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Exploring options to manage sediment loads to Western Port: further development and application of *dSedNet* in an urban-rural dominated catchment

Report to Melbourne Water Corporation

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Executive summary

Melbourne Water is the waterway manager for the Port Phillip and Westernport region and invests substantially in activities to protect and improve the health of its rivers and bays. Since the early 2000s, Melbourne Water has initiated a range of long-term catchment, instream and receiving water monitoring and research programs in the Westernport catchment where rural activities, urban growth and coastal erosion have been associated with high sediment loading and impairment of ecosystem condition within the bay, especially its seagrass meadows.

One activity has been ongoing investment in the modelling of sediment generation and transport for integrating data and knowledge of catchment processes, land use and rehabilitation effects. This report describes the outcomes of a two-year project (2017-2019) to improve on previous modelling. For this, a *dSedNet* model for Westernport was built, together with a Catchment Planning Tool for reporting results. These products are called:

- *dSedNet* (dynamic sediment network model) – coded as a plugin to the Source platform
- Source+*dSedNet*@Westernport - the Source and *dSedNet* models configured for Westernport, the Source model adapted from the existing Port Phillip-Western Port (PP-WP) catchment model
- CPT@Westernport – the Catchment Planning Tool configured to report on Source+*dSedNet*@Westernport.

A suite of data products (including new active gully and streambank heights maps) and model enhancements have also been produced as part of the project.

dSedNet - the *dSedNet* model is a time-stepping, spatially distributed, sediment budget model for predicting daily sediment loads in river basins. The budget includes the sediment sources (gully and hillslope) from adjoining subcatchments to the river network (characterised using a link-node representation), erosion from streambanks, and deposition and remobilisation within the network. The resulting sediment is accumulated at each catchment's outlet.

In the Westernport catchments, the proportioning of sediment sources is important, as understanding which sources are contributing, and when, needs to be well understood in order to develop appropriate management actions.

Source+*dSedNet*@Westernport – the major catchments of Bunyip, Cardinia, Lang Lang and Bass waterways drain into the estuarine/marine receiving waters of Western Port, with other smaller creeks and local drainage also contributing. Generally the larger catchments drain from the Dandenong Ranges and Bunyip State Park in the north, and across large alluvial floodplains before discharging into the bay. 373 subcatchments were delineated for the hydrological (rainfall-runoff) and sediment modelling. Models were calibrated against observed data for these four major catchments. Hydrological modelling was calibrated to peak flows with satisfactory performance. Sediment modelling was calibrated to good overall fit to mean annual loads (as required for long-term catchment planning) and peak loads during flood events. A good performance was achieved for mean monthly and mean annual loads. Estimation of peak flood event sediment loads was challenging, perhaps due to the model not including resuspension of fine sediment and its subsequent transport.

Baseline sediment load results – Over the period 2001-2016, the model estimates a mean annual fine sediment load to the bay of 35.4 kilotonnes/year, with streambank erosion dominating (65.4%), followed by urban areas (18.2%). The four major catchments produce 75% of the sediment load. Results can be explored through the CPT@Westernport.

The load is significantly higher than the SEPP target of 28 kilotonnes/year, which is based on earlier studies. *dSedNet* almost certainly has overestimated streambank erosion in the channelised (and well vegetated) reaches. Additionally, sediment is removed from those channels. The current version of the *dSedNet* model does not incorporate this, nor does it have instream deposition and resuspension enabled. These two limitations together could account for 20% of the estimated load, resulting in an estimated load to the Bay of 28.3 kt/yr.

Catchment planning – One of the many benefits of a simulation model is its ability to run 'what-if' analyses (set up as 'scenarios' in the models). Catchment management options were elicited via a series of workshops with Melbourne Water and DELWP staff. In summary, the greatest interest was in exploring the likely impacts on sediment loads of different scales of interventions (e.g. streambank and/or gully erosion controls), land use change, changing climate, at local and regional (to the bay) scale.

One urban (all existing areas conform to BPEM stormwater management targets); two gully (20% and 60% of active gullies remediated); one streambank (riparian vegetation restored on all streambanks); and one cover (hillslope vegetation cover improved by a factor of 2) management actions have been implemented. Combining these five actions gives 23 scenarios, the results of which can be interrogated through the CPT@Westernport. These show the impact of the revegetation of streambanks management option, with those scenarios that include that option showing reductions of up to 15 kilotonnes/year in sediment load to the bay.

Advances – Within the two years of the project, the Source hydrology model was updated, a new sediment model was built, models were calibrated and validated, data was collected and/or inferred through remote sensing, GIS and other analytical methods, and the CPT was designed, coded and implemented.

Being able to model the effect of management changes on loads at the outlet is a step forward, as is the ability to reflect seasonal changes in vegetation cover. Sediment source contributions to load are now much improved; as is the ability to disaggregate by land use which is a significant advance on the annual Sednet model.

The CPT reduces the requirement for in-house modelling expertise through providing an easy-to-access entry point to the models and their results.

Next steps – While all care was taken to populate the models with the 'best' data available, many of these data (e.g. density of active gullies within catchments, condition of riparian areas) were inferred and need to be validated, requiring new field work (survey and monitoring) and longer-term research. Melbourne Water staff anticipated many uses for the CPT. To realise these requires further development of the CPT, and expansion of the number of catchment planning scenarios that can be modelled and then interrogated through the CPT.

Priority may be given to improved modelling of sediment generation and transport from existing and developing urban areas, how sediment generation changes under climate change, and how to prioritise actions to meet sediment load targets to the bay.

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Acknowledgements

The project was planned and conducted as a research collaboration between Melbourne Water and CSIRO and brought together hydrology and sediment transport modellers, GIS and software specialists, software engineers, decision support design specialists and waterway managers. We would like to thank Melbourne Water for their commitment to continue their long engagement with CSIRO on tracing and mitigating sediment delivery to Western Port. Staff gave generously of their time to participate in discussions/presentations and provided significant input to the modelling and associated software products. Of special note are Trish Grant, Louise Kerferd, Kathy Cinque, Penny Rogers, Leigh Smith, David Reginato, Tom Hurst, Lizzie Younger, Bronwen Hutchinson, Udaya Kularathna, Rowan Hore, Rachael Bathgate, and Alison Rickard.

We would also like to thank Dr Shiroma Maheepala, DELWP, who kept the project team informed of Integrated Water Management Forums and other strategy initiatives of the Victorian government relevant to Westernport; and Dr Baihua Fu, The Australian National University, for her review of an early draft of this report.

In terms of the lineage of the *dSedNet* plugin, we have been fortunate that the Queensland Department of Natural Resources and Mines (now Department of Natural Resources, Mining and Energy) made available the code and documentation for their dynamic SedNet plugin, which we have built on. We hereby acknowledge this contribution and thank the Department for their support.

CSIRO and Melbourne Water respectfully acknowledge Aboriginal and Torres Strait Islander peoples as the Traditional Owners and custodians of the land and water on which all Australians rely. We look forward to incorporating their knowledge of country into the next generation of catchment planning models and decision support tools.

We also take this opportunity to highlight the value of building long-term partnerships between research providers (private and public) and practitioners. This project continues a long tradition of Melbourne Water working closely with CSIRO and local consulting companies to advance the science of integrated water resource management.

The project team and their key roles:

- Susan Cuddy, CSIRO, project lead
- Tony Weber, CSIRO visiting scientist from Alluvium, modelling lead
- Dr Lydia Cetin, CSIRO visiting scientist from Jacobs, modelling team & link to Port Phillip Bay modelling
- Dr Scott Wilkinson, CSIRO, sediment modelling adviser
- Dennis Gonzalez, CSIRO, data collation and spatial analysis specialist
- Andrew Freebairn, CSIRO, software engineering, model development
- Dr Rhys Coleman, Melbourne Water Research Manager, project initiator and industry lead
- Dr Antonia Gamboa Rocha, CSIRO, fluvial geomorphologist and project support
- Peter Thew, CSIRO, workflows and project support
- Joel Rahman, CSIRO visiting scientist from FlowMatters, CPT design and implementation.

Glossary

Term	Description
application	The use of Source to model a catchment and river system processes within a region (e.g. a river basin such as the Murrumbidgee, or an area such as Western Port Bay) is a Source application
BPEM	Best practice environmental management. Commonly used to describe Victoria's Water sensitive urban design (WSUD) and Integrated Water Cycle Management (IWCM) policies
coarse sediment	Sediment with a particle size > 63 microns
component	Similar to module – the component parts
constituent	A measurable item of water quality e.g. sediments, total phosphorus, and total nitrogen are the constituents of *dSedNet*. This term is often used in preference to 'contaminant' as it is neutral
core	The term used to refer to code that is written as integral to the Source code base
CPT	Catchment Planning Tool – a web-based application to view and analyse the results of the modelling
EMC/DWC	Event mean concentration/dry weather concentration. EMC is the flow-weighted average constituent concentration over a storm event. DWC is the constituent concentration measured during dry weather
FDC	Flow duration curve. This is a cumulative frequency curve which shows the frequency of occurrence of various rates of flow
fine sediment	Sediment with a particle size < 63 microns
functional unit (FU)	Describes the spatial delineation of the landscape, within sub-catchments (which are generally delineated using a DEM). It can be based on combinations of landscape characteristics (e.g. slope and soil type) or function (e.g. land use). Whatever is used, it is the base spatial layer to which all other data are attached. Once defined, it cannot be changed without having to re-parameterise the model
HWS	Healthy Waterway Strategy https://yoursay.melbournewater.com.au/healthy-waterways/document-library
link	linkage between nodes and where routing and flow models are configured
model	Traditional concept of a model – code that describes a process or a relationship - has inputs, state variables, outputs, etc. As used herein, *dSedNet* is a **model** which is a collection of components, some being models (e.g. gully erosion). These are encoded as **modules**
module	Separate parts that are used to construct a more complex structure – each module performs a defined task and can be linked with other such parts to form a larger system. Models (e.g. the gully 'model') are implemented as modules within *dSedNet*
node	Points of entry to the river system network
parameter	Either input data to a model or individual data that affects the operation of a model
persistence	saving information/data to disk for later use
platform	Source is often referred to as a platform as it has been designed as a system on which other application programs can run
plugin	This term refers to a piece of code that is compiled separately to the Source codebase, but registered into Source at runtime
PP-WP	Port Phillip and Western Port (Source) model
resample	Rescaling data to change its resolution, for example from changing pixel cell size from 10^2m to 50^2m
SIMHYD	A rainfall-runoff model that is distributed with, and as part of, core Source
Source	A hydrological modelling platform which integrates catchment hydrology (rainfall-runoff), with river system processes and operations to provide a whole-of-system modelling environment

Term	Description
TSS	Total suspended sediment or total suspended solids, the latter including organic material. When used in the context of modelling, TSS refers to sediment; when used in the context of water quality sampling, TSS most commonly refers to solids
VLUIS	Victorian Land use Information System http://vro.agriculture.vic.gov.au/dpi/vro/vrosite.nsf/pages/vluis

1 Introduction

Melbourne Water is a statutory corporation owned by the Victorian State Government and is responsible for looking after Melbourne's water supply catchments, treatment and supply of drinking water, removing and treating most of Melbourne's sewage, providing recycled water for non-drinking purposes and managing around 25,000km of rivers, estuaries and major drainage systems throughout the Port Phillip and Westernport region. Guided by their Healthy Waterways strategies, Melbourne Water invests substantially in activities to protect and improve the heathy of rivers, creeks, estuaries and bays. As part of understanding the current status of waterways, trajectory of condition, major threats and management opportunities, Melbourne Water has initiated a range of long-term catchment, instream and receiving water monitoring and research programs. This includes a focus on the Westernport catchment since the early 2000s (Wallbrink et al 2003a,b,c; Tomkins et al 2014; Wilkinson et al 2016), where rural activities, urban growth and coastal erosion have been associated with high sediment loading and impairment of ecosystem condition within the bay, especially its seagrass meadows. The Western Port marine and coastal environment supports a diverse range of aquatic animals such as waterbirds, fish, marine invertebrates and mammals and is of international significance (e.g. UNESCO Biosphere Reserve, Ramsar convention listing for migratory waterbirds), as well as containing three of Victoria's 13 marine national parks (Melbourne Water 2018a). On the basis of previous sediment studies, a sediment load target to Western Port was recently incorporated into the Victorian State Environment Protection Policy (Waters) (Victorian Government 2018). The target for the period 2018 to 2028 is an average annual load of total suspended solids entering Western Port from the catchment and coast <= 28,000 tonnes. This target essentially seeks to maintain current sediment loads in the context of continued urban growth, land use change and changes in climate (e.g. rainfall intensity and frequency, sea level rise) (Melbourne Water 2018a). The policy also states that the Department of Environment, Land, Water and Planning (DELWP), in conjunction with Melbourne Water and EPA Victoria, must develop and implement a plan to meet this target.

Melbourne Water and their partners make significant ongoing investments in catchment management to control the sediment and nutrients to freshwater systems and the bay, through actions such as streamside revegetation, rural land management and urban stormwater mitigation. Recognising the extent of available information on sediment generation and transport and the need to understand the most cost effective strategies for managing sediment loads to Western Port to underpin the State Environment Protection Policy sediment loads plan, it was decided that a dynamic sediment generation and transport simulation model would be valuable for integrating data and knowledge of catchment processes, land use and rehabilitation effects to support management of sediment generation and its transport through the catchment and river system to protect the health of Western Port.

1.1 Motivation

One of the recommendations for further research set out in Wilkinson et al (2016) was the need to implement a catchment model that could represent the primary land use sources of sediment. Having such a model, that was update-able and informed by recent data, would help inform priorities for erosion management and to evaluate the effects of changes in management.

CSIRO's dynamic sediment network (*dSedNet*) model is such a model. It supports the exploration and calibration of sediment and nutrients transport at the reach to basin scale, has been integrated into Australia's national hydrological modelling platform, Source[1], and has been extended to incorporate temporal dynamics at a daily time step (as opposed to steady state). *dSedNet* has multiple modules (hillslope, gully, streambank, floodplain, instream) that can simulate the movement of sediment through a catchment and is designed to work as a Source plug-in. Source with *dSedNet* is then a powerful tool for exploring likely impacts on generation and fate of sediments and nutrients as a result of changes in climate, land and water management/use within the catchment. The outputs of Source and *dSedNet* can be passed as input to other models such as coastal water quality models.

Bringing water quality and quantity modelling into the one platform provided a significant opportunity to Melbourne Water, and, after a series of discussions in early 2017, CSIRO and Melbourne Water entered into a two-year (July 2017–June 2019) research collaboration to implement *dSedNet* for the Westernport catchment, and to develop a 'front-end' stand-alone product (called the 'Catchment Planning Tool' [CPT]) to make the modelling available to Melbourne Water catchment planners (without the overhead of learning how to use Source). This product was to support 'what-if' analysis (via model scenarios) of a range of changes to the catchment (e.g. land use change, land and/or stream management practices, changing climate). The nature of those scenarios was to be developed as the project progressed, and as Melbourne Water staff became more familiar with the capability (and limitations) of the models.

Building on earlier work by CSIRO and others in the region, the project team adapted the Port Phillip - Westernport Source catchment model to provide a higher resolution Westernport Source catchment model which included a new release of CSIRO's *dSedNet* plugin to model the transport of fine sediment generated by erosion throughout the waterways in the Westernport catchment.

The Catchment Planning Tool was jointly scoped by CSIRO and Melbourne Water, and developed using applications provided by FlowMatters Pty Ltd.[2]

1.2 Products

In addition to this report, and material prepared for workshops, the project has delivered six new products:

1. A new release of the *dSedNet* plugin, distributed as a community plug-in for Source. CSIRO requests attribution as 'CSIRO 2019'.
2. The Source+*dSedNet* model configured for Westernport catchment (Source+*dSedNet*@Westernport). This application is the property of Melbourne Water.
3. The Catchment Planning Tool (CPT) – a web-based decision support tool, the architecture and coding of which is retained by FlowMatters Pty Ltd.
4. The CPT@Westernport, which contains a database of results from running the model multiple times (baseline plus scenarios) and contextual information. This is the property of Melbourne Water.

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[1] https://toolkit.ewater.org.au/

[2] https://www.flowmatters.com.au/

5. A suite of workflows that manages pre-processing, preparation of the model for multiple runs (baseline plus scenarios), and post-processing to prepare the database of results that are then accessed by the CPT. These are packaged with the CPT and are the property of Melbourne Water.
6. Updated and new datasets for Westernport including (1) an updated land use map, (2) a channel-enforced digital elevation model (DEM) and derived hydrology, (3) monthly cover factor grids (Feb 2000 to May 2018), (4) revised gully mapping, (5) LiDAR-based streambank height estimations, and (6) riparian vegetation density. These are the property of Melbourne Water.

Melbourne Water and CSIRO have provided to each other the right to use these products for ongoing research and development purposes.

Brief overviews of these products are given below and described in more detail in later sections of this report.

1.3 The *dSedNet* plugin

The *dSedNet* plugin is an implementation of dynamic SedNet – a time-stepping spatially-distributed sediment budget model for predicting daily sediment loads in river basins; and is based on a link-node representation of a hydrologically calibrated river system network. For each link (conceptually a reach of stream between upstream and downstream confluences with other links, and the sub-catchment draining to that) in that network, the model constructs daily budgets of fine (and coarse) sediment – source and deposition. These are accumulated through links downstream to the catchment outlet. Erosion rates (hillslope, gully and streambank erosion) and fine sediment sinks (floodplains and reservoirs) are disaggregated from mean annual rates, based on daily rainfall and runoff. The underlying modelling approach is well described in Wilkinson et al (2014) and we refer the reader to that journal article as the definitive source of information on the model conceptualisation. The model as a stand-alone module has been evaluated in the Burdekin basin in tropical Australia (Wilkinson et al, 2014), concluding that a regionalised model (such as SedNet) is useful for long term modelling. Some component parts had been implemented as *dSedNet* in the Mt Lofty Ranges (Freebairn et al, 2015) with promising results.

The *dSedNet* plugin is an extension to the existing behaviours and usage of Source. The constituent generation models are implemented in the same way existing Source models are, with the addition of enhanced spatial and temporal data parameterisation functionality. In addition to integrating streambank erosion and floodplain deposition into *dSedNet*, the project updated the *dSedNet* plugin to include:

- adding temporal variation to cover (to mimic seasonal change in % cover)
- development of a sediment mass transformation module to provide a relatively simple way to simulate attenuation (in this case of sediment load) within a stream link
- in-depth investigation of how to prepare the data for the parameters in the USLE hillslope erosion equation, resulting in a revised method to calculate length of slope (LS) (such that L could be set by the user).

The content of the plugin, and its use, is more fully described in Appendix A .

1.3.1 Source+*dSedNet*@Westernport

The Port Phillip and Westernport (PP-WP) Source catchment model, which has been designed as a regional-scale management tool, was made available to the project team. The Westernport portion was extracted and used as the spatial backbone for the *dSedNet* application. Both Source and *dSedNet* use land use as the basis for breaking the catchment up into more homogeneous units. The *dSedNet* application uses more land use classes and thus has more units than the PP-WP Source Model – however boundaries are coincident, allowing flow volumes and sediment loads to be compared (and contrasted) between the PP-WP and Source+*dSedNet*@Westernport models. The project team worked with the PP-WP modelling team to ensure the alignment of the two models – with input data being shared, calibration being evaluated using the same metrics and the same observed data, results being analysed and interpreted using the same assumptions and diagnostics.

1.3.2 The Catchment Planning Tool (CPT)

The project proposal envisaged a sequencing of tasks, with the model being completed, and then the Catchment Planning Tool (CPT) being built as a tailored product to provide an interface to the Source+*dSedNet* model. In fact, these activities overlapped with the first task of the CPT being to provide the modelling team with a visualisation tool for checking results. Access to all model run results (baseline and scenarios) is through the CPT. The CPT architecture and code remains the property of its developers (FlowMatters Pty Ltd).

While the design of the CPT was informed through discussions with Melbourne Water staff, it was designed as a minimum viable product (MVP)[3]. This approach reduces up-front over-design while still being user-centric. The intent is that the CPT has enough functionality that Melbourne Water staff can see its potential and build their capacity in using the models (and the CPT) for scenario exploration, to inform any further development of the tool.

1.3.3 CPT@Westernport

The Westernport CPT is a 'hardwired' application of the Tool to the data and interests of Melbourne Water. It contains contextual information that describes the catchment, visualises some of the input data (e.g. land use, rainfall, topography) and presents model results at temporal and spatial scales of interest to Melbourne Water. It does not run the underlying models – rather it accesses a database of pre-run model results. It provides links to relevant literature (mainly reports) and supports dynamic updating of the contextual information. The contextual information can be updated by Melbourne Water to include additional text, for example to include additional interpretation of scenario results. This product is the property of Melbourne Water.

1.3.4 Workflows

A suite of workflows was scripted using Jupyter[4] Python notebooks to automate the 'back-end' operations. These allowed bulk changes to be made to the model, including the preparation of input

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[3] MVP – describes a product with sufficient content and functionality to be accepted by early adopters, and thus provides a testbed for learning

[4] https://jupyter.org/

data and model calibration. The notebooks also enabled batch running of the Source+*dSedNet* model to help test the system and, by modifying model parameters, produce scenarios output.

Scripts were used to run post-processing over the model output to populate the database of results for interrogation by the CPT. Using workflows ensures consistency in and transparency of the processing sequence, repeatability of the process, and enables peer review, acting as quasi-Quality Assurance/Quality control tools.

1.3.5 Data products

This section lists the significant data products produced during the project. They will be available for download through both Melbourne Water and CSIRO data warehouses. Details of methods to create these products are in Appendix B.

Model parameters not listed here used data in a close to raw form, applied global values, or used values calculated within the *dSedNet* plugin parameter generation tools and their derivation is described in Appendices A and B.

Land use

An updated land use map was created using data produced by Spatial Economics for Melbourne Water and the Victorian Department of Environment, Land, Water and Planning (DELWP), reclassified and updated with specific agricultural land use data from the Victorian Land Use Information System (VLUIS, 2014). Details of reclassification are given in Section 4.3.2.

Digital elevation model (DEM)

A 10 m digital elevation model (DEM) was obtained from Melbourne Water, resampled to 20 m and improved to increase the accuracy of stream line mapping in flat areas to represent channelling in the catchment. Catchment boundaries were then derived using a minimum threshold of 5 km^2 (based on tests using a variety of thresholds and analysis of the results).

Cover factor grids

Monthly cover factor grids were calculated from MODIS satellite-derived bare ground index (BGI) data (Paget and King, 2008) from February 2000 to May 2018. BGI data were inverted and relationships between ground cover and cover factor based on tabulated ranges for different vegetation types given in Rosewell (1993), were used to calculate cover factors for different land uses.

Gully density mapping

Gully density was calculated following a revision of active gullies in the catchment originally mapped by Hughes et al (2003). Aerial imagery acquired from 2013 to 2018 was used to identify gully activity based on visual interpretation, e.g. where a gully had sharply incised banks and/or presence of bare ground at base or edges. The density of the active gully network was calculated as length per unit area (km/km^2).

Streambank height

Bank height, i.e. the active height of streambank exposed to erosion potential, was estimated from LiDAR data using a point buffer sampling method and adjusted according to comparison with surveyed sections (DELWP, 2010).

Riparian vegetation density

Riparian vegetation proportion was calculated from tree canopy data for riparian zones (within 200m stream buffer) provided by Melbourne Water. The proportional area of tree canopy occurring per unit area was represented at 20 m resolution.

1.4 Structure of this report

The following diagram represents the inputs to the project and the products produced: arrows on the right-hand side indicate which section of the report documents the product and the processes that were undertaken. Green boxes represent the products produced by this project. White boxes are external sources and yellow is an internal process.

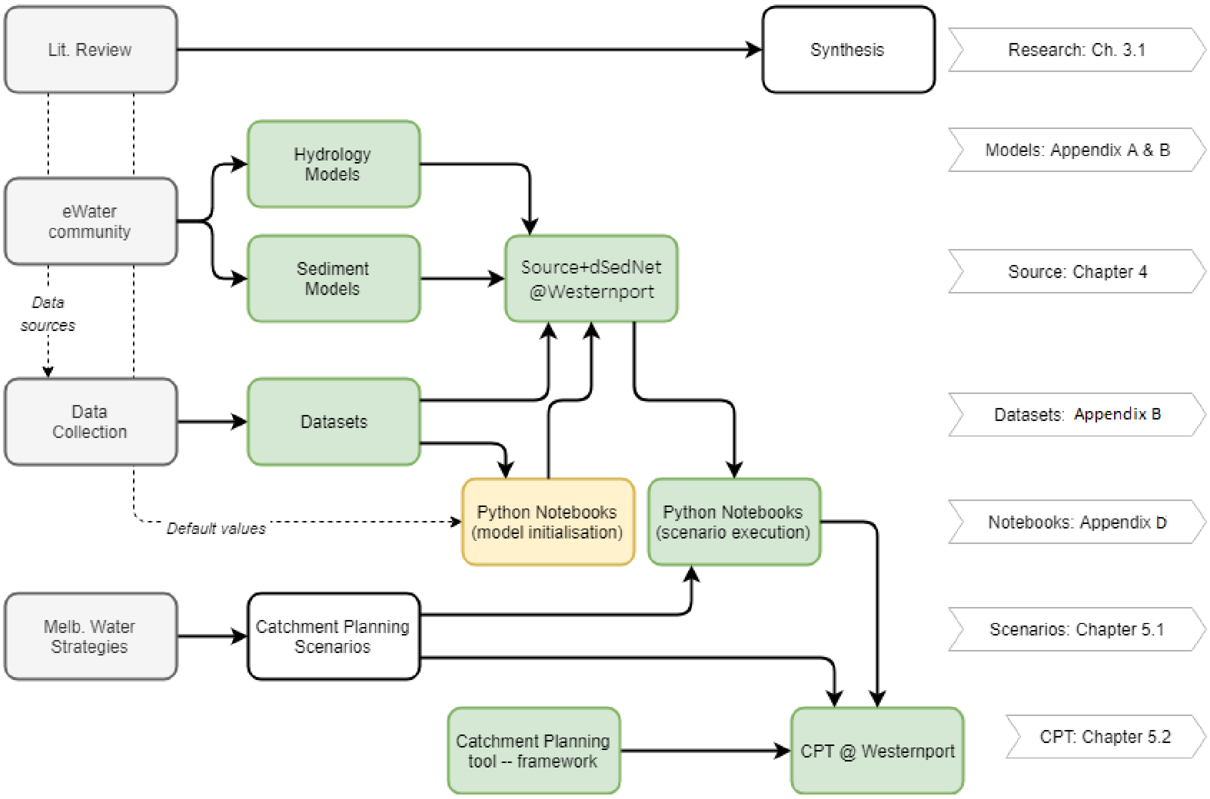

Figure 1 Structure of this report and how it relates to the components of the project and its products

1.5 Audience for this report

The target audience for this report is people who are interested in how models, specifically a combined water quantity-quality model, can be used in catchment planning. It has some technical detail as is required to provide confidence in the quality of the modelling (including its data and presentation and interpretation of its results). It is also, currently, the only reference for the most current implementation of the *dSedNet* plugin for Source, and for its application to the Westernport catchment.

