of the total. Therefore, the key impact is from anthropogenic activity.

The only option that can reduce annual zinc inputs involves a reduction in source area. This is possible with regards to reductions in impervious surface areas over time, e.g. by retrofitting/converting existing paving to permeable paving, and behaviour change related reductions in vehicle use.

Of concern is not only the total amount of zinc deposited in the estuary but its concentration.[4] Concentration is dependent on sediment loads. During the historical boom development phase of the city in the 1960's and 1970's, much sediment from erosion was transported downstream (Williamson & Morrisey 2000). Today, sources of sediment are mainly in-stream erosion as the downstream area is almost fully developed. In theory, any development in the foothills of the Waitakere Ranges has to put measures in place to eliminate erosion as well as create hydrologic neutrality, i.e. there should be no increased run-off or sediment outflow from the development (H Chin 2007, pers. comm. 29 June). Therefore, annual sediment inflow is likely to be fairly constant. Calculating zinc concentration in sediment would then be straightforward but would require data on existing sediment in the estuary as well as annual loads.

The results mirror other simulation results in principle (Wong *et al.* 2001; Auckland Regional Council 2004a; Walsh *et al.* 2005; Xiao *et al.* 2007) and thus support standard low impact development strategies as advocated by researchers and public water managers of public authorities. However, it is also apparent that because there is no outflow, zinc will keep accumulating until the inflow has ceased. This will only occur when zinc is replaced with other substances, e.g. as happened in the case of lead. It is interesting to note that water managers are usually only interested in annual flows[5], neglecting the ongoing accumulation of heavy metals in the estuary as well as underestimating the impact of annual pollutions flows. This behaviour has been observed in other circumstances (Van den Belt 2004, p. 1):

"Humans respond to a strong signal that something is wrong but have more trouble stopping a negative trend that evolves with a slow pace and which involves many interlinked variables that are hard to track."

Sources of Uncertainty

Uncertainty in model output is high mainly due to a lack of reliable data. The following sources of uncertainty are apparent:

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[4] Figure 3 shows prediction of zinc concentrations across the whole Waitemata harbour, not just Henderson Creek. Although Henderson Creek does represent a main source of zinc input into the harbour, Whau Creek and Meola Creek also significant amounts of zinc. Therefore Figure 3 cannot serve as a behaviour-over-time comparison graph to the results in this study but it can provide an indication.

[5] As is evident in e.g. Timperley *et al*. (2005) or Liebman *et al.* (2004).

Source yields. Zinc yield rates were originally derived from a combination of local and international studies but not from data available from PTS catchment.

Source areas. The composition of roof materials is based on default values developed from investigation of Auckland City (Timperley & Green 2005; Timperley & Reed 2008). The similarity to roof composition with PTS catchment or Waitakere City has not been investigated. Impervious surface coverage was based on available GIS data from Waitakere City Council but from the year 2005. The land use split was calculated from 2005 GIS data based on Waitakere City Council definitions of land use zones. There was an error component in all GIS data provided.

Load reduction factors. The impacts of stormwater treatment and source control management options are based on averages derived from local and international studies (Timperley & Green 2005), but may not fully represent LID designs and implementation experience in New Zealand.

Future source areas. The future composition of roof materials, population growth, impervious surface coverage, land use split and vehicle travel is unknown. Population growth estimates provided by Waitakere City Council were used to inform area growth assumptions. Changes in car use and the impact of increased public transportation are hard to estimate. Timperley (in prep) analyses sensitivities to future uncertainties in vehicle travel and source areas.

Excluded variables. Any of the excluded variables listed in Table 3 could, if included, have a potentially large impact on simulation results. However, this potential impact is unknown.