2 *dSedNet* – the model

This section provides a brief outline of the historical development of *dSedNet*, and how it has been further developed and implemented in Westernport catchment.

2.1 Lineage

The original SedNet[5] process was used to model sediment budgets for river networks using long-term data sets to derive mean annual sediment loads. This was useful for understanding the overall sediment budget of river systems, but obviously was unable to resolve the temporal dynamics associated with sediment generation, transport and delivery. To resolve this, work as part of the development of Paddock to Reef models in the Great Barrier Reef catchments looked to implement a finer temporal scale model that was able to not only account for hydrologic dynamics, but also accounted for the range of other SedNet parameters that may be influenced by temporal changes. This led to the development of a 'dynamic SedNet' model (Wilkinson, et al 2014) that was able to accommodate finer temporal scales.

The *dSedNet* model is therefore an implementation of dynamic SedNet – a time-stepping spatially-distributed sediment budget model for predicting daily sediment loads in river basins. It is based on a link-node representation of a river system network. For each link in that network, the model constructs daily budgets of fine (and coarse) sediment. The budget includes the sediment sources to the link from adjoining subcatchments, and deposition and remobilisation within the link; the resulting sediment is accumulated at each catchment's outlet. A focus of this implementation was to establish a modular structure in the software which enables user flexibility by way of selecting alternate modules for sediment sources and sinks to construct sediment budgets structured to suit a particular catchment.

Erosion rates (for hillslope, gully and streambank erosion) and fine sediment sinks (floodplains and reservoirs) are calculated at each timestep, based predominately on rainfall and runoff in that timestep. Typically, the model is run on a daily timestep.

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[5] https://toolkit.ewater.org.au/Tools/SedNet . This model was a suite of ARCINFO scripts, described in Prosser et al (2001b)

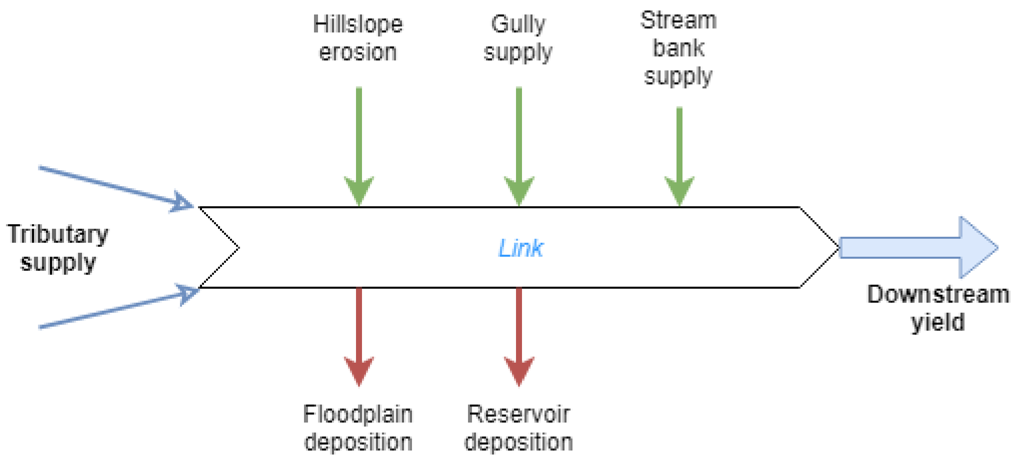


Figure 2 *dSedNet* schema [adapted from Wilkinson et al 2014]

Both dynamic Sednet, and *dSedNet,* have been implemented as plugins to Source, extending the existing behaviours and usage of Source. The constituent generation models (e.g. hillslope and gully modules) are implemented in the same manner as existing (built-in) constituent models (ie, a hillslope module is assigned to a Functional Unit; a streambank erosion model is assigned within a link), with the addition of enhanced spatial and temporal data parameterisation functionality.

2.2 Implementation in this project

The implementation of *dSedNet* to Westernport catchment is described in Section 4. A brief outline of the process is:

The model evaluates the amount of rainfall occurring at each timestep in each subcatchment within the model. This rainfall is used to calculate parameters of the hillslope component of *dSedNet* (using the Revised Universal Soil Loss Equation, or RUSLE) and also to generate subcatchment runoff. This runoff is then transported down the stream network and influences streambank supply, reservoir deposition and floodplain deposition components. Independently, the gully model is run based on long-term gully sediment supply rates calculated from spatial information (gully mapping) and specific gully parameters. The amount of sediment from this long-term calculation is then disaggregated to a daily timestep according to the flow at each timestep.

In the Westernport catchments, the proportioning of these sources is important, as the understanding of which sediment sources are likely to be contributing to the receiving environments needs to be well understood in order to develop appropriate management actions i.e. the fine sediment fraction is primary driver of poor water clarity in the bay (Hancock et al 2003).

The final adopted *dSedNet* model is shown conceptually in Figure 3.

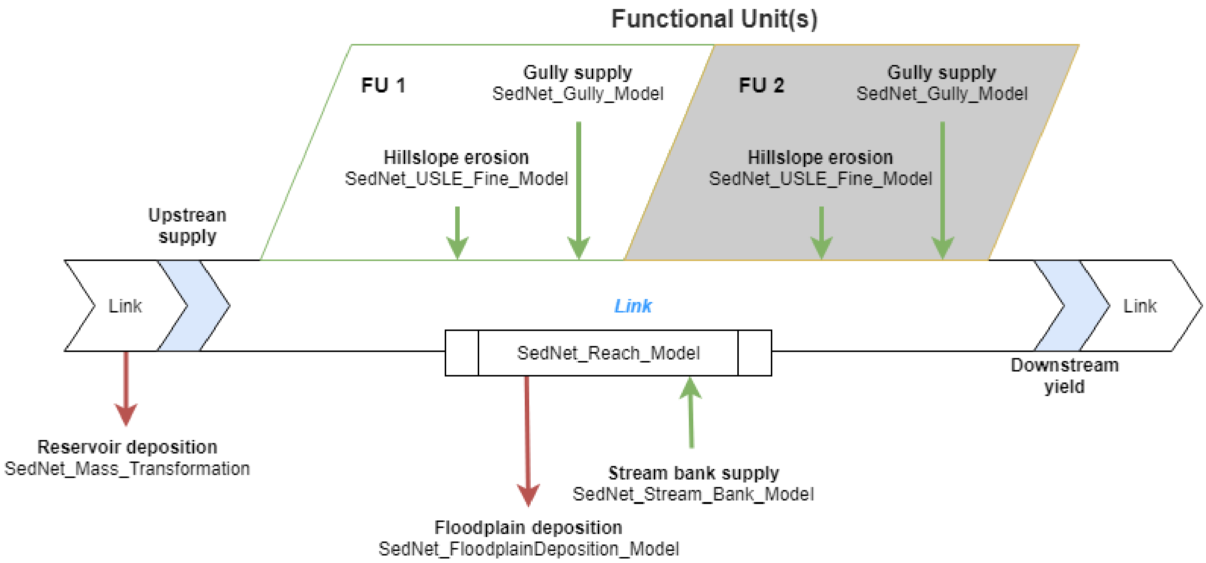


Figure 3 Final *dSedNet* model schematic

Through this project, understanding of the sources and sinks and their importance has been developed through the analysis of datasets supplied to the project team, discussions with the project team, field visits and development of the *dSedNet* model. This has highlighted the importance of understanding dynamics around vegetative cover, areas of streambank vegetation and existing streambank erosion. Consideration of the role of existing reservoirs at Cardinia and Tarago in terms of sediment trapping was also made, resulting in the development of a ‘mass transformation’ model to account for the likely attenuation within those structures (see Appendix B.6).

It should be noted that *dSedNet* is effectively a landscape model and is not suitable for modelling urban areas which do not conform to the hillslope and gully erosion processes that are embedded in *dSedNet*. The modular structure of *dSedNet* as developed here enables development and use of other erosion and deposition processes relevant to other catchments.

2.3 Enhancements made in this project

In addition to completing the coding of the streambank erosion and floodplain deposition module (the reach module) and instream and reservoir deposition modules (the gully and hillslope modules had been coded in an earlier Goyder Institute for Water Research project in the Adelaide Hills (Freebairn et al, 2015)), the team added five major enhancements to the *dSedNet* plugin (more fully described in Appendix A):

1. Ability for multiple sources, e.g. gully and hillslope, within a functional unit (FU) (previously a user could only define one process per FU)
2. Ability for parameter dependencies between generation/filter modules, i.e. a parameter in one module can be dependent on parameters from another module
3. Ability to play a time series of values to a model’s ‘input’ parameter, allowing for temporal variation in that parameter’s values (e.g. seasonal cover)
4. Ability to generate parameters for link models/modules using spatial data
5. Ability to insert a mass transform model at a link to enable simple simulation of reservoir or in channel deposition.

3 An overview of Westernport catchment and earlier sediment studies

Westernport catchment occupies an area of 3755 km2 where waterways support a variety of uses and values, and where source and groundwater springs support many streams, estuaries and wetlands (Melbourne Water 2018b). The marine ecosystem in Western Port is of regional, national and international importance (Melbourne Water 2011, 2018a), representing an UNESCO Biosphere reserve and being in the Ramsar convention listing for migratory waterbirds. It contains a variety of habitats (including mangrove, saltmarsh, mudflats, seagrass meadows and rocky reefs), which support diverse species including fish, marine invertebrates and mammals (ibid).

Over the past 200 years, the environment of Western Port and the Westernport catchment has undergone significant change, such as catchment and coastal vegetation clearing, draining of large areas of swampland (e.g. the expansive former Koo Wee Rup swamp) and a progressive growth of agricultural, industrial and residential areas (Melbourne Water 2011, 2018b).

Land use in the Westernport catchment has gradually been urbanised and more areas are projected to become developed. Cardinia and Casey shires are identified for their remarkably fast population growth and the rate of urban expansion in the Pakenham-Cranbourne growth area identified as being the fastest in the State (Melbourne Water, 2011). At present, most of the catchment supports rural and green wedge land uses, though there are still some significant areas of remnant vegetation. Primary industries in the catchment include dairy farming, beef production, poultry, horticulture and quarrying. Urban development, industrial zones, tourist development, lifestyle and hobby farms represent a smaller proportion of the area.

Additionally, the continued urban development expansion in the catchments, and projected changes in climate that will influence rainfall patterns, together with water temperatures and sea level rise, will impose pressures on the health of the bay and the Westernport catchment (Melbourne Water 2018a).

Catchment sediment supply is identified as a causal stressor impacting water quality in the bay, with potential to affect estuarine, coastal and marine vegetation (e.g. seagrass), as well as other habitats within streams and wetlands in the Westernport catchment (Wilkinson et al 2016a; Melbourne Water 2011, 2018a). Causal interactions and the effects of sediment supply on water turbidity, water clarity and quality were explored by Wallbrink et al (2003b) and Wilkinson et al (2016a), both investigations driven by a significant loss of seagrass detected along segments of the bay (further discussed below).

In the 2018 Melbourne Water summary of research findings under the Western Port Environment Research Program, catchment sediment supply was identified to have reduced in recent years, with an estimated mean annual suspended solid delivery from the catchment into Western Port of 23.8 kilotonnes/year since 1980 (Section 2, Melbourne Water 2018a). However, a key action to improving water quality to levels suitable for seagrass maintenance and restoration has been set to restrict sediment loads (from the catchment as well as the coastline, a mean of 4.2 kilotonnes/year (Tomkins et al 2014) to less than 28 kilotonnes/year within the new State Environment Protection Policy (Victorian Government 2018)). Therefore, improving the management of catchment loads is a priority for the Western Port environment as it reduces further sediment deposition and remobilisation of fine material (Melbourne Water 2018a).

Maintaining water quality entering the bay through adequate catchment management is also critical for maintaining fish biodiversity and sustaining recreational fishing in Western Port (Section 7, Melbourne Water 2018a, notes that the Rhyll Segment is an area of high fish-catch rates for most fish species and is strongly influenced by water quality from the north and north east parts of the catchment).

One priority for further research recommended in that same analysis (ibid) was to monitor river loads to carry out modelling of fine sediment and nutrients (with a catchment model such as Dynamic SedNet) to inform erosion management and to facilitate evaluating the effect of potential changes in management on sediment loads.

Some of the goals for the Westernport catchment listed in The Healthy Waterways Strategy 2018-2028 (Melbourne Water 2018b) include:

- that the waterways and their estuaries across the catchment are managed to maintain and improve coastal and marine ecosystems in Western Port
- that water quality and sediment impact from urbanisation, forestry, agriculture, industry and transport are mitigated to reduce impacts on waterways and the receiving ecosystem of Western Port
- that natural and modified waterways across the catchment are managed for instream habitats, long term ecological resilience and fluvial processes; balancing the needs for flood mitigation, agriculture water diversion, and social value
- that flow management of waterways are improved to protect groundwater dependent ecosystems, base flows and environmental flushing flows to sustain instream ecosystems.

Capturing the linkages between sediment supply and redistribution processes with land cover and land use change, our study focuses on establishing the sediment budget in the Westernport catchment. We identify the proportional relevance of catchment sediment sources supplied from gully, hillslope and streambank erosion as well as for in-stream deposition in reservoirs and floodplains.

Thus, our study contributes to identifying priorities and supports planning of the most effective management actions in the Westernport catchment including the identification of cost effective actions that are most likely to achieve the State Environment Protection Policy sediment load target of <=28 kilotonnes/year (Victorian Government 2018), with the view of minimising risks to the critical ecological processes of the bay. In relation to this, Melbourne Water (2018b) has already considered that an adequate rural land program in the Westernport catchment would support minimising sediment and nutrient loads, for example, to the estuary of Cardinia Creek (p 57 of the Strategy). Capturing Melbourne Water's knowledge and appreciation of the catchment, we explored different management and development scenarios for Westernport (Section 5.1).

3.1 Previous estimations of sediment sources

Sediment re-distribution processes in the Westernport catchment include those of Hughes et al (2003), Wallbrink et al (2003b), and Wilkinson et al (2016a). We have considered them to compare our results and to calibrate the implementation of the Westernport catchment model.

Using SedNet modelling, geochemistry to investigate providence, radionuclide tracing to establish sediment accumulation in the bay and available information from the literature, Hughes et al (2003) identified the type of erosion source (either subsoil or surface) and erosion processes occurring in nine major catchments of Westernport and the bay.

Their results suggest that the two most important sediment sources in the catchment are from streambank and gully erosion of subsoil (Table 1). They found that their SedNet-derived estimates compared well with those obtained from trace geochemistry, and identified the Bunyip and Lang Lang Rivers as the major sources of sediment (silt and clay) (Figure 4 and Table 2).

Table 1 Source, erosion processes and status as identified in Wallbrink et al (2003a)

Source	Status	Erosion source	Erosion process	Short term recommendation / action	Long term recommendation / action
Clay banks	Major	Shoreline erosion	Slumping/wave attack	Stabilisation	Re-establishment of mangroves
Bunyip River	Major	Subsoil	Bank erosion Gully erosion (Ratio 68:32[a])	Stabilise banks	Reconnect channel to floodplains: re-establish and manage riparian corridors
Lang Lang River	Major	Subsoil	Bank erosion Gully erosion (Ratio 39:61)	Stabilise gullies	Re-establish and manage riparian corridors
Cardinia Creek	Major[b]	Subsoil	Bank erosion Gully erosion (Ratio 75:25)	Stabilise banks	Reconnect channel to floodplains: re-establish and manage riparian corridors
Bass River	Minor	Subsoil	Bank erosion Gully erosion (Ratio 80:20)	Stabilise banks	Re-establish and manage riparian corridors
Unsealed Roads	Minor	Surface	Mechanical action/Surface washoff	Improve roadside drainage to buffers	Establish buffers around runoff rains
Yallock Creek	Minor	Subsoil	Bank erosion Gully erosion (Ratio 54:46)	Stabilise gullies	Reconnect channel to floodplains: re-establish and manage riparian corridors
Bass River	Minor	Surface soil	Sheet and rill erosion	Investigate land uses	Improved land management and re-establishment of riparian corridors
Lang Lang Cliffs	Minor	Subsoil	Mechanical failure /wave attack	Natural	

[a] Ratio between bank erosion yield and gully erosion yield within that tributary sub-catchment derived from Tables 2 and 3 in Hughes et al (2003).

[b] Status derived from the geochemistry data, although SedNet results indicate that this is the least important of the major sources

Hughes et al (2003) results contributed to the construction of a suspended sediment and bedload budget for the Westernport catchment and its bay. Their modelled sediment budget for the catchment predicted that over 60% of the sediment delivered to streams is exported to the Bay, the rest is stored on floodplains or on waterways beds.

They also determined sediment storage in the catchment: 1% deposited in dams, 18% along the floodplains (we assume these would be finer sediment fractions), and 40% stored in the channels (we assume these would be coarser sediment fractions (as described in Hughes et al (2003) page 24)).

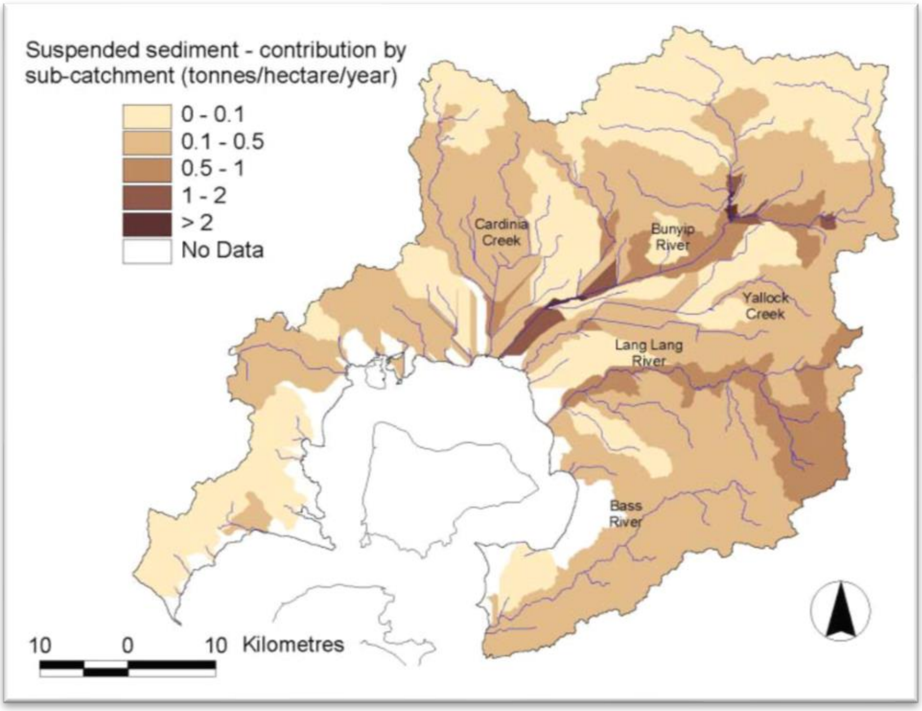


Figure 4 Predicted suspended sediment contribution to the Bay by catchment, from Hughes et al (2003), (Figure 11, p32)

Table 2 The total suspended sediment export from the main Western Port catchments as predicted with SedNet by Hughes et al (2003) (reproduced from Table 5, p26)

Watershed	Area (km^2)	Total suspended sediment export (kilotonnes/yr)	Rank by load	Suspended sediment yield per unit area (tonnes/ha)	Rank by yield
Bass River	266	8	3	0.30	2
Bunyip River	890	22	1	0.25	3
Cardinia Creek	398	6	5	0.15	5
Lang Lang River	423	20	2	0.47	1
Yallock Creek	286	6	4	0.21	4
TOTAL	2263	62			

Later analysis of these results by Wilkinson et al (2016a) indicated that this over-estimation was likely due to model assumptions, including a linear rate of gully network expansion.

Wilkinson et al (2016a) identified streambank as the largest form of erosion in the catchment (using SedNet, not *dSedNet*). Runoff delivering topsoil was also identified as being another important source. They concluded that, in the bay, sediment resuspension by tides and wind driven waves is the largest impact on particulate concentrations and water clarity at sub-daily to annual time-series, but additionally, ongoing episodic river inputs elevate the background levels of turbidity for months to years.

Wilkinson et al (2016a) reported that load estimates for recent decades have generally been lower than earlier decades, and postulated that this was consistent with stabilisation of the river channels since the 1970s. Prior to the 1980s, a phase of accelerated river channel erosion occurred, presumably due to river channelisation and floodplain drainage. They estimated:

- an annual total suspended solid load of 12.9 kilotonnes/year over the period 2001-2014
- the sum of the four river stations they used (i.e. Bunyip and Lang Lang and Bass Rivers, and Cardinia Creek) to be 17.7 kilotonnes/year in the period 1980–2014
- the river total suspended solid export to the Western Port bay to be 23.8 kilotonnes/year (ibid).

Using total suspended solids data from gauges of the four of the largest contributing catchments to the bay, Wilkinson et al (2016a) established the contributions of each subcatchment to the total river suspended solids load, in decreasing order below:

- Lang Lang with 41%
- Bunyip with 31%
- Bass with 16%
- Cardinia with 12%.

Their estimates are based on Total Suspended Solids, which would presumably be higher than the suspended sediment proportion (given that total solids accounts for additional undissolved particulate matter, e.g. organic matter).

In our study, we take as a premise that suspended sediment is supplied to a river link from four sources: streambank erosion, gully erosion, hillslope erosion and tributary inputs of suspended sediment yield.

Importantly, in their analysis Wilkinson et al (2016a) suggest future studies to continue developing sediment load modelling of the waterways in the Westernport catchment by implementing a catchment model such as *dSedNet*, which can be associated to land uses and sources of sediment. They considered that such an exercise would contribute to inform and identify priorities for erosion management, and even help evaluate the effect of related changes in management. The Catchment Planning Tool (CPT) is designed under that view (see Section 5.3).

Whilst contributing to the development of *dSedNet*, our project complements the existing sediment modelling studies. Additionally, the Catchment Planning Tool (CPT) supports decision making through exploring simulated responses under diverse development, planning and management scenarios in the catchment.

4 Source+*dSedNet*@Westernport

This section describes the baseline implementation of the model (Source+*dSedNet*) for the Westernport catchment. In this context, the term 'baseline' means that the model is configured using 'current' data and is the implementation of the model that is calibrated against observed data. Other model configurations to support catchment planning, e.g. to simulate a change in land use, or application of a management intervention, are configured as 'scenarios' and these are described further in Section 5.1. This section provides information on:

- How the system was conceptualised for modelling
- How the catchment was characterised for modelling
- Data requirements and how they were met
- Hydrology (rainfall-runoff) modelling (set up and performance evaluation), using SIMHYD
- Sediment modelling (set up and performance evaluation), using *dSedNet*.

4.1 Pilot catchment testing

The Bunyip River catchment was selected as a pilot to test data inputs, model schematisation and model performance before scaling out to the whole of Westernport. This catchment was selected as a pilot because it has a relatively good spread of flow gauges, the upper parts of the catchment are useful to test hillslope and channel erosion, and it contains areas of gully erosion.

The results of the pilot are reported in an internal progress report to Melbourne Water (CSIRO 2018) which is available on request to the authors or Melbourne Water.

After the development of the Bunyip pilot, operationalising *dSedNet* across the catchments draining to Western Port meant refining and redeveloping components from the existing Port Phillip and Western Port (PP-WP) catchment Source model. The PP-WP Source model has been developed over several years by Melbourne Water and the Department of Environment, Land, Water and Planning (DELWP) and the intention of this project was to ensure that the models developed were consistent in terms of hydrology, catchment boundaries, climate and land use.

4.2 System conceptualisation

The major catchments of Bunyip, Cardinia, Lang Lang and Bass waterways drain into the estuarine/marine receiving waters of Western Port, with other smaller creeks and local drainage also contributing. Generally, the larger catchments drain from the Dandenong Ranges and Bunyip State Park in the North and across large alluvial floodplains before discharging into the bay. Figure 5 illustrates this with the Dandenong Ranges in the far background with the large flat floodplain areas also shown.

Figure 5 Looking over the catchments of Western Port, with the Dandenong Ranges in the background (Photo credit: Tony Weber)

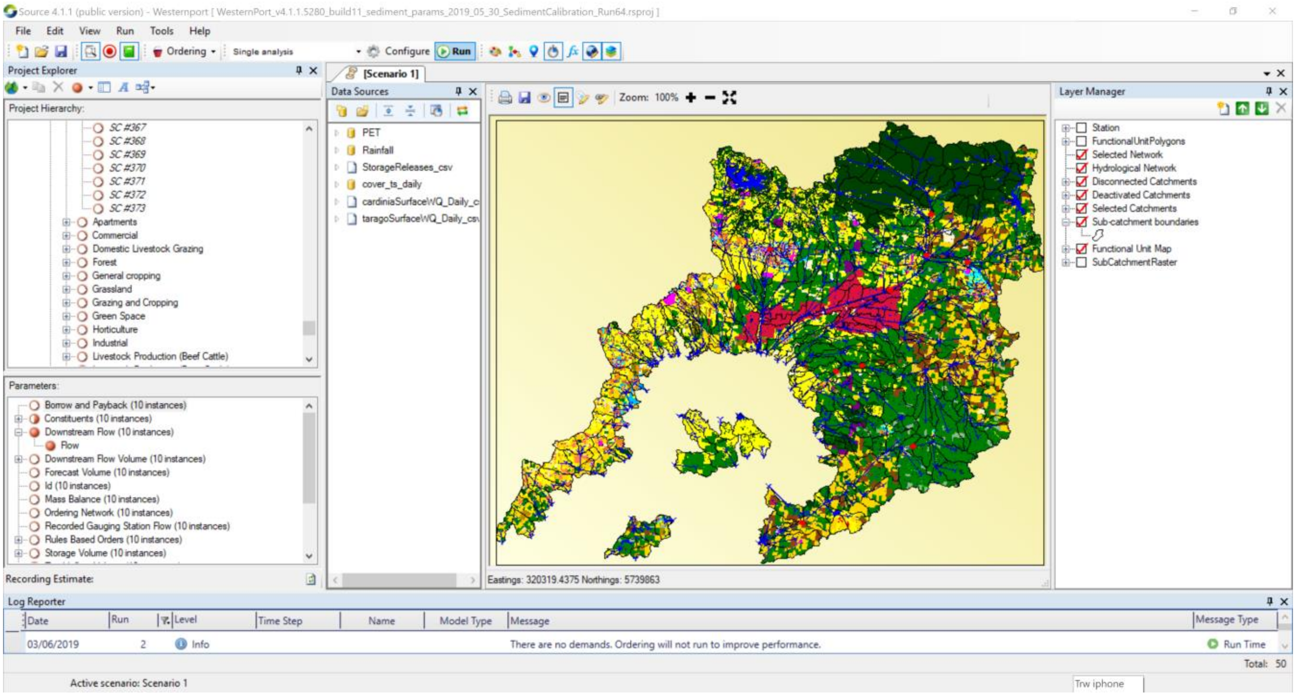
In developing the catchment model, particular attention was given to ensuring model performance for both the steeper terrain and flatter areas were properly represented, especially in the constructed drainage lines around the lower areas. Of key concern was ensuring adequate representation of the anthropogenic channelisation and interconnectivity of the former Koo Wee Rup swamp and the combined major basin outlets where multiple rivers flow in parallel through a combined drainage channel, each remaining relatively isolated from the other through channels and levees. This required significant attention to the analysis of the digital elevation model to derive appropriate subcatchments that remained aligned to the drainage channels.

We assumed that existing land use characterisation was suitable to conceptualise differences in hydrologic response across the basin (Section 4.3.2), though this was also enhanced through rainfall heterogeneity being accounted for through using gridded daily rainfall.

4.3 Catchment characterisation

A total of 373 subcatchments were derived from a pit-filled and stream burned DEM (Appendix B.1). The model conceptualisation was checked against the subcatchment boundaries of the Port Phillip and Western Port (PP-WP) model to ensure consistency, the same DEM and land use datasets were used in both models. A screenshot of the developed model is shown in Figure 6 .

Cardinia and Tarago water supply reservoirs were included in the model as inflow nodes with a daily timeseries of storage releases, provided by Melbourne Water.


Source 4.1.1 (public version) - Westernport [WesternPort_v4.1.1.5280_build11_sediment_params_2019_05_30_SedimentCalibration_Run64.rsproj]

Log Reporter

Date	Run	Level	Time Step	Name	Model Type	Message	Message Type
03/06/2019	2	Info				There are no demands. Ordering will not run to improve performance.	Run Time

Total: 50

Active scenario: Scenario 1

Eastings: 320319.4375 Northings: 5739863

Figure 6 Screen shot of Westernport model implemented in Source, showing the stream links as blue lines, with other colours showing land uses

4.3.1 Catchment delineation

Consistency has been retained between catchments boundaries created with the DEM and the larger spatial resolution of subcatchments delineated for the current revision of the PP-WP Source model, being refined by Jacobs for Melbourne Water and DELWP (Jacobs, 2019). Figure 7 illustrates the smaller subcatchment sizes developed for the *dSedNet* Westernport model in comparison to the regional scale of the PP-WP Source model, but alignment between the models has been maintained. Smaller subcatchments were used to disaggregrate key areas in finer detail, such as the complexity of the Koo Wee Rup drainage area, but also to provide smaller 'planning units' to allow some better resolution of the spatial locations of sediment sources. The subcatchment is the smallest spatial unit in the Source model, as any other spatial information such as land use or vegetation data is used to 'lump up' results as an overall subcatchment input. The size of the subcatchment then dictates the smallest spatial unit available to discretise catchment loads and sources.

Figure 7 Revised finer resolution Westernport Model subcatchment delineation (left) compared to coarse resolution subcatchment delineation for the regional Port Phillip and Westernport Source model (middle). On the right is the two model subcatchment boundaries overlayed illustrating consistency between the two models

4.3.2 Land use and functional units (FU)

Land use data produced for Melbourne Water and DELWP by Spatial Economics as used in the Port Phillip and Westernport Source model (under revision by Jacobs) was initially adopted. To suit the range of anticipated scenarios, land use groupings were reclassified to include more detail for agricultural land uses, using the Victorian Land Use Information System (VLUIS) 2014 dataset (VLUIS, 2014).

Land use types of interest identified by project stakeholders – the potential for land management for livestock production classes (including dairy cattle, beef, and sheep), and several specific crop classes – were extracted from the dataset and used to update the Spatial Economics land use data for the Westernport catchment. These classes in the VLUIS data coincided with the broader grazing and cropping classes in the Spatial Economics land use data. The combined Spatial Economics and VLUIS land use data were resampled to match the extent and resolution of the 20m DEM data.

A summary of the land use classes and their areas with the Source+*dSedNET*@Westernport model is given in Table 3 and shown in Figure 8.

Table 3 Land use classes adopted for mapping FUs in the Source+*dSedNet*@Westernport model

Land use	Area (km2)
Grazing and Cropping	957.5
Grassland	619.6
Forest	541.5
Livestock Production (Beef cattle)*	388.7
Road	141.5
Livestock Production (Dairy cattle)*	129.1
Horticulture	124.4
Water	114.0
Low Density Residential	75.4
Agricultural Industry	43.7
Green Space	28.5
Domestic Livestock Grazing*	24.5
Market garden*	22.1
Quarry	16.8
Vineyard*	15.9
Residential Other	15.0
Other	12.5
Industrial	10.4
Public Use	9.7
Livestock Production (Sheep)*	9.0
Railway	7.8
Orchards, groves and plantations*	7.3
Medium Density Residential	5.9
Commercial	3.5
Specialised cropping*	3.4
General cropping*	3.0
Plantation	0.8
Apartments	<0.1

*Additional landuse classification included for the *dSedNet* model from VLUIS land use data (VLUIS, 2014)

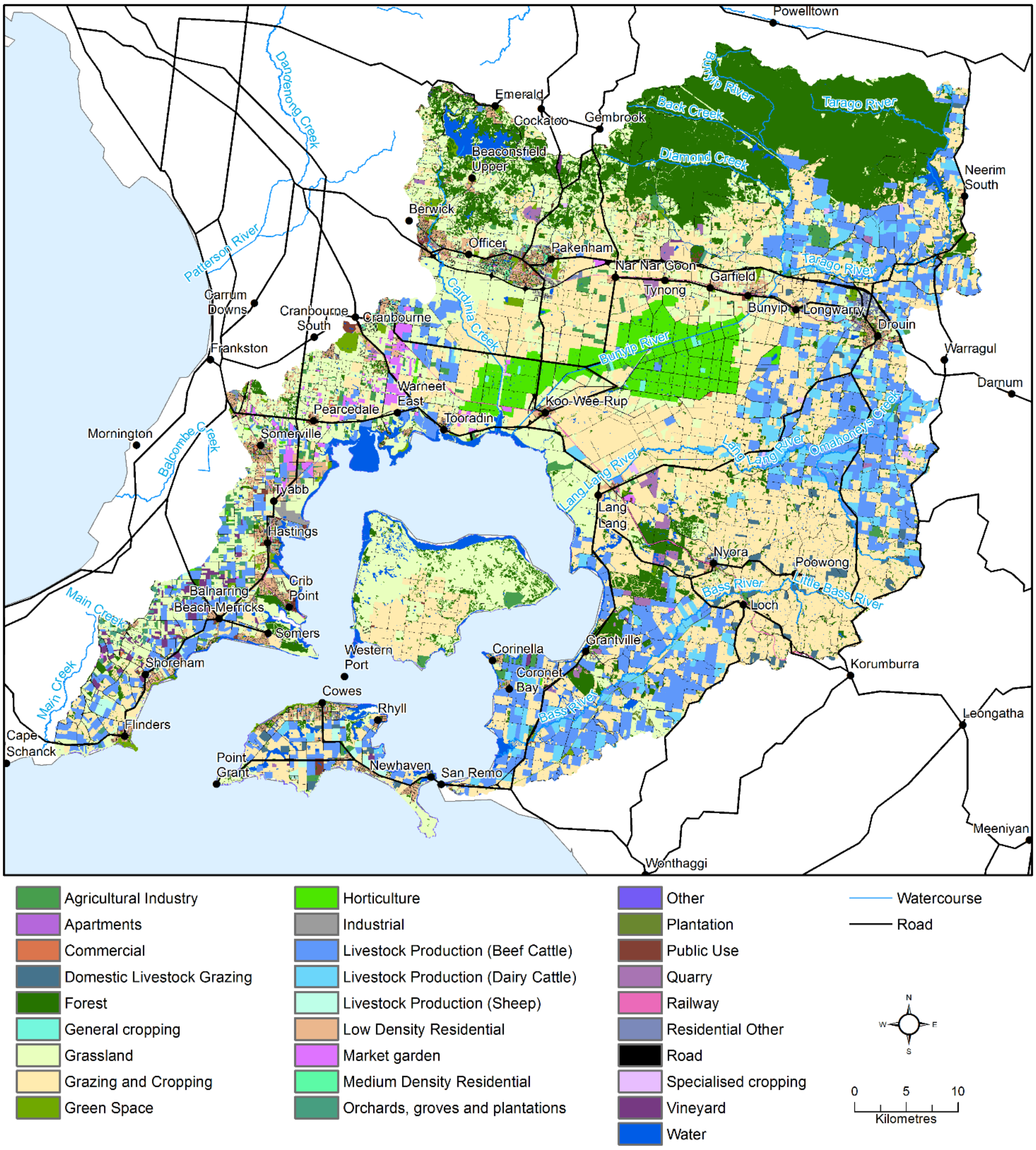


Figure 8 Map of land uses in Westernport catchment as used in Source+*dSedNet*@Westernport

This land use map is a data product from the project and is available on request from Melbourne Water.

4.3.3 Climate

The Bureau of Meteorology's Australian Water Availability Project (AWAP) gridded daily rainfall and Climate Atlas of Australia Monthly PET data were used to maintain alignment with the Port Phillip and Westernport Source model development. Gridded rainfall data spanning the full modelling simulation period, Jan 1968 to Dec 2016 were included.

Figure 9 illustrates the mean annual rainfall distribution across the both the Port Phillip and Westernport catchments, as derived from subcatchment-averaged AWAP data.

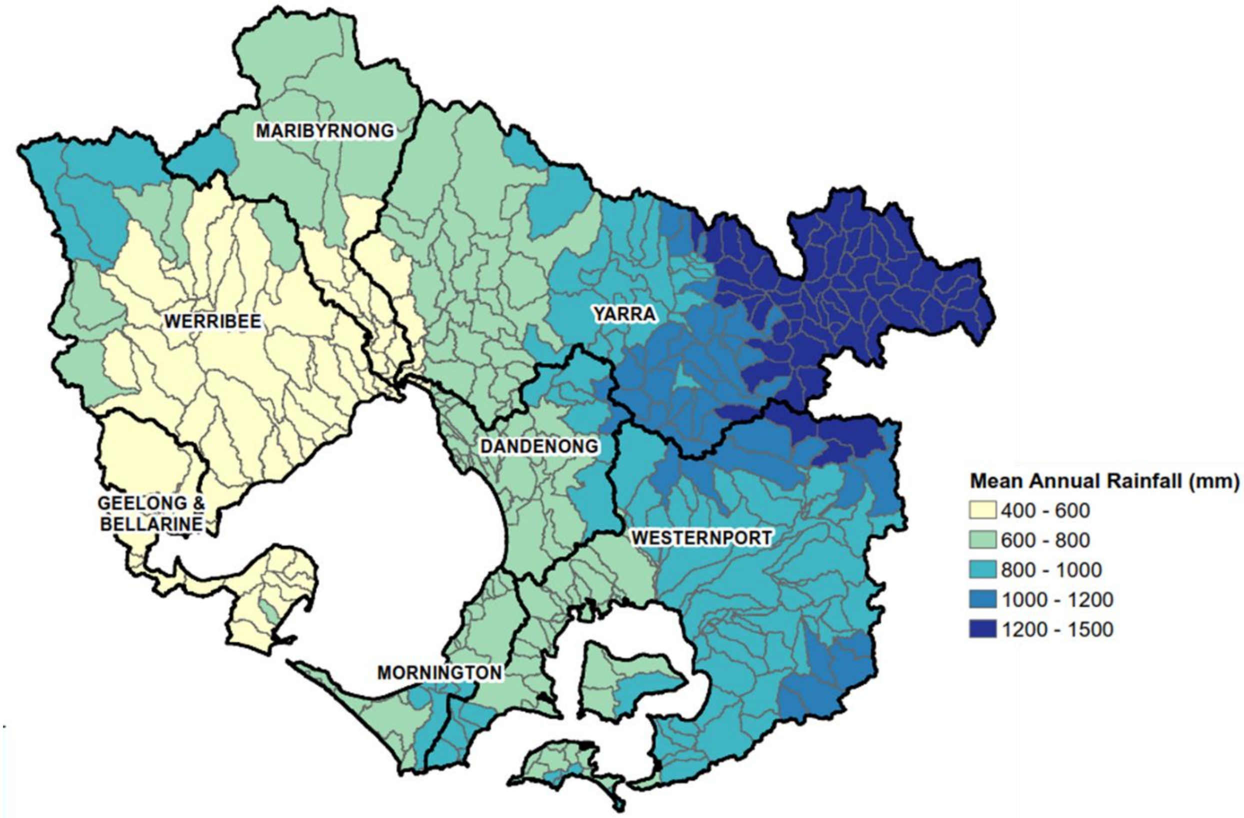


Figure 9 Climate (mean annual rainfall) map (from PPB-WP catchment model)

4.4 Rainfall-runoff modelling

4.4.1 Model set up

The primary driver of constituent generation and transport processes in a catchment is rainfall-runoff, so the configuration, calibration and validation of a suitable rainfall-runoff model is vital for a robust representation of catchment processes. Once runoff and associated constituents are generated in the model, the flows and constituent loads are delivered to a downstream link which, in the case of *dSedNet*, then allows determination of streambank and instream processes.

For Source+*dSedNet*@Westernport, the SIMHYD rainfall-runoff model was used to describe the conversion of rainfall into runoff (Chiew et al 2002). SIMHYD is a simplified version of the daily conceptual rainfall-runoff model, HYDROLOG, (see Porter 1972; and Porter & McMahon 1975) and the more recent MODHYDROLOG (Chiew & McMahon 1991). SIMHYD is a 'bucket' style model, as shown in Figure 10, with enough complexity to deal with the range of hydrologic responses which occur over a continuous time period. It is automatically installed with Source[6] and has been used in many applications across Australia, particularly where urban areas are likely to be important.

The SIMHYD rainfall-runoff model was retained for all functional units (FUs). Initially, consistent hydrologic parameters from the Port Phillip and Westernport (PP-WP) Source model were used to parameterise the SIMHYD models for the Westernport model. However, due to the finer resolution of subcatchments compared to the regional PP-WP model, some of the large flooding flows became underestimated. The simulation of peak sediment events is a key focus of the Westernport model

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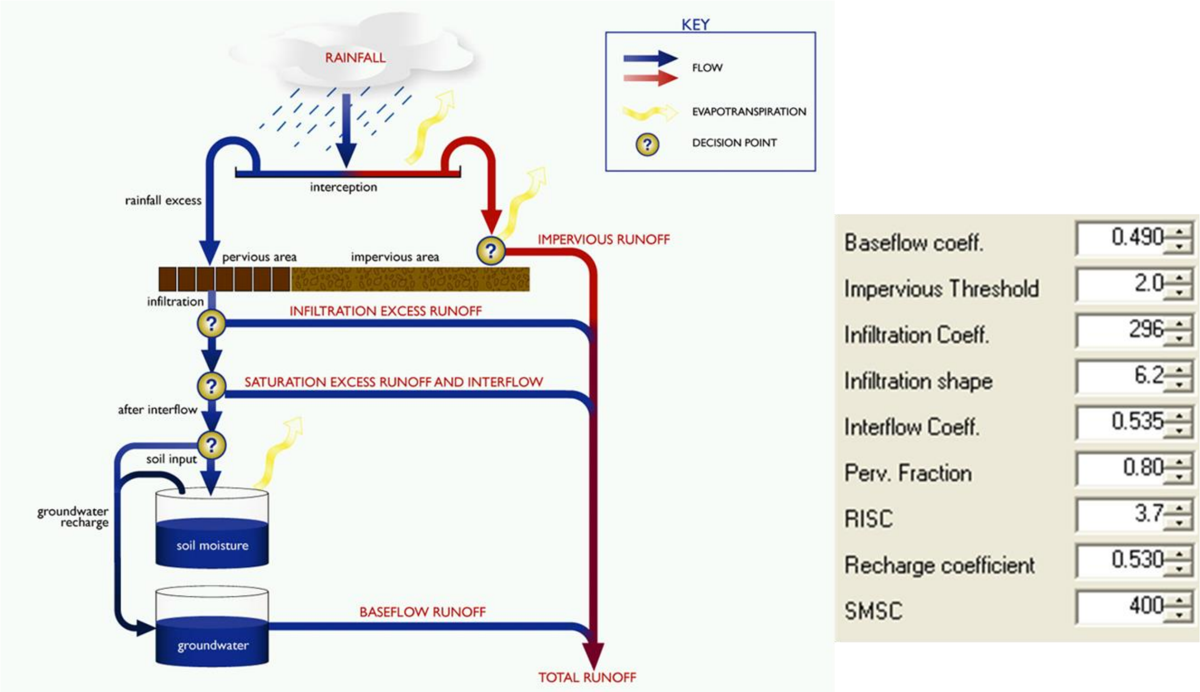
[6] SIMHYD within Source is well described in https://wiki.ewater.org.au/display/SD41/SIMHYD+-+SRGIt

calibration process as the assessment of suspended sediment loads will be driven by peak flow events within the catchment, and a good sediment load calibration is highly dependent on achieving a good flow calibration. Therefore, some adjustments to the hydrological parameters were warranted:

- Routing models were set to straight-through routing (e.g. any observed attenuation of flows would occur within less than a day). This was necessary because the observed attenuation of flows at the links specified in the Source+*dSedNet* model would occur within less than a day and hence the effect of flow routing was unlikely to be significant.
- Baseflow coefficient, Infiltration coefficient, Recharge coefficient, Infiltration shape and Rainfall Interception Store Capacity parameters were tuned to achieve a better fit to observed higher flows rather than focussing on baseflow and low flows.
- Model estimation of peak flows was favoured over achieving a good model fit to baseflows or low flows.
- Regionalisation of SIMHYD parameters followed the same methodology as per the PP-WP Source model.

In some cases, these parameter changes resulted in a poorer model fit to baseflows and low flows in favour of better estimation of peak flows.



Baseflow coeff.	0.490
Impervious Threshold	2.0
Infiltration Coeff.	296
Infiltration shape	6.2
Interflow Coeff.	0.535
Perv. Fraction	0.80
RISC	3.7
Recharge coefficient	0.530
SMSC	400

Figure 10 The SIMHYD rainfall-runoff model [Source: https://wiki.ewater.org.au/display/SD49/SIMHYD+-+SRGIt]

The final SIMHYD parameters are given in Table 4. Impervious fraction parameters from the PP-WP Source model have been retained in Source+*dSedNet*@Westernport (Table 5) for representation of hard surfaces in land uses associated with urban areas.

Table 4 Source+*dSedNet*@WesternPort SIMHYD parameters for the four catchments used for calibration

Metaparam	SIMHYD Parameter	LangLang	Bass	Cardinia	Bunyip
Urban	Baseflow coefficient	0.30	0.30	0.30	0.30
Urban	Impervious Threshold	2.00	2.00	2.00	2.00
Urban	Infiltration coefficient	100.00	100.00	100.00	100.00
Urban	Infiltration shape	6.60	6.60	8.95	7.38
Urban	Interflow coefficient	0.69	0.85	0.20	0.44
Urban	Rainfall Interception Store Capacity	3.50	3.50	3.50	3.50
Urban	Recharge coefficient	0.10	0.10	0.10	0.10
Urban	Soil Moisture Storage Capacity	290.32	440.76	345.72	447.93
Forest	Baseflow coefficient	0.30	0.30	0.30	0.30
Forest	Impervious Threshold	2.00	2.00	2.00	2.00
Forest	Infiltration coefficient	100.00	100.00	100.00	100.00
Forest	Infiltration shape	3.50	3.50	1.00	4.86
Forest	Interflow coefficient	0.25	0.92	0.18	0.001
Forest	Rainfall Interception Store Capacity	3.50	3.50	3.50	3.50
Forest	Recharge coefficient	0.10	0.10	0.10	0.10
Forest	Soil Moisture Storage Capacity	344.55	420.94	351.90	336.60
Rural	Baseflow coefficient	0.30	0.30	0.30	0.30
Rural	Impervious Threshold	2.00	2.00	2.00	2.00
Rural	Infiltration coefficient	100.00	100.00	100.00	100.00
Rural	Infiltration shape	3.00	3.00	1.58	3.25
Rural	Interflow coefficient	0.45	0.04	0.05	0.23
Rural	Rainfall Interception Store Capacity	3.50	3.50	3.50	3.50
Rural	Recharge coefficient	0.15	0.30	0.11	0.07
Rural	Soil Moisture Storage Capacity	478.52	247.29	450.00	439.90

Table 5 Functional unit types and imperviousness fractions

Land use	EIA [7] Factor	Land use	EIA Factor
Agricultural Industry	0.3	Grassland	0.06
Commercial	0.54	Grazing and Cropping	0.06
Industrial	0.54	Green Space	0.06
Apartments	0.51	Other	0.3
Low Density Residential	0.36	Horticulture	0.06
Medium Density Residential	0.45	Public Use	0.42
Residential Other	0.45	Quarry	0.12
Railway	0.42	Forest	0
Road	0.39	Plantation	0.06

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[7] Effective Impervious Area fraction (EIA)

4.4.2 Model calibration

Fine tuning SIMHYD parameters focused on the four main flow gauges that coincided with good quality sediment data and load estimates from Wilkinson et al (2016a):

- 228209 - Lang Lang River at Hamiltons Bridge
- 227231 - Bass River at McGraths Rd
- 228213 - Bunyip River at Iona
- 228228 - Cardinia Creek at Chasemore Rd.

Figure 11 illustrates the location of the key flow and sediment calibration gauges.

The rainfall-runoff models were calibrated at a daily time step. Split-sample calibration/validation was adopted with the calibration period chosen generally from 1990 to 2016, and validation period 1989 to earliest period of record for each gauge (with at least 10 years of data for validation).