Given these uncertainties it is questionable what insights can be derived from a comparison of our results with those from other models. Further work that reduces uncertainties will not change the overall message: low impact stormwater management techniques are useful in slowing the accumulation of contaminants in receiving environments. The more interesting question then becomes: *Why then are they not more widely applied?*

Implementation Problems

Even though there is by now overwhelming theoretical justification for low impact development, implementation is not forthcoming. This begs the questions a) why, and b) shouldn’t the simulation show this behaviour? In order to show this behaviour the simulation needs to include social variables that model uptake dynamics as well as existing barriers to implementation. The problem here is in selecting appropriate measures and quantification. Moreover, there needs to be a desire on the part of the decision makers to engage with models that integrate physical and social aspects. The following observations about model resolution and delineation have been made in relation to this study:

Model Complexity - Resolution. Virtually all stormwater simulation models are physical models designed to calculate stormwater run-off, peak discharge or flow volume based on physical catchment information such as soil types, rainfall distribution and intensity, topography, vegetation cover, among others. There are only a few models that also simulate water quality (Zoppou 2001). Simulation is often short-term, e.g. focussed on single storm events, due the fact that exact rainfall data has very small time units. There is no integration of non-physical aspects (with the exception of infrastructure life-cycle costs). Also, there is an expectance among stormwater managers that quantitative models are spatially explicit. As a result, other simulation models are generally not accepted for reasons of representativeness, uncertainty and unreliability. Spatially explicit, dynamic, non-linear models with long time horizons and short time steps may nowadays be feasible but are they useful? Clearly, the compounding errors and uncertainty alone would make results highly questionable (Costanza & Ruth 1998), not to mention the lack of adequate data.

Model Boundary – Delineation. Unfortunately, model boundaries are naturally restricted by data availability. Data that show the coupling between social and ecological subsystems do not exist in the context of urban stormwater management. If spatial GIS data exist, they often only reach back a few years. Generalised data may exist, e.g. the average composition of roof types in a catchment, but for water managers who are used to detail and accuracy in models this is likewise often not acceptable.

In this context it appears that a quest for high resolution[6] and model boundaries that are restricted by lack of data not only results in the rejection of models and their results but also discourages pro-active decision making. This supports the status quo.

4 Implications

Placing the results of this simulation work in light of these broader considerations about SDM, it appears that ‘hard’ system dynamics methodology is not as useful as originally anticipated to address the complex socio-ecological issues in stormwater management. While the quantitative simulation has provided insights into the pollution accumulation problem in PTS catchment in the long-term, the model fails to:

- reflect critical social realities, for example the disconnection between the public and their local environment,
- provide recommendations that can effectively stop or reduce the environmental impact of stormwater on receiving environment.
- provide recommendations that are implementable. The lack of current implementation is testimony to this fact. Even recommendations that reduce annual zinc loads (reduction in source areas) cannot be implemented in the current cultural, economic and political climate.

In this work and for the reasons outlined above, the inclusion of uptake dynamics in the simulation has not been possible. Barriers for implementation of LID are not entirely well understood let alone their effects quantified. Recent studies point to institutional factors as the likely culprits (Brown 2005, 2008; Roy *et al.* 2008). So far lacking is an understanding of the

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[6] What one reviewer called the “study to death” syndrome.

mental models driving societal, not just institutional, engagement with and choices regarding stormwater management.

Our work provides an example for how physical modelling (independent of the underlying methodology used) concentrates on what can be measured and thus, by design, leads to solutions aimed at technology and devices, whether high impact or low impact. On the other hand, support for community-oriented solutions, such as community-led stormwater management and stream restoration is entirely lacking. While experts are preaching low impact technological solutions to remedy current environmental deterioration, uptake is marginal at best. Researchers look for deficiencies in institutional settings and policies, while the public remains at large unaware of any problems or responsibilities, and partially hostile to government institutions and their proposed solutions.

Despite this, a few more enterprising, visionary institutions travel the path less taken and engage in community development as part of an environmental repair process[7]. They have understood that LID will not achieve its intended long term goals without genuine engagement and commitment of stakeholders, particularly the public. Engaging in community-based resource management requires appreciation of differing mindsets, a willingness to listen, trust and cooperation. The main objective of such a process is the reconnection of people with nature in their local environment.

Will system dynamics play a role in providing solutions for socio-ecological problems at this scale and scope? System dynamics advocates simple models that have a specific problem focus. However, these tend to ignore complex social and ecological relationships and lack "the policy space for designing any mechanisms of change" (Saeed 1992). Clearly, unless data are grounded and make sense to the public, results will not be accepted. On the other hand, quantitative models may just not be the gold standards in situations where complex social-ecological systems are to be modelled and there is an inevitable lack of adequate data. Available options include incorporating social components and feedbacks in otherwise purely physical models, and putting aside concerns for quantification and hard system dynamics and engaging in group systems thinking exercises that focus specifically on understanding system structure and the implementation of solutions (Senge *et al.* 2008).

The neglect for implementation in many system dynamics projects restricts their application to theoretical findings, failing to create successful system dynamics interventions. This was a key focus in several long-winded discussions on the email list of the System Dynamics Society (Threads: The death of System Dynamics, Future development directions, Policy paradox and SD, Society strategy development) in 2007 and 2008. Our work may provide a reason for the lack of success and hence lack of application of system dynamics work: sometimes we do not include relevant aspects into our models and our results thus reinforce technocratic solutions rather than enable change. Therefore, system dynamics projects are not based on a sound understanding of systemic structure and fail to lead to better solutions.

It appears that widespread implementation of LID requires more than just behaviour change on the part of a few individuals or top-down enforcement but rather what has been termed a

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[7] For example, Project Twin Streams; the Stream Doctor Project in Gaithersburg, Maryland (Middleton 2001); or the Lower Paint Creek Association in Fayette and Kanawha Counties, West Virginia.

’regime shift’ – a profound cultural transition towards adaptation to current challenges (Folke *et al.* 2004; Beddoe *et al.* 2009).

5 Conclusions

A system dynamics simulation based on an extension of the CLM spreadsheet model developed by Auckland Regional Council, New Zealand was introduced. The model calculates annual zinc loads from different sources in PTS catchment over a 50 year time horizon. Since many required data were lacking, estimates were substituted. Results show that low impact design measures can reduce annual zinc loads. This is not surprising and mirrors other available results in principle.

Instead of engaging with the model and its results more deeply we then discussed the more interesting question of implementation: *Given the widespread support for LID techniques, why are they not applied more widely?* Here, we noted that the ‘hard’ system dynamics model fails to address the wider social issues that can increase or restrict LID implementation. Therefore a need emerges for research that engages more meaningfully with different perspectives that exist within society regarding problems, solutions and their implementation in urban stormwater management.

Understanding stormwater management as a social-ecological system is the pre-requisite for developing and implementing integrated solutions. Integrative approaches to management need to be underpinned by integrative science. Holistic problem understanding is not possible based on quantitative data and black box modelling. A move towards integrative models will require the use of qualitative data, either on its own through qualitative modelling or in combination with quantitative simulation. A *genuine* commitment to sustainable stormwater management needs to service social *and* environmental objectives.

Future research that builds on this work could involve introducing the model as an interactive learning environment to a variety of stakeholders and testing their understanding of system behaviour, particularly the long-term accumulation process, before and after the explanation of the model.

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Appendix

Stocks
dim PavedArea = (NoPavedTypes)
init PavedArea = [2836288,453563]
flow PavedArea = +dt*Paving
doc PavedArea = Residential and industrial/commercial paved area. Assumption informed by comparison between GIS and Timperley and Reed (2008) data.

dim RoadArea = (NoRoadTypes)
init RoadArea = [2074400,1163600,616800,155900,0,0]
flow RoadArea = +dt*Roading
doc RoadArea = Road areas of different road types. Calculated from GIS and Timperley and Reed (2008) estimates for road usage.

dim RoofAreas = (NoRoofTypes)
init RoofAreas = [200797,522060,199896,425418,58893,551705,1728,823778,339532]
flow RoofAreas = +dt*Roofing
doc RoofAreas = Initial roof areas calculated from GIS and roof material estimates from Timperley and Reed (2008)

init ZincInEstuary = 0
flow ZincInEstuary = +dt*CombinedAnnualZincLoad
doc ZincInEstuary = Accumulation of zinc in estuary.

Flows
aux CombinedAnnualZincLoad = ARRSUM(ReducedLoadFromRoofs)+ARRSUM(ReducedLoadFromRoads)+ARRSUM(ReducedLoadFromPavedAreas)+LoadFromUrbanStreamChannel
doc CombinedAnnualZincLoad = Combined annual zinc loads from all sources.

dim Paving = (NoPavedTypes)
aux Paving = PavedArea*PavingGrowthFactor/100
doc Paving = Newly paved residential and industrial areas per year.

dim Roading = (NoRoadTypes)
aux Roading = RoadArea*RoadGrowthFactor/100
doc Roading = Annual additional roads built.

dim Roofing = (NoRoofTypes)
aux Roofing = IF(RoofAreas-RoofAreas*RoofGrowthFactor/100<0,0,RoofAreas*RoofGrowthFactor/100)
doc Roofing = Newly created roof area per year.