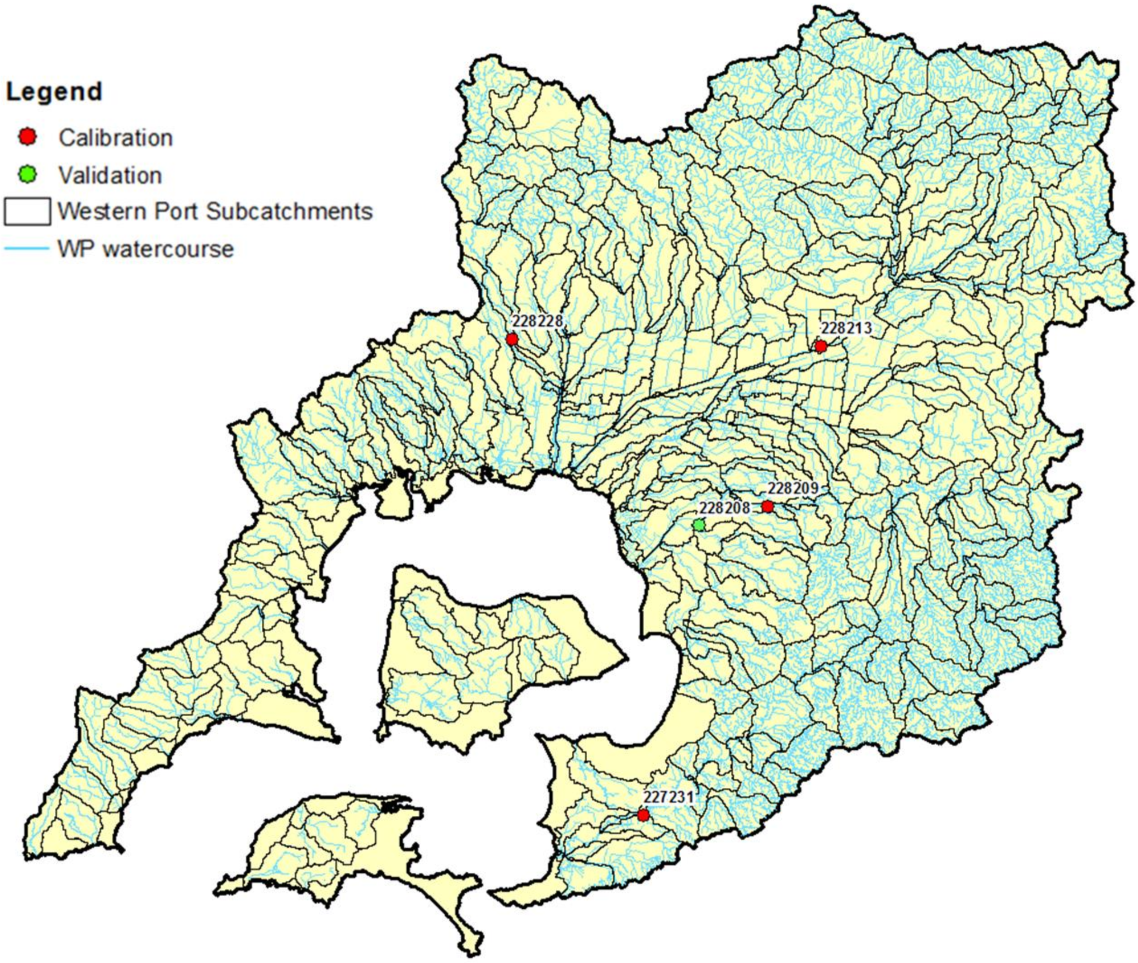

Figure 11 Location of the four gauged flow sites within Westernport catchment, used for model calibration

4.4.3 Calibration performance

Performance measures

There are many approaches to evaluating model performance, however there is general acceptance of the approaches recommended in Moriasi et al (2007) and the subsequent revision in Moriasi et al

(2015). In those articles, a number of metrics are proposed for assessing hydrologic models, of which we selected NSE and PBIAS. How their measurements match with performance indicators is given in Table 6, followed by a short description of their classification (performance indicator classes), as used for this calibration.

Table 6 General performance ratings for model statistics for a monthly time step –streamflow (adapted from Moriasi et al 2007)

Performance rating	PBIAS (%) streamflow	NSE
Very good	PBIAS < ±10	0.75 < NSE ≤ 1
Good	±10 ≤ PBIAS < ±15	0.65 < NSE ≤ 0.75
Satisfactory	±15 ≤ PBIAS < ±25	0.5 < NSE ≤ 0.65
Poor	PBIAS ≥ ±25	NSE ≤ 0.5

The Nash-Sutcliffe model Efficiency (NSE) coefficient is used to assess the predictive power of hydrological models. An efficiency of 1 corresponds to a perfect match of modelled discharge to the observed data. An efficiency of 0 indicates that the model predictions are only as accurate as the mean of the observed data. An efficiency of less than 0 occurs when the observed mean is a better predictor than the model. We used this summary statistic, based on daily flows.

Percent bias (PBIAS) measures the average tendency of modelled data to be greater or less than the corresponding observed data. We used this summary statistic, based on % difference between modelled and gauged mean daily flow (where a positive % bias indicates underestimation and negative % bias indicates overestimation compared to observed).

Additionally, we compared modelled and observed mean annual flow (MAF) of each gauged dataset, and conducted a visual inspection on daily flow timeseries plots, flow duration curves, and cumulative daily flow to evaluate hydrologic model response.

In summary, we used two performance measures (NSE and PBIAS), mean annual flow (MAF) and visual inspection to evaluate the performance of the SIMHYD rainfall-runoff model.

Performance evaluation

A summary of the evaluation results is presented in Table 7 and comparisons between modelled and observed flows as timeseries and flow duration curves (FDCs) are presented in Figure 12 to Figure 15. The summary statistics (NSE and PBIAS) illustrate that the model performance against measured streamflow data meets the good to satisfactory evaluation criteria (as defined in Moriasi et al 2007) in most cases.

Table 7 Summary statistics on SIMHYD model performance

Flow Gauge site		PBIAS (%)	NSE	Observed MAF (ML/d)	Modelled MAF (ML/d)
228209 Lang Lang River at Hamiltons Bridge	Calibration	5% (v. good)	0.65 (good)	136	130
228208 Lang Lang River at Lang Lang	Site Validation	10% (good)	0.65 (good)	192	172
227231 Bass River at McGraths Rd	Calibration	-3% v. good)	0.53 (satisfactory)	126	130
	Validation	13% (good)	0.71 (good)	158	138
228213 Bunyip River at Iona	Calibration	-19% (satisfactory)	0.55 (satisfactory)	294	350
	Validation	-25% (satisfactory)	0.67 (good)	288	360
228228 Cardinia Creek at Chasemore Rd	Calibration	-20% (satisfactory)	0.63 (satisfactory)	39	47

The timeseries graphs and FDCs show that the model performs reasonably well in estimating peak flow events which are likely to deliver high sediment loads to the bay. The FDCs indicate areas of the flow periods where the model and observed data match. As can be seen in many of them, the model is providing reasonable estimates in the lower exceedance percentages, with some deviation across higher exceedences. To interpret these, lower exceedance percentages mean those flows occur less frequently, and are therefore associated with higher flow rates, with higher exceedance percentages associated with lower event flows and baseflows. As can be seen, the model is reproducing the higher flows well, but there is some deviation across the lower flows and baseflows. This is consistent with how the model was parameterised and calibrated (i.e. to be able to better estimate higher flows when sediment loads to the bay are expected to be the greatest) and the results are to be expected.

The time series graphs provide an indication of how well the model is capturing the hydrologic response of the system in terms of seasonality and the way the model simulates the return to baseflows after rainfall-runoff events. These graphs show that the model is reproducing the hydrologic response very well, with good matches between the observed and modelled timeseries.

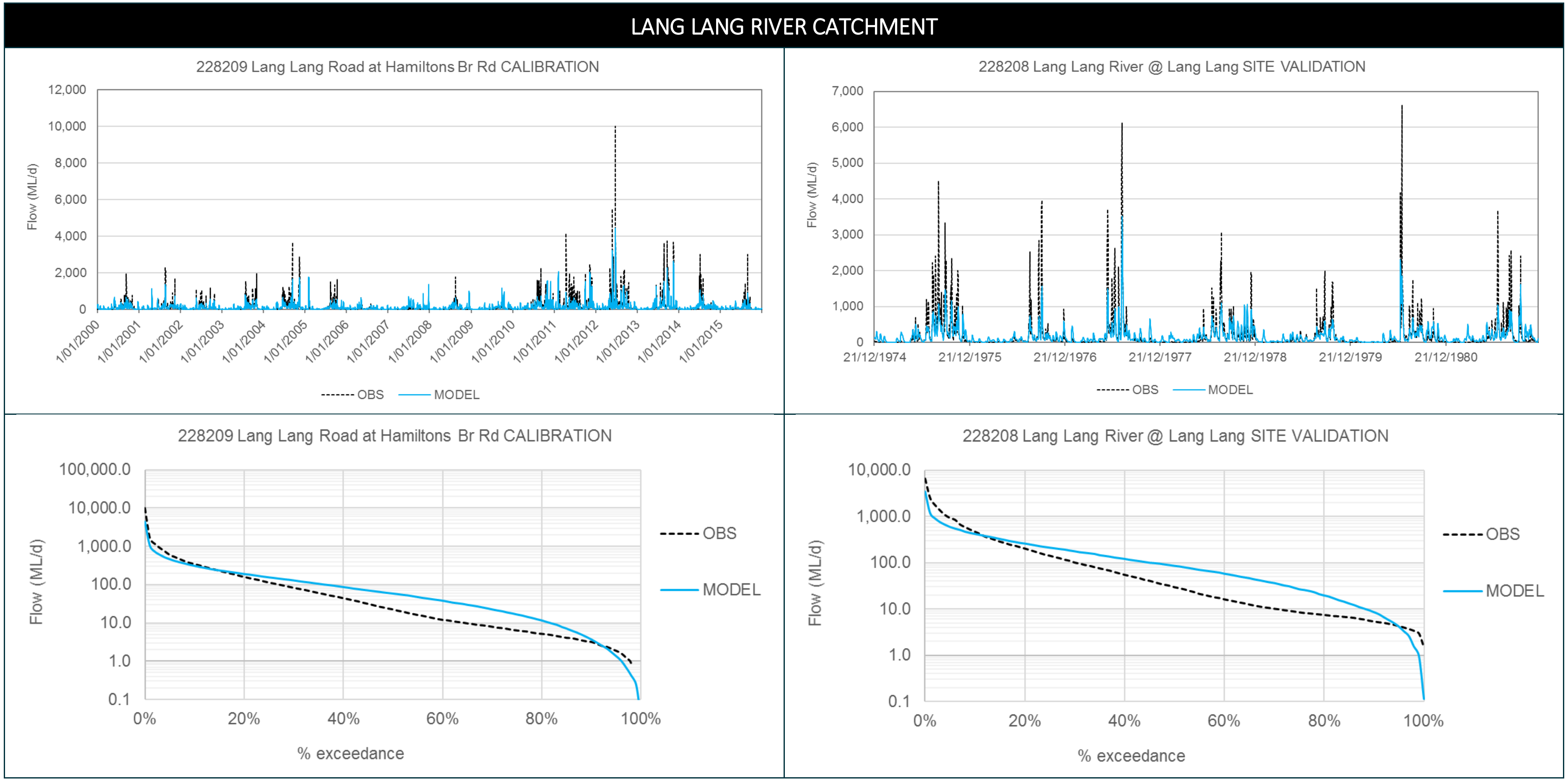

Figure 12 Lang Lang River Catchment: Comparison of modelled and observed flows for both calibration and validation periods. There was insufficient flow record for split sample calibration. Therefore, gauge 228208 in the upper Lang Lang catchment, was used as a site validation

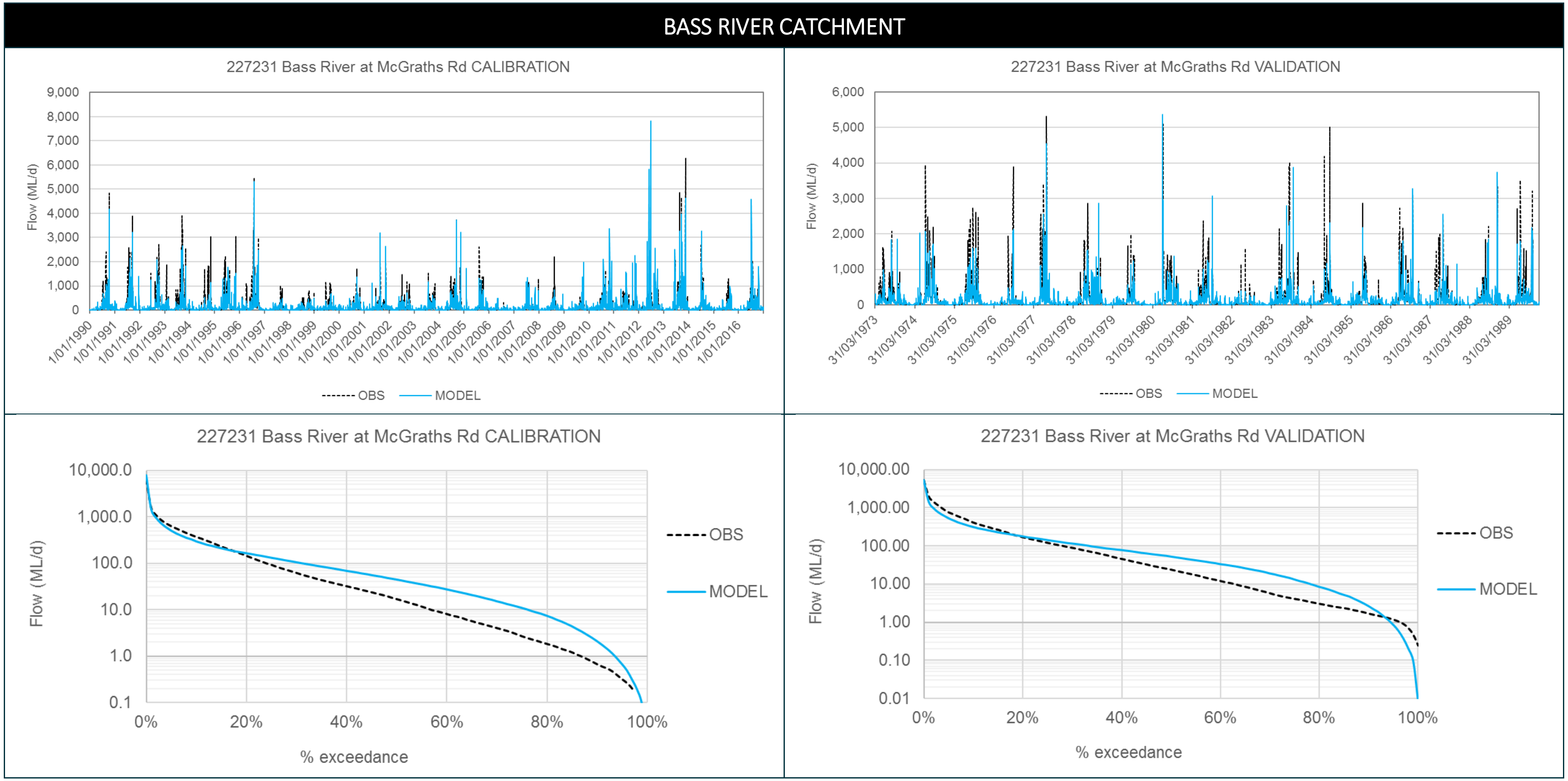

Figure 13 Bass River Catchment: Comparison of modelled and observed flows for both calibration and validation periods

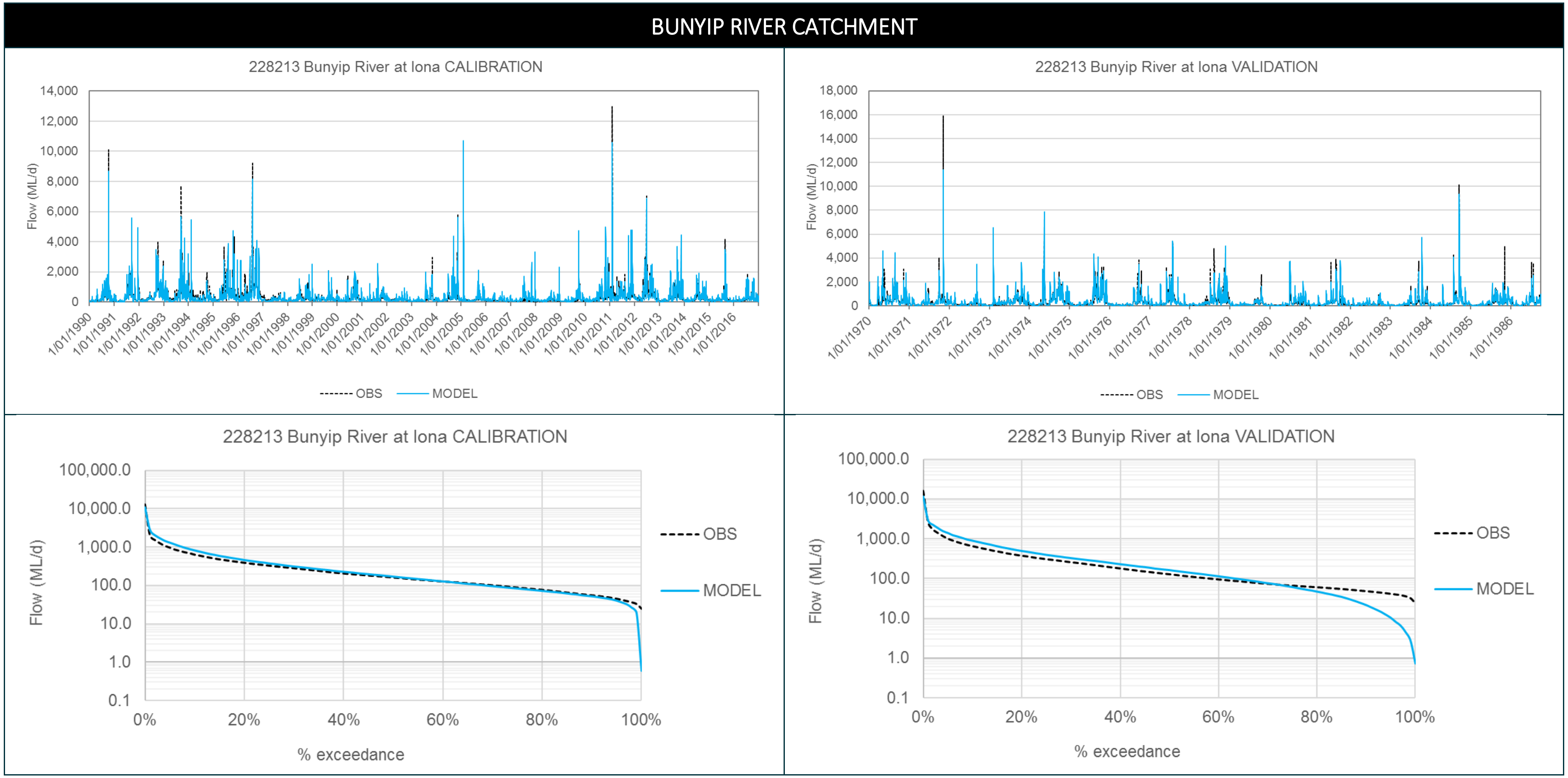

Figure 14 Bunyip River Catchment: Comparison of modelled and observed flows for both calibration and validation periods

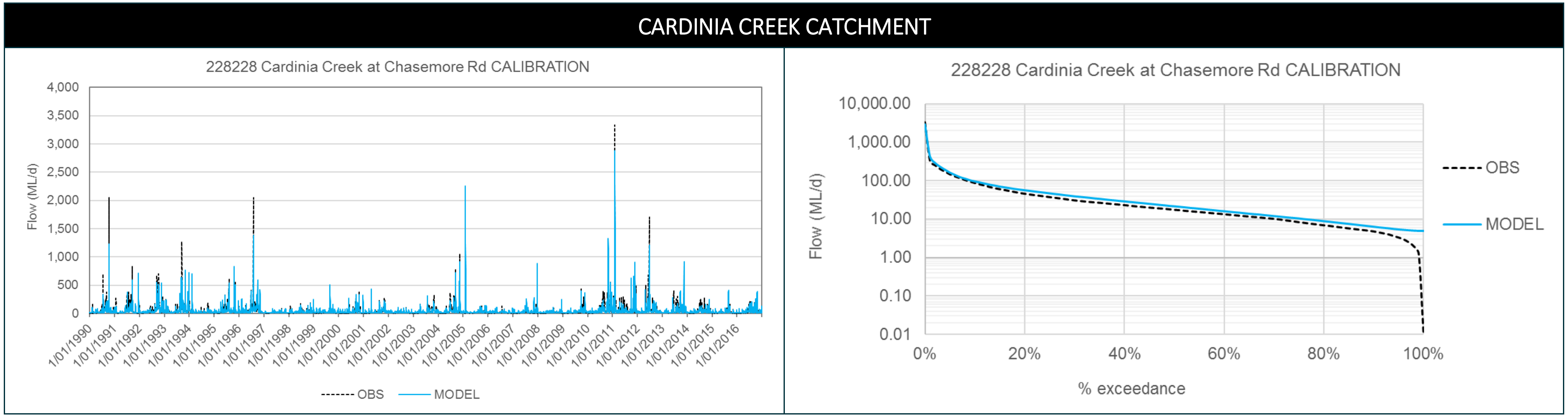

Figure 15 Cardinia Creek Catchment: Comparison of modelled and observed flows for both calibration and validation periods

4.5 Sediment modelling

4.5.1 Model set up

Fine sediments were the focus constituent configured in the model because of their dominant effect on light climate within the bay. For agriculture and forest land uses, two fine sediment sources were configured with *dSedNet* Hillslope and Gully modules. A combined streambank erosion and floodplain deposition reach model were configured in all model links.

The Universal Soil Loss Equation used to estimate sheetwash/rill and gully erosion on other land uses is not an appropriate model for urban land uses as these have such changed soil generation and transport processes to those occurring from gullies and hillslopes. For this reason, we retained the use of Event Mean Concentration / Dry Weather Concentration (EMC/DWC) models (as adopted for the PP-WP model) to model urban land uses, parameterised based on literature values (Table 8)). This demonstrates the flexibility of *dSednet* to apply modules that are locally relevant.

Storage deposition was represented as a simple mass transformation model in the link downstream of each storage release inflow node for both Cardinia and Tarago reservoirs. A 90% reduction in loads from storage deposition was adopted based on information obtained from Waters and Lewis (2017) which examined trapping efficiency of reservoirs.

A series of python notebooks and the Veneer plugin (Appendix D.1) facilitate model set-up and parameterisation. The python notebooks provide a workflow for *dSedNet* and EMC/DWC model assignment and parameterisation. These are described in Appendix D .

Table 8 Literature values adopted for urban fine sediment models

FU Type	EMC	DWC	Literature Source
Road; Railway	100	25	Fletcher et al, 2004
Green Space	500	50	Adopted Horticulture values from Batley et al 2012
Quarry	84	8	Calibrated based on the PP-WP Source model
Residential; Public Use; Commercial; Industrial	100	30	Fletcher et al, 2004

4.5.2 Data requirements

Each of the *dSedNet* plugin's modules (hillslope, gully, streambank and floodplain deposition, transformation) have their own data requirements listed in Table 9. Descriptions for each parameter and how they have been populated for Westernport is given in Appendix B .

Table 9 *dSedNet* module parameters

Hillslope erosion	Gully erosion
Hillslope delivery ratio (HSDR) – Fine	Proportion fine (Pf)
Rainfall erosivity (R)	Soil bulk density (Pb)
Soil erodibility (K)	Gully cross-sectional area or depth (aG)
Slope length factor (L)	Gully density or gully length (LG)
Slope steepness factor (S)	Gully age (T)
Cover factor (C)	Gully activity factor (fG)
	Management factor (Mg)

Streambank erosion	Floodplain deposition
Link streambed slope (Sl)	Floodplain area (Af)
Bankfull discharge (Qbf)	Floodplain deposition (lf)
Proportion of fine sediment in bank subsoil (pF)	Sediment settling velocity (Vp)
Streambank subsoil dry bulk density (ρS)	Bankfull flow (Qbf)
Bank height (h)	Long term average daily flow (QL)
Link length (Ll)	
Erodibility exponent (b)	
Erodible soil extent (SoilErod)	
Riparian vegetation proportion (RipVeg)	
Maximum vegetation effectiveness (MaxVegEff/MaxVegEffectiveness)	

Coarse sediments were initially to be included for modelling. However, as there were insufficient observed data (e.g. to establish the transport capacity of channels requires information on particle size, channel slope, manning's channel roughness, etc) to adequately parameterise a coarse sediment model, modelling of the coarse fraction was not progressed. This is a limitation within this implementation of the model.

4.5.3 Model calibration

The same four gauges used for rainfall-runoff calibration were used for *dSedNet* calibration:

- 228209 - Lang Lang River at Hamiltons Br
- 227231 - Bass River at McGraths Rd
- 228213 - Bunyip River at Iona
- 228228 - Cardinia Creek at Chasemore Rd.

Calibration was focused on achieving a good fit with observed sediment loads, with preference placed on achieving a good comparison with peak loads during flood events and overall a good fit with mean annual loads, given the tool will be used for long-term catchment planning. The *dSedNet* parameters that were tuned in the model to match the modelled sediment loads with the observed are outlined in Table 10.

Table 10 *dSedNet* parameters tuned for sediment calibration and resulting calibrated parameter

dSedNet parameter	Application in model	Calibrated value
Hillslope module – alpha (R factor)	Applied to all catchments	0.56
Gully module – gully activity factor	Applied to all catchments	1.7
Link Streambank erosion module – erosion coefficient	Bunyip	0.0004
	Lang Lang	0.001
	Bass	0.002
	Cardinia	0.001
Link Streambank erosion module – daily flow power factor	Bunyip	1.8
	Lang Lang	1.8
	Bass	1.8
	Cardinia	1.3

4.5.4 Calibration performance

Performance measures

The measures used to assess model performance are the same as those used to assess the performance of the rainfall-runoff (SIMHYD) model., namely:

- Nash-Sutcliffe model Efficiency (NSE) statistic (as a measure of goodness-of-fit, where 0 is poor and 1 is a perfect fit to observed data)
- Percent bias (PBIAS) (% difference between modelled and observed loads; positive % bias indicates underestimation and negative % bias indicates overestimation compared to observed)
- comparison of modelled to observed mean annual sediment load
- visual inspection on monthly load timeseries plots, scatter plots, and cumulative monthly load
- visual inspection on mean annual bar charts.

The resulting model fits were assessed using evaluation criteria developed by Moriasi et al (2007) (Table 11). In the case of sediment, an NSE of greater than 0.55 was considered a good fit between monthly modelled and observed loads.

Table 11 Performance ratings for *dSedNet* model statistics for a monthly time step (adapted from Moriasi et al 2007)

Performance rating	PBIAS (%) streamflow	NSE
Very good	PBIAS < ±15	0.75 < NSE ≤ 1
Good	±15 ≤ PBIAS < ±30	0.55 < NSE ≤ 0.75
Satisfactory	±30 ≤ PBIAS < ±55	0.3 < NSE ≤ 0.55
Poor	PBIAS ≥ ±55	NSE ≤ 0.3

Performance evaluation

Summary statistics for model calibration are presented in Table 12. The model achieved a good calibration performance according to the Moriasi et al (2007) criteria for both mean monthly and mean annual loads. The ability to estimate the majority of peak sediment loads and baseflow loads is demonstrated in the following figures for Lang Lang (Figure 17), Bass (Figure 18), Bunyip (Figure 19), and Cardinia (Figure 20). Estimation of the peak flood event sediment loads from early 2011 were challenging and it is thought that resuspension of fine sediment and the subsequent transport through the catchments may be a missing component of the *dSedNet* model, which is causing this underprediction of loads. Nevertheless, the mean annual loads for each catchment is well represented by the model.

Table 12 Summary statistics on Source+*dSedNet*@Westernport model calibration performance

Gauge site	Monthly loads PBIAS (%)	Monthly loads NSE	Observed mean annual load (kt/y)	Model mean annual load (kt/y)
WPLAN0373 Lang Lang River at Hamiltons Bridge	17% (good)	0.58 (good)	5.8	4.8
WPBAS0233 Bass River at McGraths Rd	-16% (good)	0.64 (good)	3.1	3.6
WPBUN0707 Bunyip River at Iona	-27% (good)	0.6 (good)	2.7	3.4
WPCAR0133 Cardinia Creek at Chasemore Rd	-28% (good)	0.31 (satisfactory)	0.5	0.7

Comparison of the performance of Source+*dSedNet*@Westernport and the PP-WP regional Source model (which used EMC/DWC for all land uses), against observed mean annual loads for each of the main catchments is presented in Figure 16. Overall, *dSedNet* has greater skill in estimating mean annual loads than the EMC/DWC model utilised by the PP-WP Source model, although both models underestimate the 2011 observed loads.

Both models are suitable and fit-for-purpose for their respective modelling applications, however, the Source+*dSedNet* model is perhaps more useful in that, as well as generally better estimates of sediment loads, it provides information and scenario management levers for the explicit sediment sources, and thus provides more flexibility for the end-users.

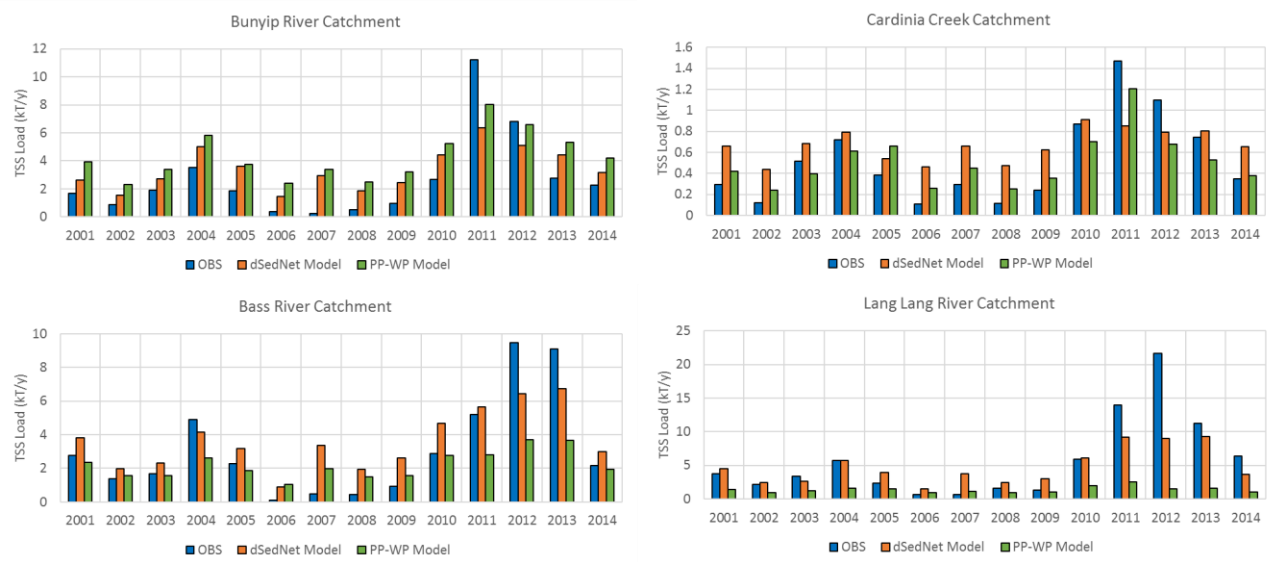

Figure 16 Comparison of modelled (Source+*dSedNet*@Westernport and PP-WP regional Source model) and observed mean annual loads over the period 2001-2014 for the four calibration catchments

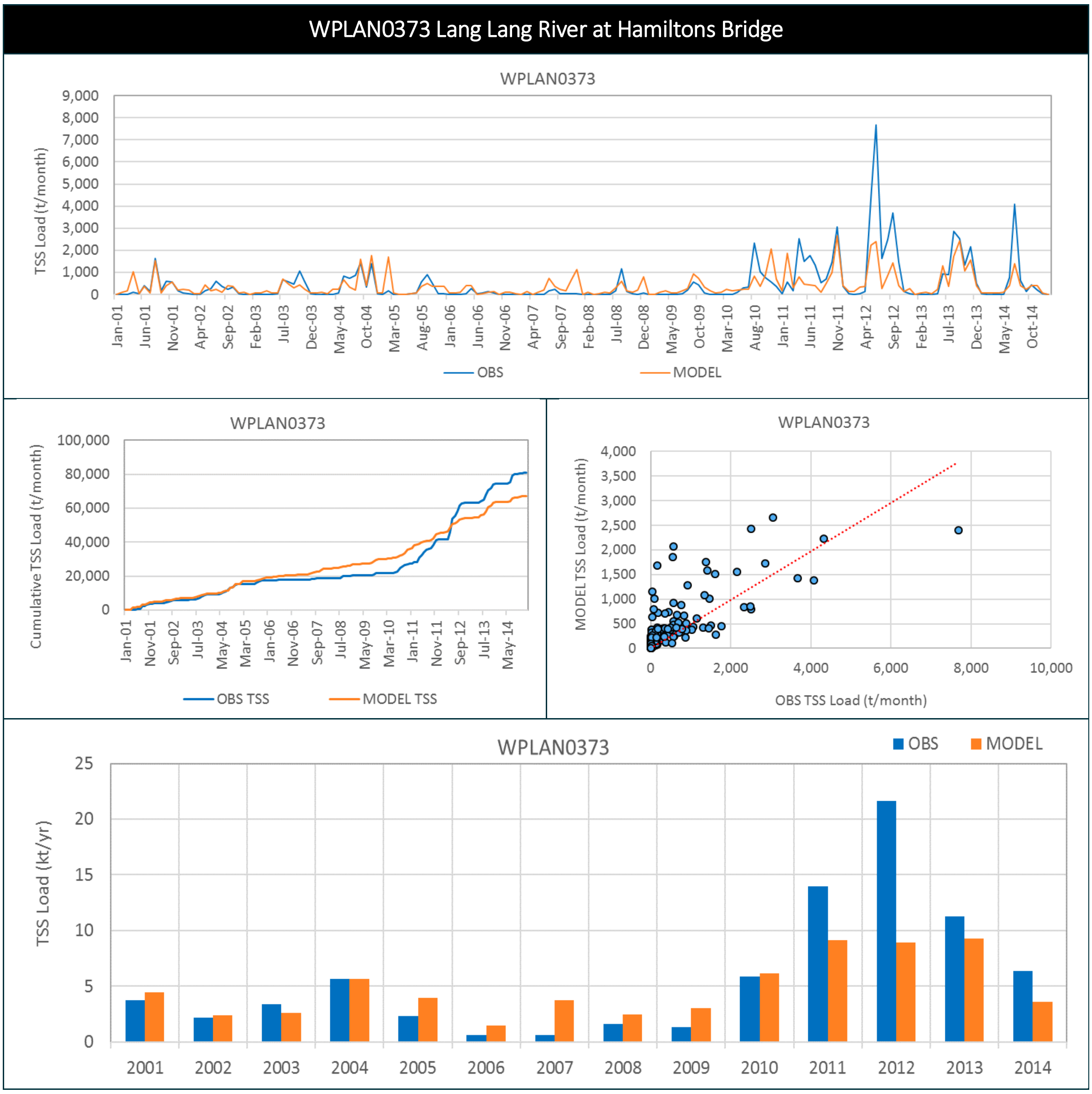

Figure 17 Lang Lang River Catchment: Comparison of modelled and observed total suspended sediment (TSS) loads

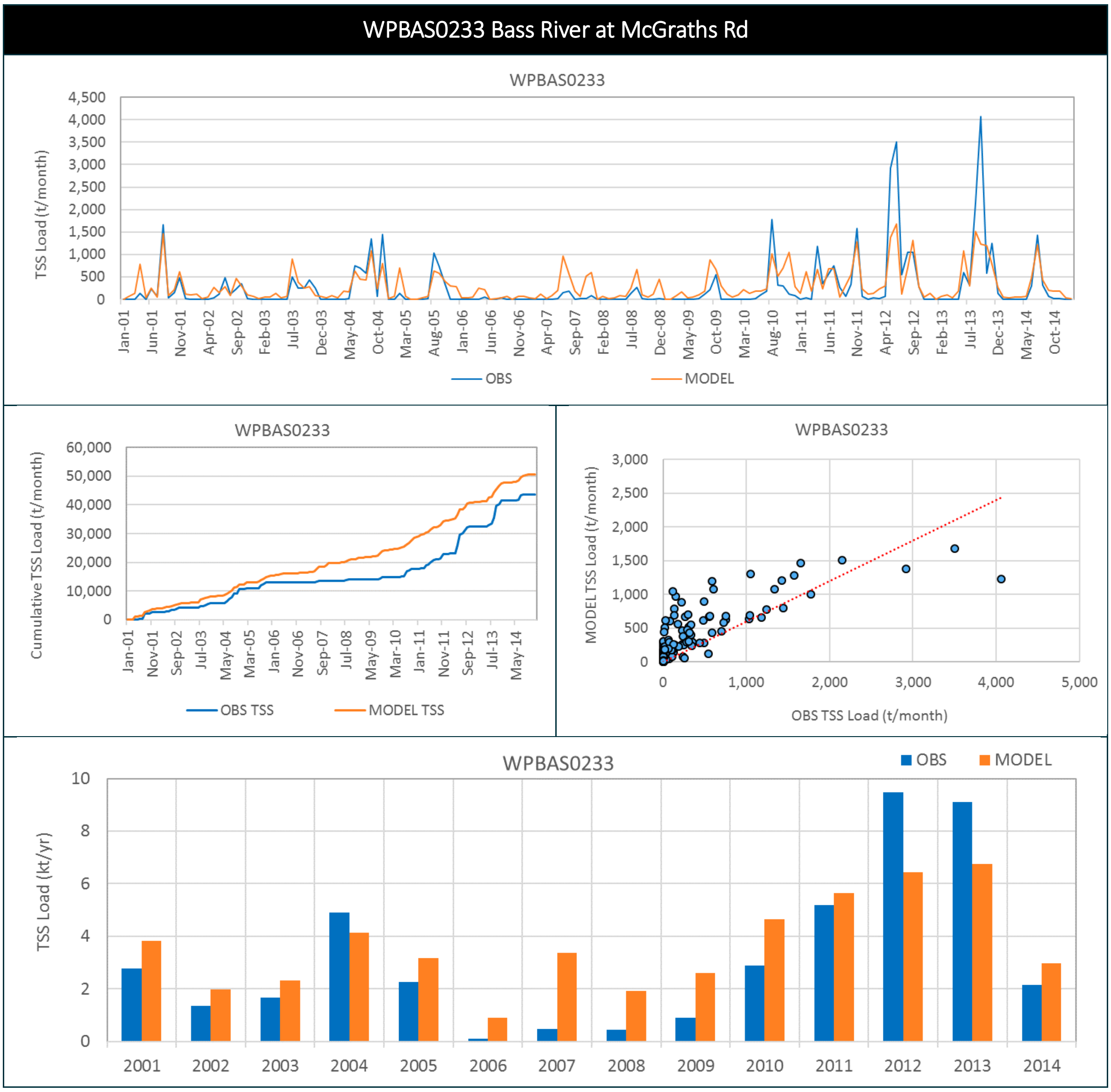

Figure 18 Bass River Catchment: Comparison of modelled and observed total suspended sediment (TSS) loads

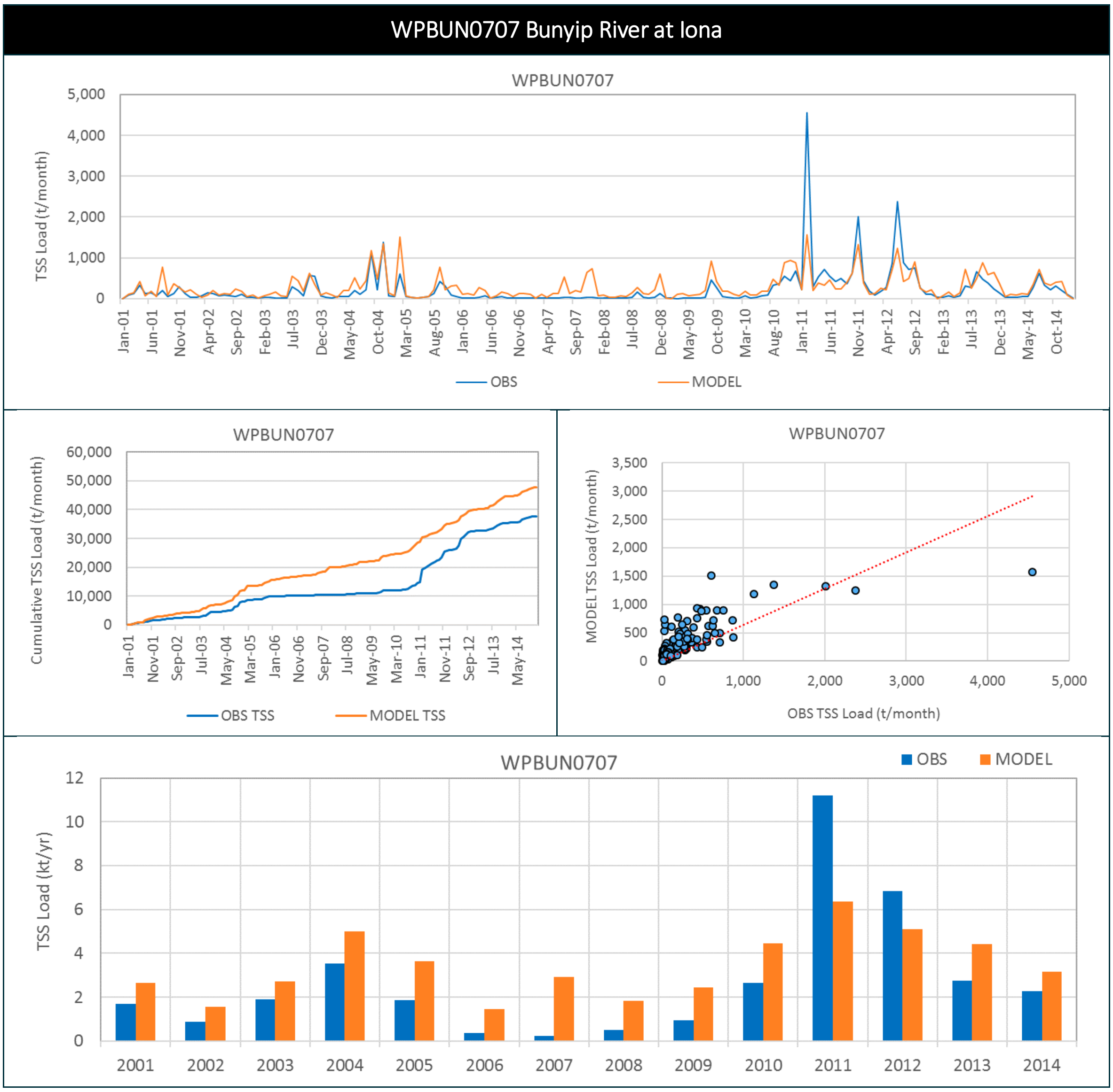

Figure 19 Bunyip River Catchment: Comparison of modelled and observed total suspended sediment (TSS) loads

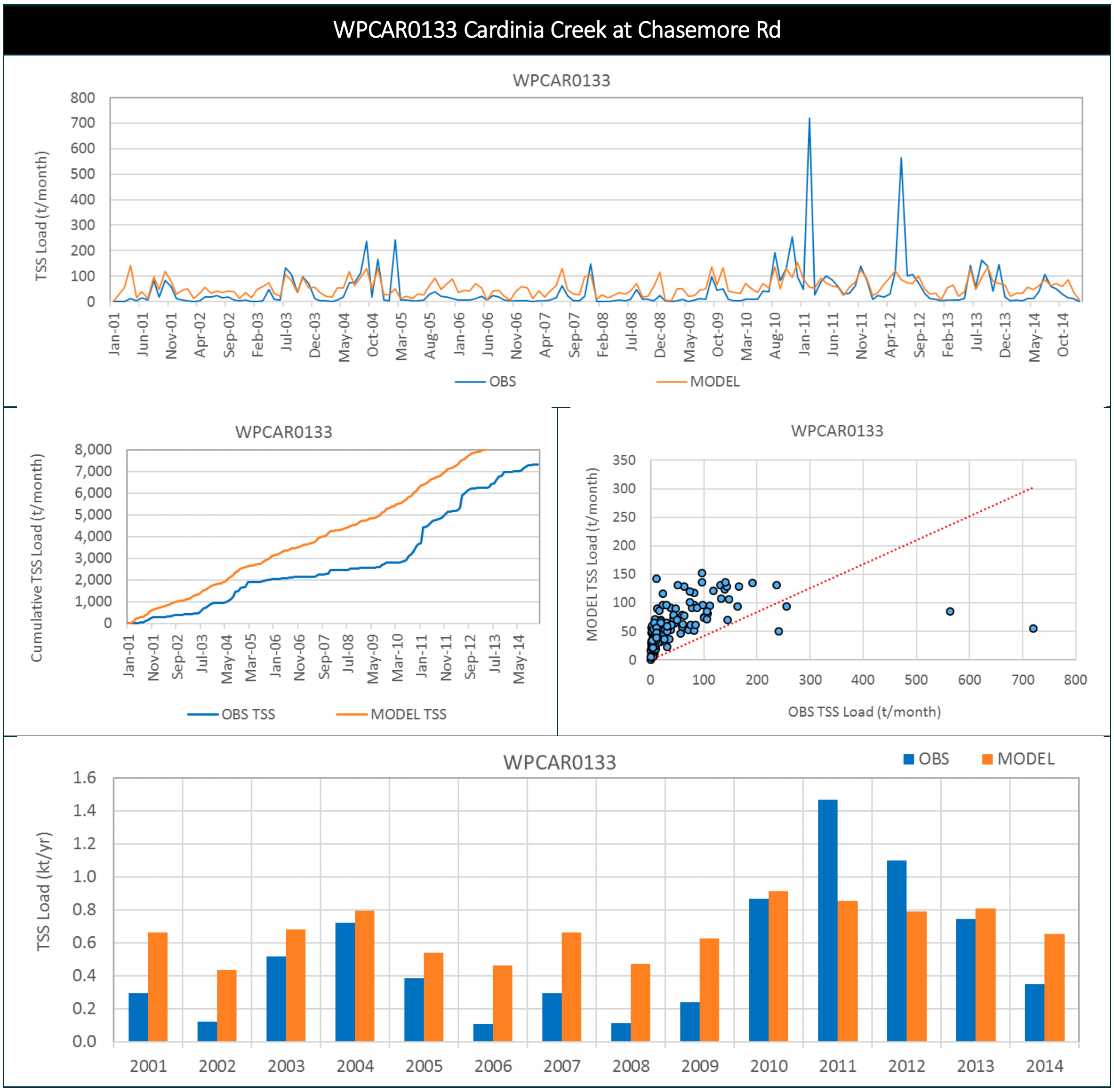

Figure 20 Cardinia Creek Catchment: Comparison of modelled and observed total suspended sediment (TSS) loads

4.6 Baseline results and discussion

Over the period 2001-2016, Source+*dSedNet*@Westernport estimates a mean annual fine sediment (silt and clay) total load of 35.4 kilotonnes/year. Sediment load is dominated by the streambank erosion source (65.4%) followed by the urban source (18.2%) (Figure 21(left)). Roads (24.2%), grazing and cropping (20.8%) and low density residential (12.2%) together produce over 50% of the total sediment load generated from land uses (excludes streambank as a source) (Figure 21(right)).

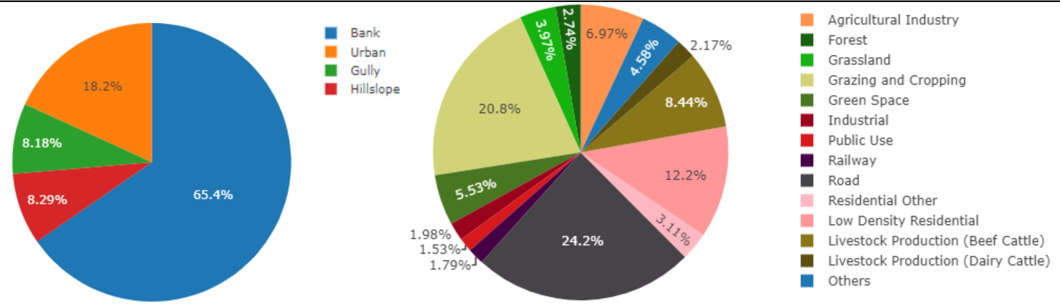

Figure 21 The contributions of mean annual sediment loads (a) from different erosion sources and (b) from land uses as modelled in Source+*dSedNet*@Westernport. (b) does not include contributions from streambank, which is not modelled as a land use. [Source: The Catchment Planning Tool, CPT@Westernport]

Figure 22 shows the modelled mean annual sediment loads for the whole of Westernport. While *dSednet* predicts the highest annual load in 2011, the prediction for three of the four major catchments is lower than the observed loads for that year (bottom plot in Figure 17, Figure 18, Figure 19, Figure 20).

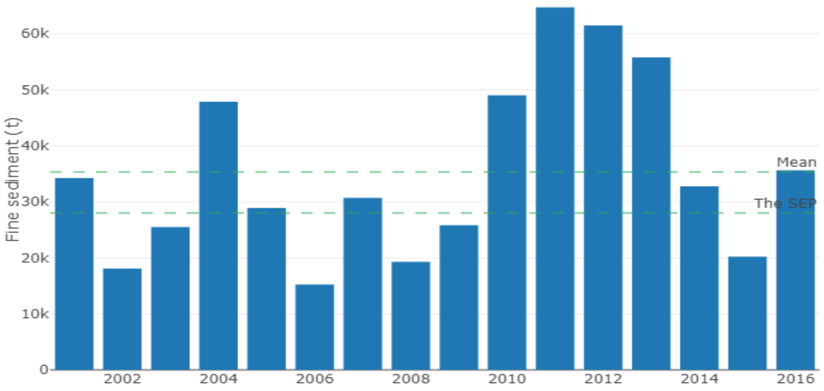

Figure 22 Modelled mean annual sediment loads to Western Port over the period 2001-2016. The broken lines show the mean load of 35.4 kilotonnes/year over the period, and the SEPP target of 28 kilotonnes/year. [Source: Catchment Planning Tool, CPT@Westernport]

The four catchments used for calibration (from west to east: Cardinia, Bunyip, Lang Lang and Bass) produce the majority of the fine sediment load (75%), with the Bunyip (34%) and Lang Lang (23%) River catchments contributing more than half of that. *dSedNet* predicts that streambank erosion is the dominant source in all four major catchments. This is consistent with earlier modelling of Westernport catchments (e.g. Hughes et al 2003; Wallbrink et al 2003b).

Table 13 *dSedNet* estimated mean annual loads for the four major catchments. The table also includes information on the land uses that dominate land-based sediment generation in those catchments (i.e. excludes streambank erosion which is the dominant source in all four catchments)

Catchment	Area	dSedNet estimation (2001-2016)		
	sq km	kt/y	%	Dominant sediment-generating land uses
Bunyip	890	12	34%	Roads (29%), grazing & cropping (13%)
Lang Lang	423	8	23%	Grazing and cropping (47%), livestock (beef cattle) (15.8%)
Bass	266	4	11%	Grazing and cropping (42%), roads (19.4%)
Cardinia	398	3	8%	Roads (30%), low density residential (26%),
Other		8.4	24%	
Total		**35.4**	**100.00%**	**Roads (24%), grazing and cropping (21%), low density residential (12%), livestock (beef cattle) (8%)**

We can explore this further and the next two figures use the Lang Lang catchment to demonstrate how data can be accessed via the CPT@Westernport[8].

Figure 23 presents the annual loads from Lang Lang catchment over the period 2001-2016, where streambank dominates (64.8%), followed by gullies (17.8%), hillslope (10%), and urban (7.4%).