Auxiliaries
dim InitialLoadFromPavedAreas = (NoPavedTypes)
aux InitialLoadFromPavedAreas = PavedArea*AnnualYieldPerPavingType
doc InitialLoadFromPavedAreas = Annual zinc load from residential and industrial paved areas.

dim InitialLoadFromRoads = (NoRoadTypes)
aux InitialLoadFromRoads = RoadArea*YieldPerRoadType
doc InitialLoadFromRoads = Annual initial zinc load on roads.

dim InitialLoadFromRoofs = (NoRoofTypes)
aux InitialLoadFromRoofs = RoofAreas*YieldPerRoofType
doc InitialLoadFromRoofs = Annual initial zinc load on roofs.

aux LoadFromUrbanStreamChannel = ZincYield*UrbanStreamArea
doc LoadFromUrbanStreamChannel = Annual zinc load from the urban stream.

dim PavedReductionFactors = (NoPavedTypes)
aux PavedReductionFactors = IF(ChosenPavedManagement=1,0.3,IF(ChosenPavedManagement=2,0.4, IF(ChosenPavedManagement=3,0.5, IF(ChosenPavedManagement=4,0.7, IF(ChosenPavedManagement=5,0.5, IF(ChosenPavedManagement=6,0.6, IF(ChosenPavedManagement=7,0.75, IF(ChosenPavedManagement=8,0.65, IF(ChosenPavedManagement=9,0.4, IF(ChosenPavedManagement=10,0.25, IF(ChosenPavedManagement=11,0.4, IF(ChosenPavedManagement=12,0.7, IF(ChosenPavedManagement=13,0.2, IF(ChosenPavedManagement=14,0.15,0))))))))))))))
doc PavedReductionFactors = From CLM

dim ReducedLoadFromPavedAreas = (NoPavedTypes)
aux ReducedLoadFromPavedAreas = MAX(InitialLoadFromPavedAreas-(InitialLoadFromPavedAreas*FractionalPavedAreaTreated/100*PavedReductionFactors),0)
doc ReducedLoadFromPavedAreas = Annual paved area zinc load taken into account the reduction of zinc due to management.

dim ReducedLoadFromRoads = (NoRoadTypes)
aux ReducedLoadFromRoads = MAX(InitialLoadFromRoads-(InitialLoadFromRoads*FractionalRoadAreaTreated/100*RoadReductionFactors),0)
doc ReducedLoadFromRoads = Annual road zinc load taken into account the reduction of zinc due to management.

dim ReducedLoadFromRoofs = (NoRoofTypes)
aux ReducedLoadFromRoofs = MAX(InitialLoadFromRoofs-(InitialLoadFromRoofs*FractionalRoofAreaTreated/100*RoofReductionFactors),0)
doc ReducedLoadFromRoofs = Annual roof zinc load taken into account the reduction of zinc due to management.

dim RoadReductionFactors = (NoRoadTypes)
aux RoadReductionFactors = IF(ChosenRoadManagement=1,0.2,IF(ChosenRoadManagement=2,0.3, IF(ChosenRoadManagement=3,0.4, IF(ChosenRoadManagement=4,0.6, IF(ChosenRoadManagement=5,0.4, IF(ChosenRoadManagement=6,0.5,

IF(ChosenRoadManagement=7,0.7, IF(ChosenRoadManagement=8,0.4, IF(ChosenRoadManagement=9,0.3, IF(ChosenRoadManagement=10,0.2, IF(ChosenRoadManagement=11,0.3, IF(ChosenRoadManagement=12,0.6, IF(ChosenRoadManagement=13,0.1, IF(ChosenRoadManagement=14,0.11,0))))))))))))))
doc RoadReductionFactors = From CLM.