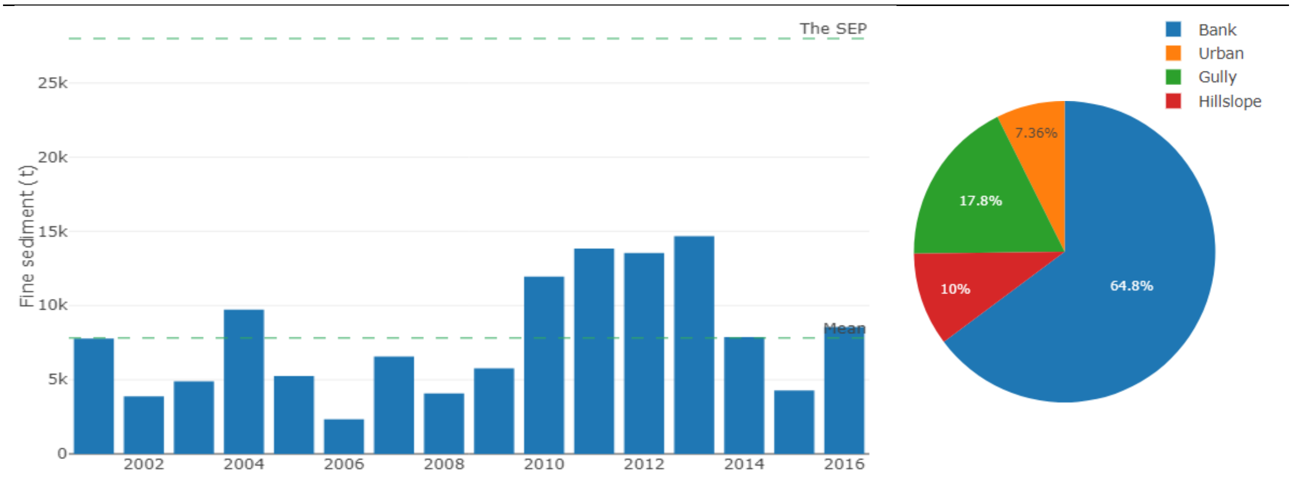

Figure 23 (left) Modelled mean annual sediment loads to Western Port over the period 2001-2016 from Lang Lang catchment. (right) Load contributions by source (urban, gully, hillslope, (stream)bank [Source: Catchment Planning tool, CPT@Westernport]

Results can be further interrogated by sub-catchment and by land use (Figure 24).

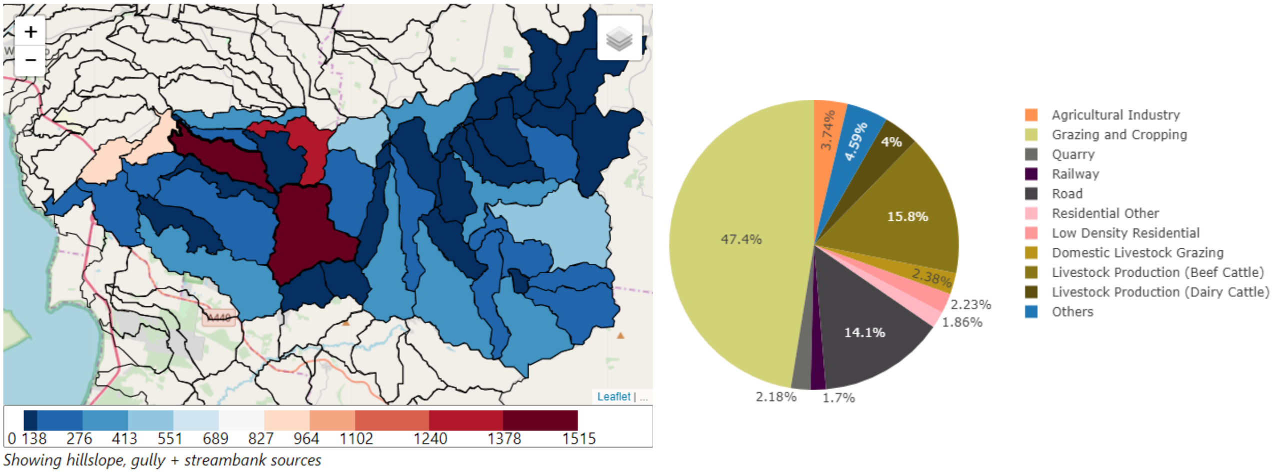

Figure 24 (left) Spatial distribution of loads within Lang Lang catchments, by subcatchments. (right) Contributions for specific land uses (excludes streambank) [Source: Catchment Planning Tool, CPT@Westernport]

The Catchment Planning Tool provides access to results by sediment source, region, catchment, land use, for individual years. The reader is referred to that Tool for detailed reporting and analysis of results.

Comparison to earlier studies

The Source+*dSedNet*@Westernport estimated mean annual sediment load to the bay of 35.4 kt/yr is higher than the 23.8 kt/yr estimated by Wilkinson et al (2016a) who used the mean annual SedNet model. The difference between this new modelling and the load estimate based on river gauge monitoring is 25%; this is

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[8] One advantage of accessing results through the CPT@Westernport is that all results are presented using the same statistics and formats, allowing for easy visual comparison of results.

within the typical difference from measured loads for these exercises and is smaller than the earlier (Hughes et al, 2003) mean-annual Sednet modelling of ~66 kt/yr (which was calculated over an earlier time period).

dSedNet almost certainly has over-estimated streambank erosion in the channelised reaches. In these reaches, bank erosion is very small because the channels are over-widened to carry flood flows. Estimation of deposition in these channels is also difficult because the beds are well vegetated and so standard algorithms do not apply well. It is likely that deposition occurs there. Additionally, sediment is removed from those channels before it reaches the bay. The current version of the dSedNet model does not incorporate this, nor does it have instream deposition and resuspension enabled.

Hughes et al. (2003), using the annual Sednet model, estimated suspended sediment mean annual load to Western Port of around 66 kilotonnes/year. This is almost double that estimated by the *dSedNet* model. Wilkinson et al (2016a) suggests that load estimates for recent decades have generally been lower than earlier estimates of longer-term sediment loads. Given the time since massive land clearance and river channelization in the catchment, a decline in catchment sediment yield may be expected, given river channels are more stable than they were in the period prior to 1970 (Wilkinson et al., 2016a). In addition, methods used to prepare data for inputs into *dSedNet* may differ from those utilised by Hughes et al. (2003) for SedNet modelling, such as the variable cover factor inputs, different SIMHYD rainfall-runoff parameterisation, revision to gully density mapping and activity/maturity.

In the 2018 Melbourne Water summary of research findings arising from the Western Port Environment Research Program (under which a group of research projects were undertaken) it is identified that catchment sediment supply appears to have reduced in recent years, with an estimated mean-annual suspended solid delivery into Western Port of 23.8 kt/year since 1980 (Chapter 2, Melbourne Water 2018). However, a key action to improving water quality to levels suitable for seagrass maintenance and restoration is set to restrict sediment loads from the catchment and coastline together to current levels (of around 28 kt/year), and improving the management of catchment loads is still considered crucial for the Western Port environment since this reduces further sediment deposition and remobilisation of fine material (Melbourne Water 2018).

Comparison to SEPP target

The *dSedNet* mean annual load estimation of 35.4 kt/year is higher than the SEPP target of 28 kt/year (visually shown in Figure 22). The same arguments apply to *dSedNet* as discussed in Wilkinson et al (2016a) (and reported in the above sub-section). Firstly, while *dSedNet* includes floodplain deposition, it does not have instream deposition (and re-entrainment) enabled (which would reduce the estimated load to the bay). It is also likely that Source+*dSedNet*@Westernport overestimates the export of sediment from the channelised reaches as sediment is regularly removed the channels in that area.

If we adopt the Wallbrink et al (2003c) heuristic that about 60% of generated sediment enters the bay (i.e. 40% is deposited within the catchment either on floodplains or in streambeds), this reduces the estimated annual load to 21.2 kt/year. Even if we adopt a more conservative figure of 80% entering the bay (i.e. 20% does not reach the bay), the estimated load is 28.3 kt/year. Alignment with the SEPP target is critically important as the modelling is intended to support the exploration of management options that will ensure that the SEPP target is maintained. Some of these management options are explored in the next section.

5 Catchment planning

The Westernport catchment has been substantially modified since the late 1800s, including the drainage of large swampy areas (particularly the Koo Wee Rup Swamp), vegetation clearing, agriculture and progressive urbanisation. As a result, catchment hydrology and water quality has been fundamentally altered, most notably by the direct connection of major waterways such as Cardinia, Toomuc and Deep Creeks, and the Bunyip and Lang Lang Rivers to the bay. Formerly flows from these streams and associated sediments terminated in swamps. These changes have resulted in an increase of sediment to the northern and eastern parts of the bay, and along with ongoing input from erosion along the Lang Lang coastline, have impacted the ability of sunlight to penetrate the waters of the bay. Both these conditions, i.e. increased fine sediment load and consequent reduced light penetration, are detrimental to the health of the seagrass meadows of the bay. Recent sediment studies indicate that sediment loads from the catchment have reduced over the past few decades (Wilkinson et al 2016), and that there has been a gradual clockwise (ie west to east) flushing of fine sediments from the bay (Hancock et al 2003; Wallbrink et al 2003), such that significant improvements in water clarity within the northern parts of the bay are likely within the next 20+ years if current catchment loads can be reduced or maintained at current levels (Melbourne Water 2018a). Although there is evidence of some improvement in the distribution of seagrass cover across Western Port, the cover is still much less than that observed in the early-mid 1970s prior to extensive intertidal seagrass loss (Melbourne Water 2018a).

A number of key threats to water quality in the waterways in the Westernport catchment and the bay have been identified, including ongoing agricultural activities (e.g. dairies, intensive horticulture), steady urbanisation (including the south east growth corridor and expansion of townships) and climate change (e.g. changes in rainfall intensity and frequency, sea level rise) (Melbourne Water 2018b). In order to achieve the State Environment Protection Policy sediment load objective for Western Port of an average annual total suspended solids load of <= 28 kt/yr for the period 2018-2028 (Victorian Government 2018), it is important to understand the most cost-effective combination of management options. It is also important to understand these possible management actions in the context of major strategies such as the Healthy Waterways Strategy 2018 (Melbourne Water 2018b) or Western Port Strategic Directions Statement (DELWP 2018).

5.1 Options for managing sediment loads

One of the many benefits of developing a simulation model is its ability to run 'what-if' analyses. In the models, these are set up as 'scenarios', generally through changing one or more module parameters, and the model re-run with that new set of parameter values.

Management option requirements were elicited via a series of workshops with Melbourne Water and DELWP staff and the full set (to this point) is listed in Appendix A [9]. In summary, there was greatest interest in exploring the likely impacts of different scales of interventions (e.g. streambank and/or gully erosion controls), land use change, and a changing climate, on sediment generation and transport, at local and regional (to the bay) scale**.**

As at the time of writing this report, 5 management actions have been implemented (Table 14).

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[9] Not all requirements can, or have, been modelled in this application – some because the *dSedNet*/Source models can't adequately represent the scenario, some because the science is not sufficiently robust, and some because they were not prioritised for this implementation.

Table 14 The five catchment planning scenarios that have been implemented in the CPT (as at July 2019), noting that these are combined to give 23 model scenarios

Scenario ID	Description
U=Urban	
U01	All existing urban areas have implemented stormwater management schemes that conform to BPEM targets, i.e. 80% reduction in TSS load. This scenario does not include the urban transition period (i.e. the construction period) when it is assumed that the 80% reduction is not achieved. It assumes perfect compliance
FU=Future Urban	
FU01	Urban land use expanded to include future urban, and with different sediment generation rates to reflect higher likely sediment export during first two years of development. This scenario was under construction @ July 2019 and results are not included in this report
G=Gully	**[These gully scenarios are mutually exclusive]**
G01	20% of active gullies have been remediated/stabilised
G02	60% of active gullies have been remediated/stabilised
B=(Stream)bank	
B01	Riparian vegetation restored on all streambanks
C=Cover	
C01	Hillslope vegetation cover has improved by a factor of 2

Climate change has not been included. While it is easy to input a different (i.e. likely future) rainfall time series through the model and thus generate a new set of results, the effect of changes in temperature and greenhouse gases on groundcover, and thus on sediment mobilisation, is not yet well studied. From a science point of view, this may require some changes to the underlying algorithms which have been developed and field tested under a historical climate regime.

As you can see from the descriptions in Table 14, the current implementation of these management options is quite ‘heavy-handed’, i.e. they are actioned uniformly across the land use areas and/or river links, to which they apply. This approach is reasonable for initial analysis, especially when a tool has been developed (the Catchment Planning Tool, see next section), which allows for exploration of their likely impact by location and/or land use. It results in a manageable number of model runs to be stored for later enquiry, as Melbourne Water did not anticipate, at time of design, that they would have in-house expertise to dynamically run the Source+*dSedNet*@Westernport model.

These scenarios have been combined (e.g. G01+B01+C01, order of combination not important) to give 23 ‘what-if’ model scenarios, requiring that the Source+*dSedNet* model be run 23 times, each run with a different set of input parameters. With the baseline run, which in Source is also called a scenario, the Westernport application has 24 model scenarios.

Reporting of loads (total annual) was requested to be:

- from specific subcatchment or groups of subcatchments representing ‘regions’
- from sediment sources (gully, hillslope etc)
- from land uses (e.g. urban, forest, types of agriculture)
- against State Environment Protection Policy (SEPP) targets for the bay
- against best practice environmental management (BPEM) targets for intervention options.

Each scenario translates into a set of model input parameters, which are then run through the model to produce reporting results for the 24 model runs.

5.2 Scenario results

Figure 25 shows the estimated mean annual loads over the period 2001-2016 from every combination of management option scenario. These results show the impact of the revegetation of streambanks (B01), with those scenarios including B01 showing significant reductions (as much as 15 kt/year) in sediment load to the bay.

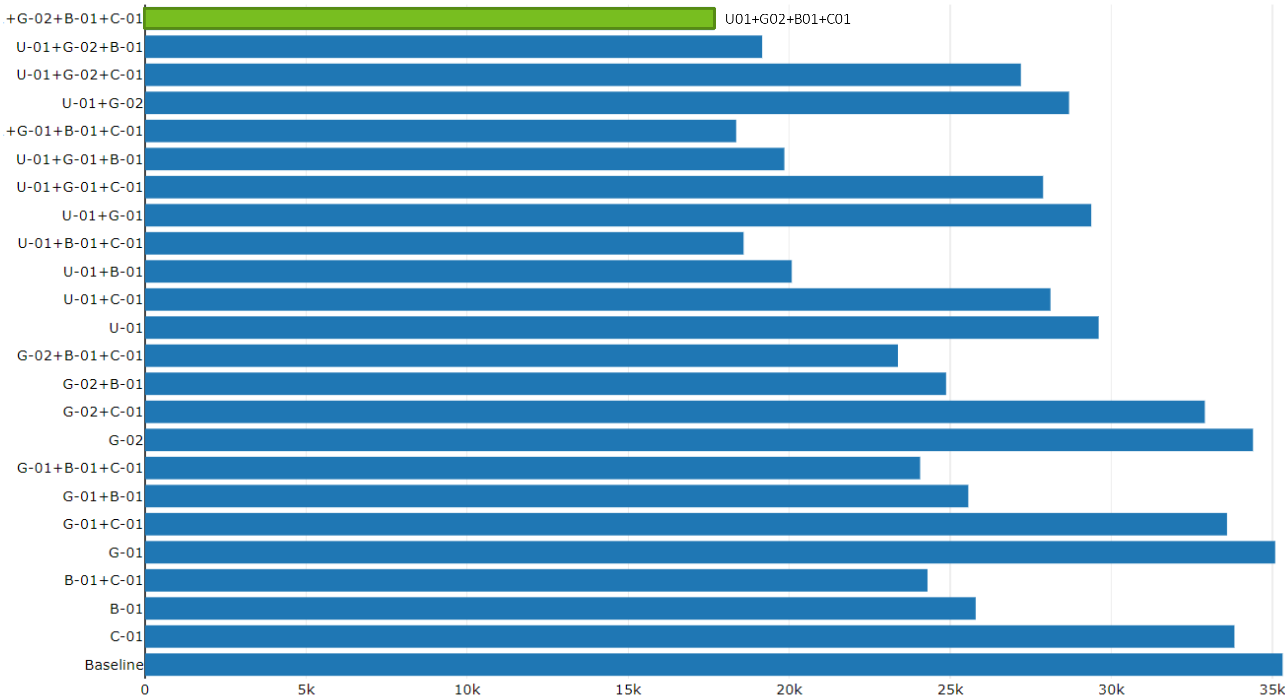

Figure 25 Mean annual loads for each combination of management option (i.e. 24 results) [Source: The Catchment Planning Tool, CPT@Westernport]

Taking the 'best' performing scenario, U01+G02+B01+C01 (identified in green above), we can explore this further. Figure 26a shows the reduction in mean annual load under this scenario compared to baseline, over the period 2001-2016. Figure 26b shows the difference in contributions from sources (the scenario is outlined in orange and baseline is shaded in blue). This scenario reduces loads from all sources, with the largest load reduction being from streambank revegetation, and the largest %load reduction being from urban areas. This is to be expected as both management options simulate best or optimal practice.

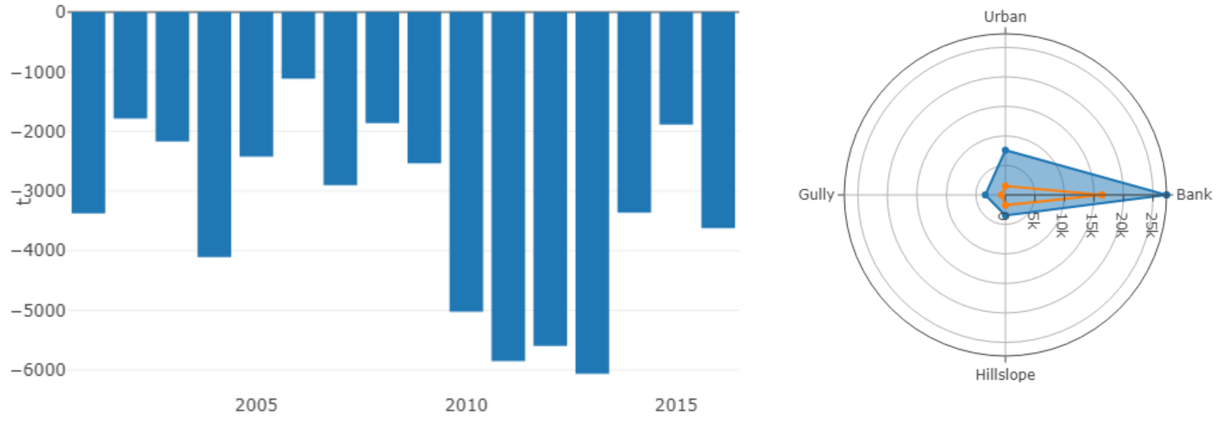

Figure 26 (a) Change from baseline in mean annual loads under the combined management options scenario (U01+G02+B01+C01) over the period 2001-2016. (b) Change in contributions by source (urban, gully, hillslope, (stream)bank [Source: Catchment Planning Tool, CPT@Westernport]

5.3 The Catchment Planning Tool (CPT)

The Catchment Planning Tool (CPT) has been developed as a web-based 'front-end' to the Source+*dSedNet*@Westernport model to provide access to an agreed sub-set of model features such as baseline information, scenarios and model results. It was recognised that running eWater Source and the *dSedNet* plugin requires considerable technical knowledge and consequently their use within Melbourne Water was likely to be sporadic. The decision was made to develop the CPT to provide a flexible interface for staff to centrally store and explore results of scenario runs.

Most of the results presented in this report have been generated through the CPT.

The CPT has 3 parts:

(1) a web-based user interface that effectively allows the user to set up queries that are sent to the back-end database which contains the results of all the pre-run model scenarios (including the baseline model run results) that are accessed and processed dynamically to suit the query.

(2) A backend dataset that contains the contextual information that is displayed. As this information is read dynamically from the dataset, edits are automatically available to the user. This supports using the CPT as a mini information system. For example, interpretations of scenario results could be included, with links to other documents and data provided.

(3) A workflow (coded using Jupyter Python notebook) that batches up all the information needed to run the scenarios, executes the models, and writes results out to the CPT database. This takes many hours and need only be run if there were a change to the configuration of the Source+*dSedNet*@Westernport model, to one of the scenarios, or if more scenarios were added.

5.3.1 A quick tour of the layout and content of the CPT

The CPT (July 2019 version) has been designed to 'tell the sediment story' visually through the use of maps and charts.

Figure 27 The entry screen to the CPT@Westernport

It is organised as follows:

Overview

- About the catchment - land use, rainfall, topography, annual groundcover maps
- Sediment budgets - annual total load for the catchment, a region (e.g. Bunyip River only), a subcatchment, a source or a land use. The default is for the baseline scenario, but results for other scenarios can be accessed
- Previous studies - background information on the catchment and sediment budgets from previous studies

Scenarios

- Descriptions of the scenarios
- Loads summarised by region, showing the difference of each scenario's load from baseline
- Scenario comparison allowing two-at-a-time comparison, with results presently in charts and maps
- Download data which downloads files of daily flow and fine sediment loads for modelled outlets

Detailed results

- Annual loads to the bay for a particular year for a selected scenario at an exit node (picked from a map)
- Annual loads from subcatchments – selectable by land use, sediment source, and year. Multiple presentations of results assist with interpreting the results (e.g. a subcatchment may produce a large load because it has a large area; or it is dominated by a high generating land use, or source)
- Annual loads from Instream processes – annual loads selectable by link, scenario, process (floodplain deposition or streambank) and year

About the Model

- Model overview - provides information on the model
- Land use – allows the user to query the land use map

- Cover – display of monthly bare ground index images for the period 2000-2018
- Gullies – display of active and inactive gullies
- Calibration - displays graphs and other details of the calibration process – of interest to modellers and hydrologists

Project

- References – citation details for relevant documents, including previous studies; where available, active hyperlinks have been included
- Data products – describes the derivation of the 6 data products created during the life of the project
- Credits and acknowledgements.

5.3.2 Uses for the CPT

The CPT design was informed by uses that Melbourne Water staff anticipated. At the time of writing this report, the CPT is still in an elementary state and in a user response phase. The focus of the July 2019 version has been to enable staff to become familiar with the catchment, and those locations and/or sources that are predicted to be the major generators of fine sediment.

In the longer term, staff anticipate using the CPT to:

- assist in annual sediment reporting, especially useful for those areas with no observed data
- explore the effect of different levels of intervention at different points through the catchment (e.g. an intervention in one subcatchment or one region may have a significant positive effect in that subcatchment, but has no effect on total load to the bay
- understand the likely sediment loads being delivered from developing urban areas and develop appropriate management options to mitigate
- understand the likely implications of climate change on sediment generation and the relative outcomes for various sediment load management scenarios
- incorporation of cost information to understand the most cost-effective combination of management actions that are likely to achieve the SEPP sediment loads target to Western Port under a changing climate and urban growth
- inclusion of coarse sediment load scenarios, such as to inform sediment removal programs for maintenance of the flow capacity in the Koo Wee Rup drainage district.

5.3.3 Accessing CPT@Westernport

CPT@Westernport can be accessed from https://www.flowmatters.com.au/viz/#/mw-cpt.

6 Reflections and future directions

This project has continued the long tradition of Melbourne Water working with research organisations, such as CSIRO, to further the science required to underpin robust and defensible catchment planning decisions. On this occasion, it has given CSIRO the opportunity to encode that science in its *dSedNet* product, the predecessor of which was first applied in Westernport in 2003, and to revisit many of the assumptions and algorithms on which that product is based - a win-win situation.

6.1 Advances

Within the two years of the project, the Source hydrology model was updated, a new sediment model was built, models were calibrated and validated, data was collected and/or inferred through remote sensing, GIS and other analytical methods, and the CPT was designed, coded and implemented.

Being able to model the effect of management changes on loads at the outlet is a step forward, as is the ability to reflect seasonal changes in vegetation cover. Sediment source contributions to load are now much improved; as is the ability to disaggregate by land use which is a significant advance on the annual Sednet model.

The CPT reduces the requirement for in-house modelling expertise through providing an easy-to-access entry point to the models and their results.

6.2 Next steps

While all care was taken to populate the models with the 'best' data available, many of these data (e.g. density of active gullies within catchments, condition of riparian areas) were inferred and need to be validated, requiring new field work (survey and monitoring) and longer-term research. Melbourne Water staff anticipated many uses for the CPT.

This section looks at – what next. This includes revisiting components of the initial project plan that were not fully addressed in this two-year project, due to re-shuffling of resources to other components, or because the knowledge and data were deemed insufficient to confidently encode in a model. These could be considered as limitations in the current model, some of which can be addressed through further investment in the model, and some of which require field work and investment in the science. Issues and associated tasks are grouped by four themes in Table 15, with an estimate of the size of the task:

- *dSedNet* model and methods
- Source+*dSedNET*@Westernport characterisation/data
- Catchment Planning Tool (CPT@Westernport)
- Catchment planning scenarios.

Many, if not all, of these issues impact on the accuracy of the model and would not be undertaken in isolation. A thorough sensitivity analysis (suggested below) would confirm what components and parameters are having the most influence on results – then decisions which balance advancement vs return on investment can be made. Additionally, there are some tasks which may not benefit the accuracy of the modelling in the short term but would make a significant contribution to the advancement of sediment modelling (e.g. developing a robust method to estimate sediment transport from urban areas).