dim RoofReductionFactors = (NoRoofTypes)
aux RoofReductionFactors = IF(ChosenRoofManagement=1,0.05, IF(ChosenRoofManagement=2,0.05, IF(ChosenRoofManagement=3,0.1, IF(ChosenRoofManagement=4,0.25, IF(ChosenRoofManagement=5,0.15, IF(ChosenRoofManagement=6,0.4, IF(ChosenRoofManagement=7,0.6, IF(ChosenRoofManagement=8,0.15, IF(ChosenRoofManagement=9,0.1, IF(ChosenRoofManagement=10,0.6, IF(ChosenRoofManagement=11,0.1, IF(ChosenRoofManagement=12,0.9,0))))))))))))
doc RoofReductionFactors = Reduction factors from CLM.

aux UrbanStreamArea = UrbanStreamChannelLength*UrbanStreamChannelWidth
doc UrbanStreamArea = Stream Area

aux ZincYield = 0.000035*SedimentYield
doc ZincYield = Annual zinc yield per sqm of urban stream. From CLM.

Constants

dim AnnualYieldPerPavingType = (NoPavedTypes)
const AnnualYieldPerPavingType = [0.140,0.330]
doc AnnualYieldPerPavingType = Residential and industrial zinc yields per sqm of paving. From CLM.

dim ChosenPavedManagement = (NoPavedTypes)
const ChosenPavedManagement = [0,0]
doc ChosenPavedManagement = Variable links paved area to management option. Is 0 if no management option for this roof type, otherwise any number between 1 and 12 signals some form of management.

dim ChosenRoadManagement = (NoRoadTypes)
const ChosenRoadManagement = [0,0,0,0,0,0]
doc ChosenRoadManagement = Variable links road type to management option. Is 0 if no management option for this roof type, otherwise any number between 1 and 12 signals some form of management.

dim ChosenRoofManagement = (NoRoofTypes)
const ChosenRoofManagement = [0,0,0,0,0,0,0,0,0]
doc ChosenRoofManagement = Variable links roof type to management option. Is 0 if no management option for this roof type, otherwise any number between 1 and 12 signals some form of management.

dim FractionalPavedAreaTreated = (NoPavedTypes)
const FractionalPavedAreaTreated = [0,10]
doc FractionalPavedAreaTreated = Fraction of paved area managed by chosen option in % of total.

dim FractionalRoadAreaTreated = (NoRoadTypes)

const FractionalRoadAreaTreated = [0,10,50,0,0,0]
doc FractionalRoadAreaTreated = Fraction of road area managed by chosen option in % of total.

dim FractionalRoofAreaTreated = (NoRoofTypes)
const FractionalRoofAreaTreated = [0,0,0,0,0,0,0,0,0]
doc FractionalRoofAreaTreated = Fraction of roof area managed by chosen option in % of total: e.g. 100 equals 100% of the area.

dim PavingGrowthFactor = (NoPavedTypes)
const PavingGrowthFactor = [1.5,1.5]
doc PavingGrowthFactor = Growth percentage for different paved types per year. From growth estimates of Waitakere City Council.

dim RoadGrowthFactor = (NoRoadTypes)
const RoadGrowthFactor = [1.5,1.5,1.5,1.5,0,0]
doc RoadGrowthFactor = Growth percentage for different road types per year. Average annual growth estimate from Waitakere City Council.

dim RoofGrowthFactor = (NoRoofTypes)
const RoofGrowthFactor = [-0.3, -0.1, -0.1, 0.75, 0.75, 1.5, 0, 0.5, 0]
doc RoofGrowthFactor = Growth percentage for different roof types per year. Assumptions informed by Timperley and Reed (2008).

const SedimentYield = 6000
doc SedimentYield = Annual suspended sediment yield per sqm of urban stream. From CLM.

const UrbanStreamChannelLength = 75000
doc UrbanStreamChannelLength = Length of urban stream channel. From GIS.

const UrbanStreamChannelWidth = 4
doc UrbanStreamChannelWidth = Average width of urban stream channel. From Timperley and Reed (2008).

dim YieldPerRoadType = (NoRoadTypes)
const YieldPerRoadType = [0.004,0.027,0.111,0.257,0.471,0.729]
doc YieldPerRoadType = Annual zinc yield per road type per sqm. From CLM.

dim YieldPerRoofType = (NoRoofTypes)
const YieldPerRoofType = [2.240,1.340,0.200,0.280,0.200,0.020,0.020,0.000,0.020]
doc YieldPerRoofType = Zinc yield of one sqm per year. From CLM.