Table 15 Issues raised during the project that should be addressed to improve the ability of the model to predict sediment generation, transport and deposition. Duration indicates whether the task is SHORT (<6 months), MEDIUM (6-12 months), or LONG-(>12 months) term. Size of task (SMALL, MEDIUM, LARGE) is a preliminary assessment of the investment required to undertake the task

Issue	Task	Duration/ Size of task
dSedNet model and methods		
The *dSedNet* and Source model are built in an old release of the Source platform last full public version as at June 2017)	It would be prudent to upgrade the models to the latest version of Source. The plugin was developed in version 4.1.1 as this was the current full public release at commencement of the project and accessible to all stakeholders. Changes in version and licensing during the project meant that while future versions of Source were available, continually updating the plugin with these ongoing changes was not efficient to delivery. Updating the plugin now that it is completed would make the *dSedNet* plugin available to all current users. Upgrading needs to consider Source licensing arrangements, and meeting requirements for dSedNet to be accepted by eWater (custodian of Source) as a community plugin	SHORT MEDIUM
Stream bank erosion is a significant sediment source, and highly dependent on estimation of (exposed) stream bank height. The estimation method used in this project, while rigorous, needs to be further tested	As discussed in Appendix B.4, the method for calculating stream bank height averaged across all streams within the buffer distance. An alternative approach would be to average across only the higher order streams represented by the links in the Source hydrology model. As this may also affect the spatial pattern, further testing of the consequences of alternate estimation methods on prediction of stream bank erosion is recommended.	SHORT MEDIUM
Modelling of coarse fraction. The code exists but was not implemented, due to resource constraints, and lack of data to validate the modelling.	While conceptually this may be just defining the total load and subtracting the fine fraction, practically it requires attaching another module everywhere, i.e. carrying both fine and coarse throughout the network. Given the processes by which sedimentation and transport differ for both fractions, they need to be treated as separate, but related, constituents within the model rather than simply a fraction of the total. This requires field work focused on the coarse sediment component of the catchment loads, re-parameterisation of the model, and model re-calibration (see issue under Westernport characterisation/data)	MEDIUM MEDIUM
Modelling of future urban areas - The existing model uses a simplistic method to account for the operational phase of future development by increasing the area of urban residential land use in the model	The current method doesn't account for the period of transition whereby areas that are proposed for future development are cleared, subdivision works are undertaken and housing construction then occurs. During those activities, it is highly likely that areas of exposed soils are present, however the activities that cause this (clearing, removal of top soil etc) will fundamentally change the characteristics that influence how the hillslope erosion model (RUSLE) calculates sediment generation. Further research and data collection are needed to better characterise the sediment generation during each phase of urban development and methods developed to simulate this. In the short term, a rapid assessment technique could be employed to generate initial estimates that then could be improved as subsequent research and monitoring data becomes available.	LONG MEDIUM SHORT SMALL

Issue	Task	Duration/ Size of task
Instream deposition and resuspension is available in *dSedNet*, but not activated due to insufficient knowledge to parameterise the model, and to maintain independence of subcatchments to support the management scenarios (i.e. instream deposition and resuspension are not independent processes but are reliant on the magnitude of upstream load and the extent deposited or available during the modelling period	If instream deposition and resuspension are enabled, then the ability to run dynamic scenarios based on a library of pre-run modelled scenarios is no longer possible. A field-based project to collect data on existing sediment supply is recommended, in addition to enabling these processes in *dSedNet*. A short-term solution could be to develop a new scenario to explore the impact of a range of instream deposition and resuspension rates.	MEDIUM MEDIUM SHORT SMALL
Source+*dSedNET*@Westernport characterisation/data		
Modelling of sediment deposition in the Koo-wee-rup swamp area can be improved through better characterisation of the system	The resolution of the modelling for the Koo-wee-rup area is not fine enough to capture its sediment life cycle, particularly the deposition phase. Improve the modelling of the channelised reaches of streams (drains) through the drained Koo wee rup swamp area. Investment in the modelling needs to be matched with collection of data, e.g. measures of the amount of sediment that is regularly removed from the channel network	MEDIUM MEDIUM
Validation of the 'new' active gully mapping, including evaluation of the significance of tunnel erosion in the catchments	DELWP raised the issue as to whether there are reductions in gully erosion and whether these may be attributed to land management actions during the late 90s/early 2000s, or simply through the gullies becoming naturally stable and vegetated. Field work required	SHORT MEDIUM
Refine soil texture data for gully and stream bank erosion	Properties from deeper in the profile are more likely to be representative of the material eroded by gullies and stream banks (eg 0.3-0.6m). Requires field work, re-parameterisation of the model, and model re-calibration	SHORT SMALL
Understanding connectivity with the floodplain is critically important. We defined the active floodplain as that reached by a 100-year flood event. Was this the most realistic?	Mapping of the active floodplain (time-weighted) is important for more than this modelling exercise. At present, the only mapping that covers the whole catchment is for a 100-year flood event. Expert opinion suggests that 50-year flood extent would be more realistic. This would require GIS mapping, reviewing and/or redoing hydraulic modelling, re-parameterisation of the Source model, and model re-calibration	SHORT SMALL
Proportion fine sediment (Pf) – Data for the 0-5 cm depth for both clay and silt were extracted for the study area, then added to give total proportion of fine sediment.	It would have been preferable to use properties from deeper in the profile, which are more representative of the material eroded by gullies and stream banks (eg 0.3-0.6m). The surface layer is typically lower in silt/clay content than subsoil. Requires field work, re-parameterisation of the model, and model re-calibration	SHORT SMALL
Future urban areas aren't captured in the current modelling	Develop map of future urban areas (which requires conversion of existing other land uses, most likely grazing or peri-urban). This needs to be accompanied by research to identify how best to model future urban – could incorporate a range of scenarios (e.g. 100% compliance to WSUD). A short-term solution would be to do the mapping and continue to use the current modelling approach while research is underway	SHORT MEDIUM LONG MEDIUM

Issue	Task	Duration/ Size of task
Particle size speciation not included in the current model	This requires sampling of sediments in the bay (ref Hancock earlier work) to develop a contemporary map of sediment particle size fractions across the bay (i.e. to compare to Shapiro 1970s and Hancock 2000s measurements) – this is likely to greatly improve receiving model predictions of benefits of sediment reduction strategies in the catchment for seagrass in the bay	SHORT LARGE
Model is over-representing low rainfall years and under-representing high rainfall years, especially in the Bunyip catchments	It would be useful to explore this further. Many of the issues listed in this table potentially contribute to this outcome. A more comprehensive sensitivity analysis would identify those parameters that are driving the results and efforts could be focussed on improving their accuracy to improve model calibration	SHORT MEDIUM
Modelling of coarse fraction not included	(see complementary issue under modelling method, and modelling of Koo-wee-rup swamp) Implement a field-based project to measure the amount of material within and removed from the floodplain drains, and then re-calibrate the models. Cost of field-work estimated at $30-50K.	SHORT SMALL
Subcatchments were developed using a stream threshold of 10 km^2 and as a result, some small areas directly adjacent to the bay are not included as they are less than the stream threshold	The model could be quickly improved by manually accounting for these areas in the model through manual definition of the subcatchment boundaries in these small, lateral flow, subcatchments to ensure that the contribution of them is not lost. The current model pre-processor relies on subcatchments defined through processing of a DEM, so additional parameterisation processes may be needed for these small catchments.	SHORT SMALL
CPT@Westernport		
The CPT was designed as a Minimum Viable Product (MVP) to avoid over-design, awaiting data on usage	Melbourne Water staff identified many uses for the CPT during the final project workshop. Evaluate the use of the CPT by Melbourne Water staff over the next 6 months, and co-design the next release	SHORT MEDIUM-LARGE
Catchment planning (Scenarios)		
The current implementation has a limited set of options/action. Another approach to creating a suite of pre-run scenarios is to create 'book-end' scenarios, e.g. rather than 2 gully remediation scenarios, you would 'book-end' with 0% and 100% and be able to pick any % in-between	This approach would require running the model potentially thousands of times to develop a suite of meta-models that would capture the shape of the response between the book-ends. It would provide a significantly greater capability to explore catchment planning strategies/actions. Another alternative would be for one or more Melb Water staff to become proficient in using Source+*dSedNet* and setting up unique scenarios, the disadvantage being that this would de-couple parts of the CPT A less expensive option is to implement what has set up as the 'prototype' in the CPT (included to show the potential of the system). This would allow users to pick and choose a set of subcatchments for interventions. This option still relies on a rather simplistic view of the network, i.e. what happens in one subcatchment does not impact on what happens in another catchment.	MEDIUM MEDIUM-LARGE SHORT MEDIUM
Climate change is not included in the current implementation of the model	Climate change impacts on sediment loads is another area that could be explored initially by understanding the implications of changed rainfall and evapotranspiration (i.e. through implementation of the current DELWP guidelines for modelling climate change). This may also be done in combination with some initial estimates of how cover may change under different climatic regimes (e.g. through examining AussieGRASS model outputs – see https://www.longpaddock.qld.gov.au/ - to identify 'bookends' of what changes could be anticipated. A short-term solution would be to include a range of likely future climates (e.g. wetter, drier, median) as part of the scenarios suite, ignoring the biotic responses which require a longer-term research activity	LONG MEDIUM SHORT SMALL

Issue	Task	Duration/ Size of task
The most cost-effective way of getting to the 28,000 tonnes/year target is required. Including scenario indicative cost was planned, but not implemented	A method is required to cost scenarios. Redesign of the CPT to calculate and display cost is not a large job -setting up the method and the input data is the most significant investment. Could consider setting up a cost component database (e.g. implementation cost, maintenance cost per area and/or time period). Look to work done as part of development the Great Barrier Reef Foundations' investment strategy	SHORT MEDIUM

7 Bibliography

7.1 References to other Westernport work

There is a significant history of sediment studies in Westernport, many of which have been conducted as research collaborations between Melbourne Water and CSIRO – these papers have been identified with a single asterisk. Note that some have not been cited in this Report but have been included here as background material.

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7.2 *dSedNet* References

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Metadata Name Description
Resource Name: ISC2010_RIVER_CENTRELINES_S
Anzlic Id: ANZVI0803005109
Custodial Program: Water Division
Custodian: Department of Environment, Land, Water & Planning

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Appendix A The *dSedNet* Plugin (SourcePlugin.CSIRO.*dSedNet*)

This Plugin was coded by Andrew Freebairn (CSIRO), using equations from Wilkinson et al (2014). It also borrows from the Dynamic SedNet plugin developed by the Queensland Government's Paddock to Reef program (Ellis and Searle 2014).

This text has been written by the developer (Freebairn) for the Source community plug-in website, and parts have been adapted for inclusion in this report for completeness.

This description of the eWater Source plugin represents the current state of its development at the time of writing this report. The behaviour described here is the code used by the project to implement *dSedNet* for Melbourne Water.

As part of CSIRO's commitment to Source, and its community, the plugin has been made available to the Source community: it is possible that the plugin may be modified in the future to include new features. For the latest information on the plugin visit the eWater web site:

https://wiki.ewater.org.au/pages/viewpage.action?spaceKey=SC&title=SourcePlugin.CSIRO.*dSedNet*

You may need to create an eWater account before accessing the page.

The plugin is a set of components, being a collection of modules and their associated management tools (e.g. spatial and temporal parameter setting tools).

The components that make up *dSedNet* are listed in Table 16. A tick (✓) in the Status column identifies those components that are completed and/or have been released, unmarked items are planned for future releases.

Note that not all modules are needed for a working *dSedNet* model – the use of a module is dependent on the landscape and the application, though it would be very unusual to have an application that did not include at least the gully and hillslope erosion modules.

Table 16 List of plugin components, ordered by function within area

Areas	Function	Components	Status
Data pre-processing	Derivations from DEM	TIME spatial analysis model (outputs for parameterisation)	✓
Modules	Generation	Hillslope	✓
		Gully	✓
		Bank	✓
		Nutrient (Dissolved, Particulate)	
	In-stream processing	Sediment (deposition)	✓
		Nutrient (deposition, decay)	
		Mass Transformation	✓
	Storage processing	Sediment (deposition)	✓

Areas	Function	Components	Status
		Nutrient (deposition, decay)	
Parameterisation	Spatial parameterisation	Generation models	✓
	Temporal parameterisation	Generation models	✓
Configuration	Validation	Land-use area definition	✓
Plug-in Management	UI configuration	Main UI additions	✓
		Access to plug-in functions	✓
	Persistence	Mapping data into a database or saving to a file	✓
Result visualisation	Statistics	Totals	
		Spatial contributions of sediment	
Quality management	Quality control	Unit testing of each component	✓
		Regression testing of components and the system	✓

A.1 The modules

The Plugin provides models for:

- Floodplain deposition
- Gully erosion
- Streambank erosion
- Hillslope erosion
- Reach – a façade for two models: Streambank and floodplain deposition. The Reach model was built to overcome a Source technical restriction

These models are access via the Plugins menu (Figure 28). Note that a *dSedNet* application does not need to have all models. For example, a catchment may not have any gullies, or floodplain.

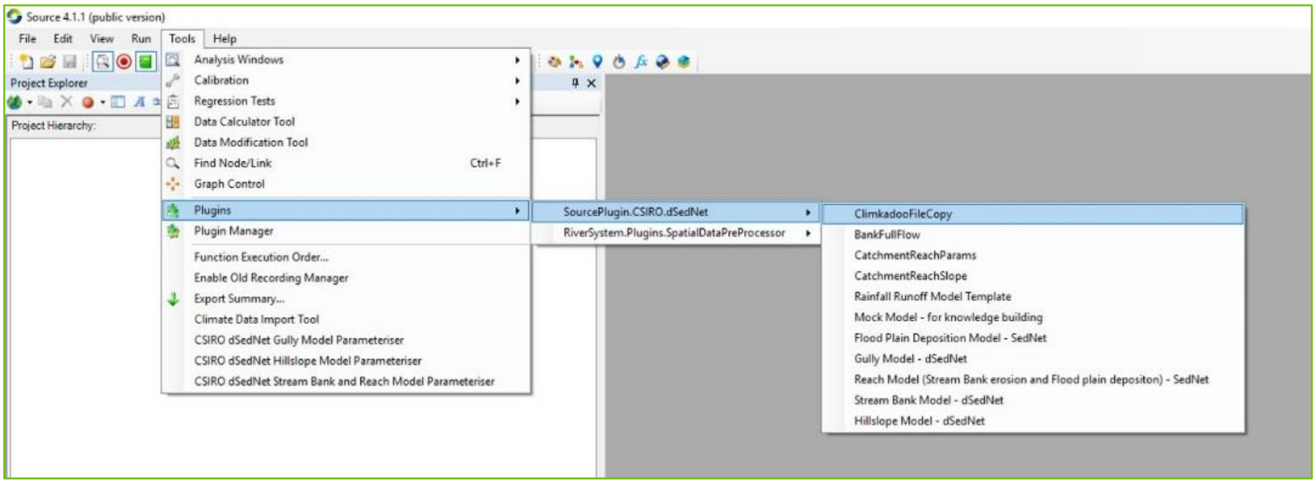


Figure 28 Accessing the *dSednet* Plugin modules from Source | Tools | Plugins

A.2 Enhancements

The project team (extending back to the earlier project during which the first two modules were developed) has been able to take advantage of relatively new functionality in Source.

The first extended the granularity at which a user can model constituent generation and filtering. Previously a user could only define one process for a functional unit. In this project, we revised the underlying architecture to support **multiple sources**, e.g. gully and hillslope. Each source can contain both a generation and filter component (as previously) which could now work together to give a summed filtered generation from each FU.

The second allowed **dependencies between generation/filter modules**, so that one module can have parameters that are dependent on parameters from another module.

Within this project, the team has implemented an **extension to the spatial parameterisation** component so that a time series of values can be 'played' to a models 'Input' parameter. For example, 'C' factor in the hillslope model parameter KLSC can now be represented as a daily value and therefore capturing the spatial and temporal variation in vegetation cover. Daily spatial layers that represent a model parameter (as above C factor) are traversed and zonal statics are produced for the defined FU areas. These make up the daily values in a time series file that are mapped to the model's parameter.

Additionally, **parameterisation of link models/modules with spatial data** has been developed. The Reach module has parameters such as 'Link Length' which can now be parameterised using a raster that represents the stream length for the associated sub-catchment.

To provide a method for reducing a constituent (not limited to sediment) as it passes through an object, the team developed a Mass Transformation module (ref Appendix B).

A.3 Guide to using the *dSedNet* Plugin

Start Source and load using the Plugin manager. Constituent generation models will appear in the Constituent Model Configuration control, **Edit–>Constituent Models**...

The Temporal Parameteriser (incorporated into Source core) is found under the **Tools** menu, ***dSedNet* Gully Model Parameteriser** and ***dSedNet* Hillslope Model Parameteriser**.

The Spatial Parameteriser is part of the Plugin and can be found under the **Edit** menu, **Edit–>Spatial Parameteriser…**

Source uses the concept of scenarios to package information for a model run, even the base configuration is called a scenario.

Steps to set up a *dSedNet* application (i.e. for a particular catchment/s) are:

1. Load the ***dSedNet*** plugin using the **Plugin Manager.**
2. Use the ***dSedNet*DerivedLayers** (ref section A.3.1) to derive useful data. Using this tool removes the need to have a DEM saved within the project file. It also generates many of the spatial parameter layers used to parameterise *dSedNet* and to construct the baseline scenario. Inputs required are:
   a. a hydrologically sound DEM
   b. stream threshold (50km^2 is default)
   c. the easting and northing of the outlet cell (if one is not given all outlets will be produced at the edge of the data provided)
   d. the path to save results.
3. Create a Source Catchments model using the **Geographic scenario**. When defining the **Network** use the option to **Draw Network** and use the layers generated from the above process.

4. **Define FU areas** (ref section A.3.2) with the use of a land-use map (raster) which covers 100% of the catchment (This is a prerequisite for using the Spatial Parameteriser).
5. Select a **rainfall runoff** model and assign parameters, then calibrate the model.
6. **Define constituents** (e.g. Fine and Coarse). You may need to define multiple sources of constituents for a given FU (e.g. Hillslope and Gully)
7. Assign models for constituent generation - (**Hillslope Model – *dSedNet*** and **Gully Model - *dSedNet***) and enter static model parameters (example Figure 32).
8. Assign spatial parameters to selected constituent generation models using the **Spatial Parameterisation** tool.
9. Execute the temporal parameterisers for associated constituent generation models.

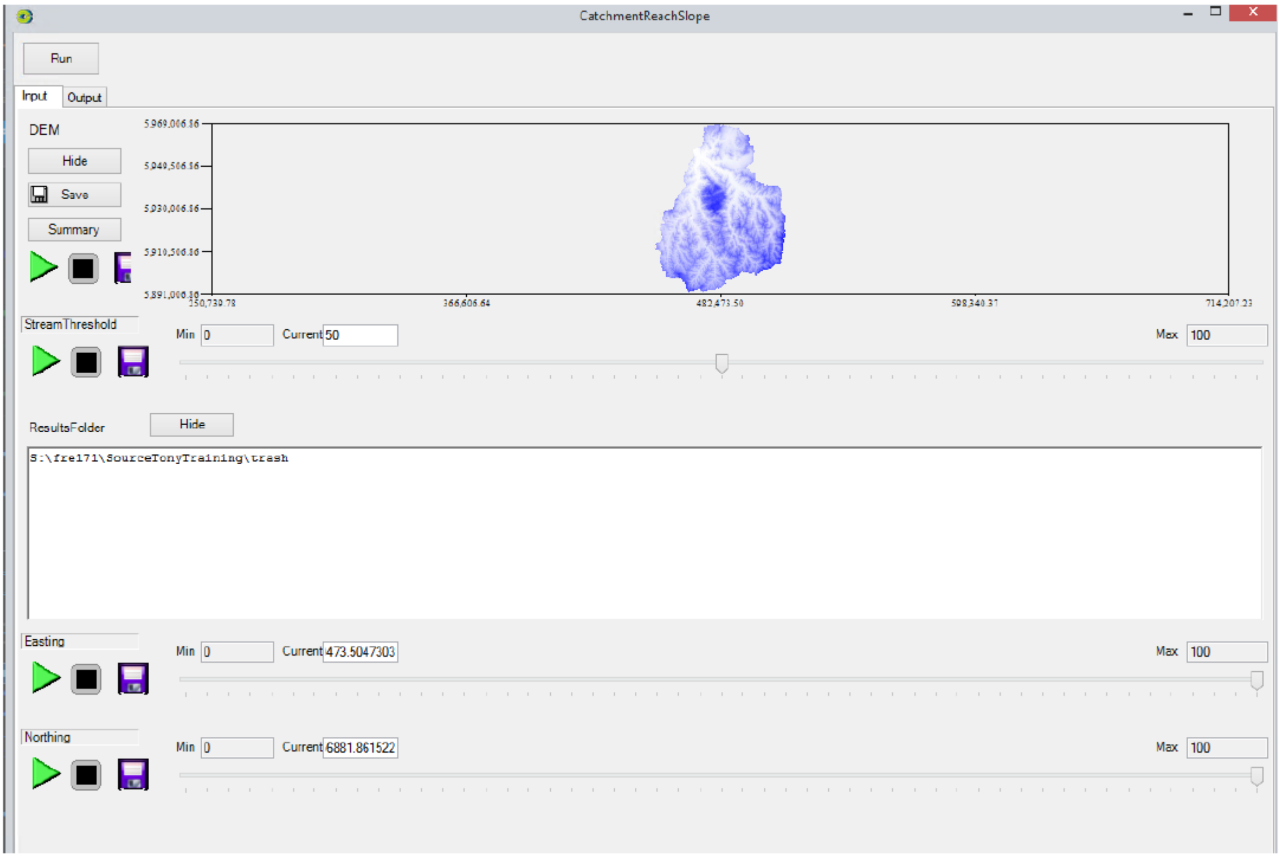
A.3.1 *dSedNet* derived layers model

The dSedNetDerivedLayers model is used to pre-process data. It is found in **Tools-->Plugins→SourcePlugin.CSIRO.dSedNet→dSedNetDerivedLayers**

Data is dragged and dropped onto the spatial component of the widget (Figure 29).

Inputs

- DEM raster (The geometry of this raster should be replicated for all others used, e.g. Land use raster)
- Stream threshold (Contributing area above a stream cell)
- Easting and Northing of outlet
- Directory path to save outputs



StreamThreshold: Min 0 Current 50 Max 100

ResultsFolder: S:\fre171\SourceTonyTraining\trash

Easting: Min 0 Current 473.5047303 Max 100

Northing: Min 0 Current 6881.861522 Max 100

Figure 29 Input screen for deriving spatial layers

Outputs

(Figure 30)

- Stream raster
- Reach slope raster (used to parameterise Gully or Reach model)
- Reach length raster (used to parameterise Gully or Reach model)
- Sub catchment raster (used to define the scenario)
- Network shape file (used to define the scenario)
- Slope raster (for reach, used to parameterise Gully or Reach model)
- Steepness factor raster (used to parameterise Hill slope model)
- Beta factor raster (used to parameterise Hill slope model)

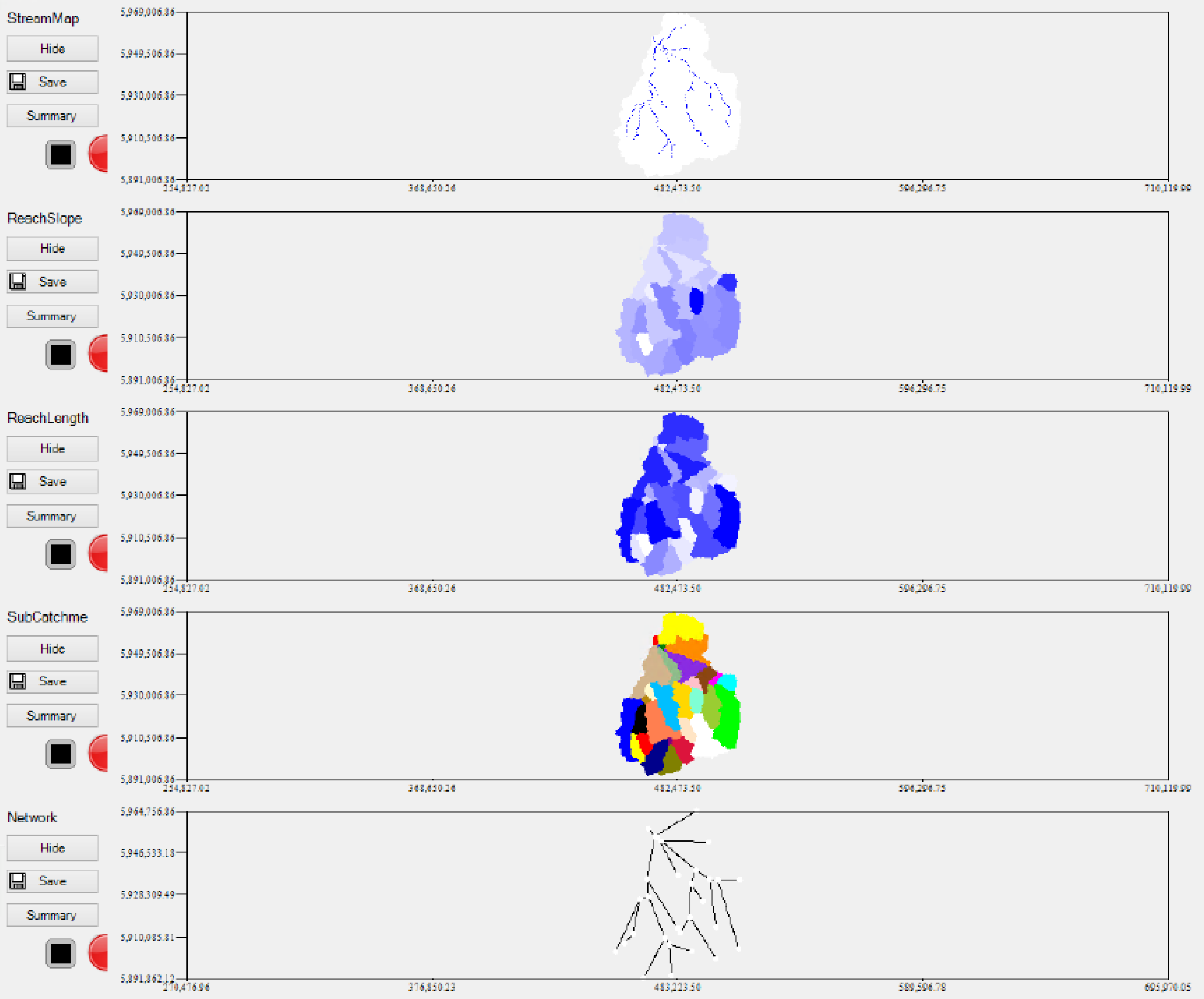


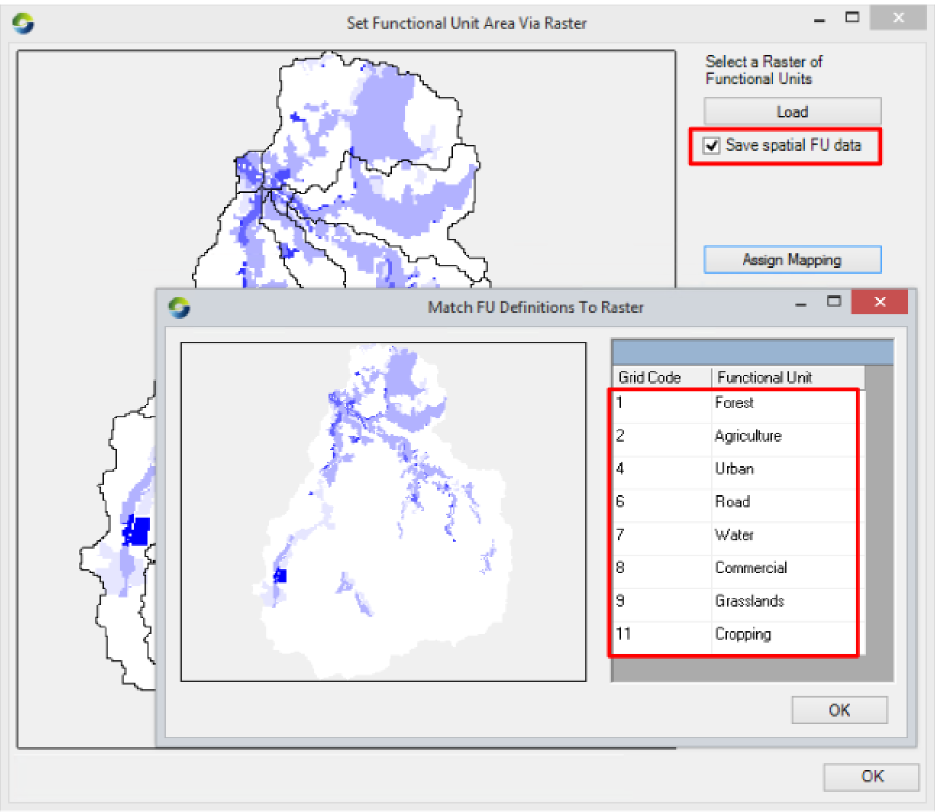
Figure 30 Output screen from deriving spatial layers

A.3.2 Defining FU areas

Functional Unit (FU) areas need to be defined with a spatial layer (often current land use) **Edit → Functional Units → Assign Area Via Raster…**

Ensure that:

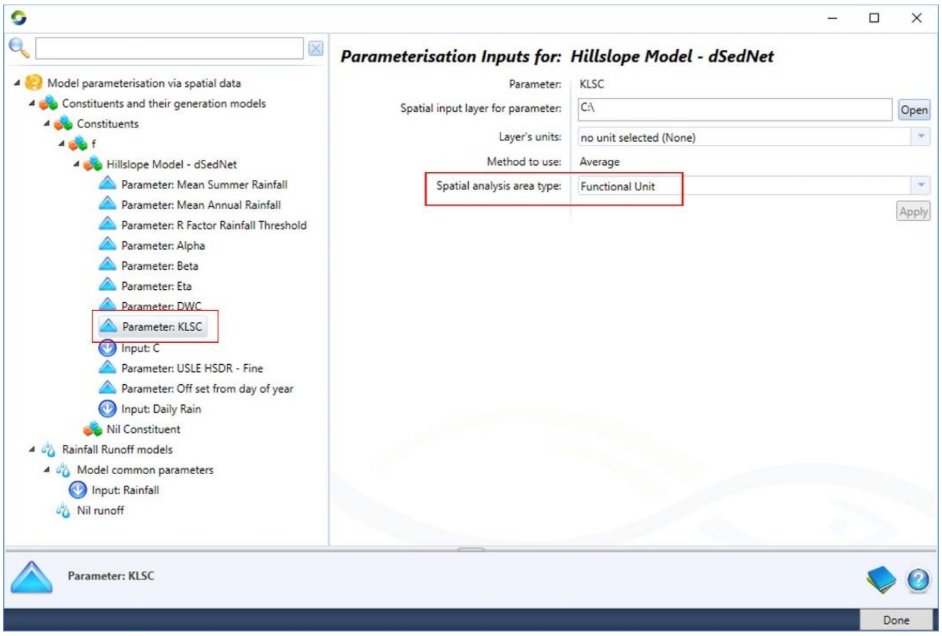
- the FU layer has the same number of land use codes and they are all mapped to a corresponding FU in the scenario, i.e. there is a corresponding value for each catchment cell
- **WARNING: If the FU layer changes then the dSedNet parameterisation needs to be redone.** (Tip - copy the scenario after you have initially defined it)
- Select the check box to Save spatial FU data (Figure 31).



☑ Save spatial FU data

Grid Code	Functional Unit
1	Forest
2	Agriculture
4	Urban
6	Road
7	Water
8	Commercial
9	Grasslands
11	Cropping

Figure 31 Steps in defining FU areas



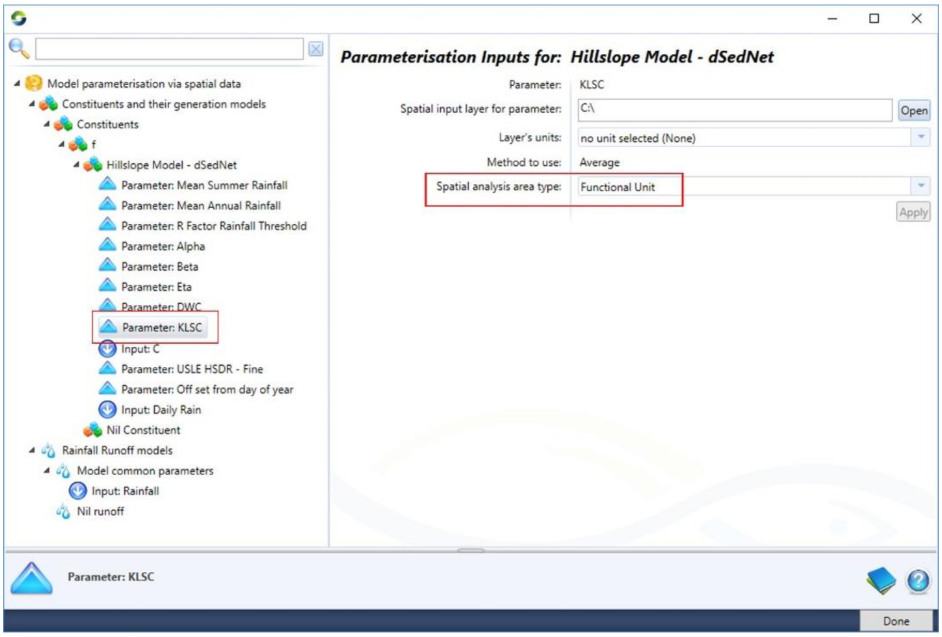
Parameterisation Inputs for: Hillslope Model - dSedNet

Parameter: KLSC
Spatial input layer for parameter: C:\
Layer's units: no unit selected (None)
Method to use: Average
Spatial analysis area type: Functional Unit

Figure 32 Interface to define a FU static parameter (e.g. KLSC)

A.3.3 Parameterising FU temporal inputs (example Cover in Hillslope Model)

On completion the time series data will be found in **Data Sources** under the subheading of **Spatial Data to TS Import**


Parameterisation Inputs for: Hillslope Model - dSedNet

Parameter: KLSC

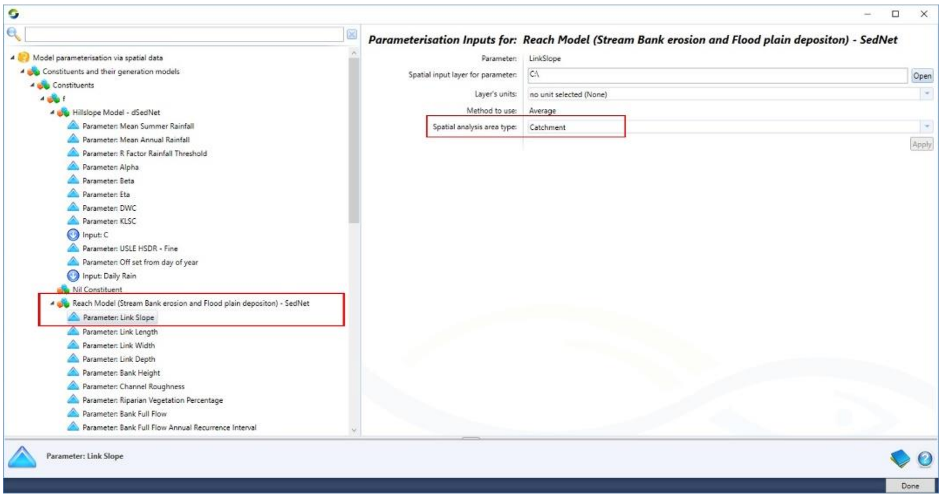
Spatial input layer for parameter: C:\

Layer's units: no unit selected (None)

Method to use: Average

Spatial analysis area type: Functional Unit

Figure 33 Interface to define a FU temporal parameter (e.g. Hillslope cover


Parameterisation Inputs for: Reach Model (Stream Bank erosion and Flood plain depositon) - SedNet

Parameter: LinkSlope

Spatial input layer for parameter: C:\

Layer's units: no unit selected (None)

Method to use: Average

Spatial analysis area type: Catchment

Figure 34 Interface to parameterise a static parameter for a LINK model (e.g. Link Slope of a Reach)

A.4 The spatial parameteriser

Spatial parameterisation has been developed within the *dSedNet* plugin. It can be used to parameterise FU, Catchment and Link models, either single parameters or played timeseries (similar to Source's *climate input tool*).

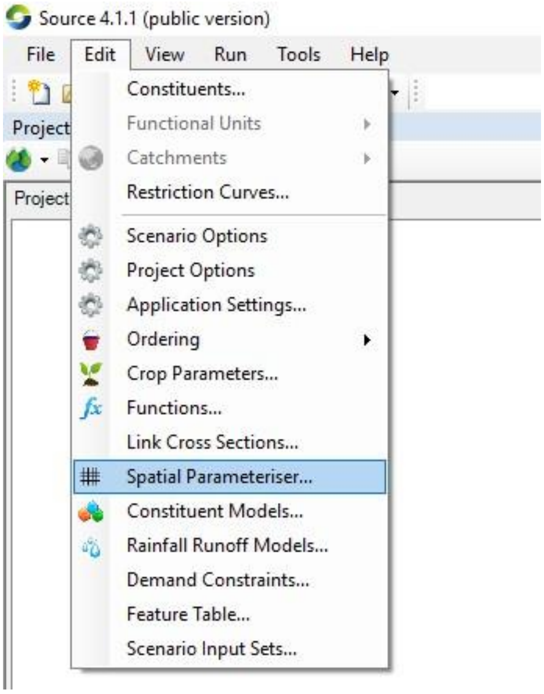


Figure 35 Accessing the Spatial Parameteriser from the Source | Edit menu

A.4.1 Precondition requirements

- FU areas must be defined with a raster and the raster values must have the same number of categories as there are FUs
- If using the spatial parameteriser, the layers used must be comparable with the land use layer used to define the FU areas: same geometry (cell sizes, number of rows and columns, lower left corner coordinates)
- **WARNING: If the FU layer changes then the dSedNet parameterisation needs to be redone.** (Tip - copy the scenario after you have initially defined it)
- There is at least one layer to process for spatially assigning inputs
  - Layers are labelled ddMMyyyy
  - Each layer represents continuous days (no gaps).

A.5 The temporal parameteriser

Temporal parameterisation has been developed within the *dSedNet* plugin. Its function is to populate model parameters with values obtained via analysis of a model’s output timeseries. For example, the long-term annual average of runoff from a FU can be used as a parameter value for a model allocated to that particular FU.

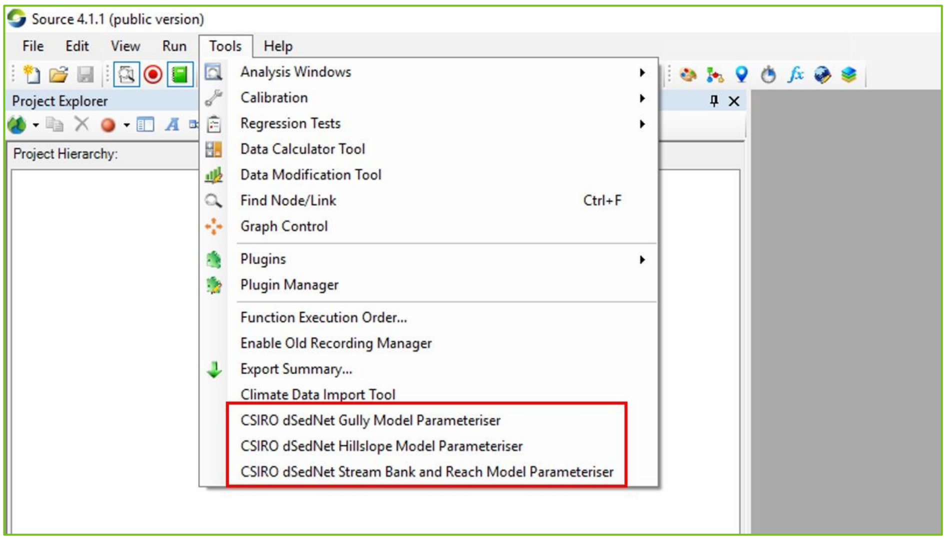


Figure 36 Selecting the dSedNet parameterisers from the Source | Tools menu

The temporal parameterisation for particular models in the *dSedNet* plugin has been implemented as a black box. The user only needs to set initial model parameter values and then run the parameteriser. The tool has been configured to record the required timeseries while the model executes one full run.

Finally, the desired statistic is calculated, and the result applied to the correct model parameter for each FU with that model. This process is executed as a pre-process step before the actual model run.

Parameters which are assigned by the temporal parameteriser include:

- Hillslope erosion model
  - Cover (C, KLSC,
  - Mean annual rainfall
  - Total gully volume
- Gully erosion model
  - Gully annual average sediment supply
  - Gully long-term runoff factor
- Streambank erosion model
  - Link stream bed slope
  - Long term average daily flow.

A.5.1 Precondition requirements

The Temporal parameteriser must be run as the last step of the model's parameterisation and requires that:

- The simulation period is defined and fixed. If the simulation period is changed then the parameterisation process must be rerun.
- The hydrological model must be calibrated.
- **WARNING: Changing the time period of the model run will produce different values. This may be a problem if the model is later executed over a different time period, e.g Drought vs Normal season**.

A.6 *dSedNet* Plugin code

The Plugin code is available in: https://bitbucket.org/ewater/sourceplugin.csiro.*dSedNet.*

Appendix B Data requirements and how they were met

This Appendix describes the parameters for the *dSedNet* models, and how they were populated for Westernport. Each parameter is discussed, and then summarised in Table XXXXXXX.

The parameters for the *dSedNet* models usually mirror those used in the formulas from Wilkinson, et al 2014. However, there are some model parameters that allow alternative ways to configure the model and affect its internal processing, for example assigning a constant value or a timeseries to a parameter.

B.1 Digital elevation model (DEM)

A digital elevation model (DEM) was obtained from Melbourne Water representing a 10m cell resolution for the entire Westernport catchment. Existing mapped watercourses provided by Melbourne Water were used to then prepare a stream line raster for further refinement of the DEM, as the lower parts of the catchment have very little slope and the DEM was not able to be used to derive subcatchment and stream boundaries properly in this region. The original DEM was resampled to 20m to be more workable within the Source model (i.e. it is a smaller dataset which helps manage load and processing times) and the stream line raster was then merged onto the DEM at 1m lower elevation than the point at which it was merged. This process, called ‘stream burning’, creates channels in the DEM consistent with the stream locations based on mapping, rather than allowing these to be created from the DEM itself. It is particularly useful in flatter terrain and especially where there are multiple channels such as those in the lower parts of catchment through the former Koo Wee Rup swamp.

From this, catchment boundaries were created using a 5 km^2 stream threshold generating 373 subcatchments for the full Westernport catchment model.

B.2 Hillslope erosion model

Hillslope erosion in each FU is estimated using the Revised Universal Soil Loss Equation (RUSLE) (parameters R*K*L*S*C*P) (Eqn 2). This is multiplied by the area of the FU (A in eqn 1) and a hillslope delivery ratio (HSDR). FU area is provided by Source, and HSDR is a ratio [0…1] set by the expert user.

Hillslope supply from each subcatchment is then the sum of the contributions from all FUs in the subcatchment (Wilkinson et al 2014).

Eqn. 1

$$H_x = \sum_{i=1}^{n} E_i A_i HSDR_i$$

Eqn. 2

$$E_i = RKLSCP$$

Hill slope delivery ratio (HSDR)

Hill slope delivery ratio (HSDR) can be manually input at the functional unit (FU) level or spatially parameterised. A HSDR value of 5% is appropriate for hillslope delivery in southern Australia (Prosser et al 2001a). The study applied 0.05 universally across the catchment, though this could be refined further if additional evidence on hillslope delivery became available. It could be argued that higher ratios should apply according to stream proximity in order to represent the potential for higher sediment delivery near watercourses; however the net effect of this across the hillslope scale is likely to be minor as these areas would typically comprise a small proportion (e.g. <5%) of the total subcatchment area.

Rainfall erosivity (R)

Rainfall erosivity (R) is an indicator of the ability of water to detach and transport soil particles; thus erosion is sensitive to the intensity and duration of rainfall (Teng et al, 2016). The *dSedNet* model calculates R from daily rainfall used in the model and globally set parameters associated with 30 minute duration rainfall intensity. The R parameter is calculated daily within the model.

Soil erodibility (K)

Soil erodibility (K) represents the susceptibility of the soil to erosion as measured under the standard unit plot condition (Teng et al, 2016). K was mapped across Australia by Teng et al (2016). This work showed that K was reasonably uniform at 0.027 tonnes ha h ha^{-1} MJ^{-1} mm^{-1} across Westernport catchment, and this value was adopted for the Westernport *dSedNet* Model as a global parameter.

Slope length factor (L)

The slope length factor (L) is defined as the horizontal distance from the original point generation of overland flow to the point where the slope decreases to the extent that deposition begins, or where runoff flows into a defined channel (Teng et al, 2016). Teng et al (2016) present a series of equations for its calculation based on DEM derived parameters at RUSLE plot scale, e.g. based on slope angle, flow accumulation and ratios of rill to inter-rill erosion. This requires additional data at fine (plot) scale. Given L sensitivity in the hillslope model is relatively low and that in areas of low gradient where land use and hillslope erosion are most important the hillslope length is difficult to define (Lu et al 2003), it is defensible to ignore the parameter, i.e. set as 1 (Wilkinson pers.comm.).

Slope steepness factor (S)

The slope steepness factor (S) is spatially parameterised and is calculated either directly from the DEM outside of the model or within the spatial parameteriser provided with *dSedNet*. It is simply related to the gradient of the slope. In Source+*dSedNet*@Westernport, this was derived from the DEM using the *dSedNet* spatial parameteriser. Overall, the slope steepness in the Westernport catchments is resolved down to a 20m by 20m grid which provides consistency with the DEM used to derive subcatchment boundaries and is also fine enough to resolve the flatter terrain in the lower parts of the catchment.

Cover factor (C)

Cover factor (C) is a dimensionless parameter that represents the effects of vegetation canopy and ground cover, surface roughness, land use, mulch cover and soil organic matter in reducing soil loss (Teng et al, 2016, Yang, 2014). Within this project, the *dSedNet* model was modified to allow for temporally varying cover factors to be used. This was achieved by compiling C grids at a given time step as a data cube and generating a time series using a data drilling method. Data coverage must be 100% across the study area as the model requires continuous data at the FU scale. Currently, the best available data allows for monthly cover grids to be generated, however if data provision improves, this could be refined to shorter time periods (e.g. a cover model could be used to provide daily cover grids).

C can be derived from vegetation ground cover data. Rosewell (1993) provides tables relating C to percent ground cover for different vegetation types. In this study, the tables relating to permanent pasture and undisturbed forest land were applied (Tables D-5 and D-4 respectively in Rosewell, 1993). For a set of 200+

random points within the forested land use areas, total monthly ground cover derived from MODIS satellite data (Paget and King, 2008) from Jan 2017 to May 2018 were extracted. There was no apparent change across the time series and values were generally close to 100% total cover (5th%ile = 90%).

Table D-4 relates 75-100% total cover (canopy and undergrowth) to a C factor range of 0.0001 to 0.001 (Rosewell, 1993) and we adopted a static value of 0.001 for forested land.

The curve for permanent pasture, derived from Table D-5 (Rosewell, 1993) was applied to all other areas where the hillslope erosion module was active (mainly grazing/cropping, livestock production and grassland). Data were fitted with a 3-order polynomial trend line which gave a coefficient of determination (R^2) of >0.99 (Figure 37). The equation of the line was used to convert ground cover raster data to C for these areas.

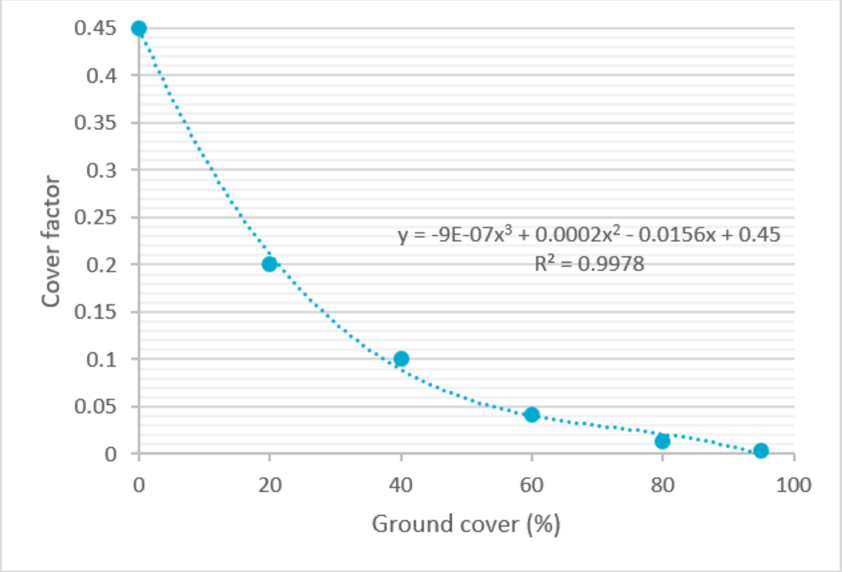


Figure 37 Relationship between cover factor and ground cover for permanent pasture and rangeland or scrub (Rosewell, 1993)

Ground cover can be derived as the inverse of bare soil proportion from remote sensing data. Monthly bare soil index data derived from MODIS satellite data at 500m resolution (Paget and King, 2008) were evaluated. Validation of the MODIS product against 1171 field observations across Australia resulted in a root mean square error (RMSE) of 17% for the bare soil proportion (Guerschman et al, 2012). Coverage was complete for the study area (excluding large open water bodies like Cardinia Reservoir) across a time series from February 2000 to present (May 2018 at the time of writing). Geoprocessing of these data involved 3 main steps; 1) inverting bare soil proportion to vegetation cover, 2) extending the grid to fully cover the catchment area using a bilinear interpolation method, and 3) converting ground cover to C by applying the equations and values based on tables D-4 and D-5 in Rosewell (1993). The 220 monthly C factor grids were processed at 20m resolution matching the DEM and land use grids.

Seasonal fractional vegetation data (TERN AusCover, 2018b) based on Landsat data at ~30m resolution for the study area were also evaluated. Fractional cover model validation produced a RMSE of 13% for bare soil (TERN AusCover, 2018b). These data had very patchy coverage, typically in the order of about 50%, across the Westernport catchment. Cloud masking and atmospheric disturbances can affect data acquisition and areas with >15% tree canopy cover are also subject to high error –hence the absence of data particularly in the forested headwaters of the Westernport catchment. The large gaps across similar areas prevented filling in using data from previous time periods and interpolation techniques were inappropriate at this scale (over 10s of kilometres). To highlight the spatially coinciding data gaps an overlay of all 2016 and 2017 data (8 grids total) shows these large areas of no data, particularly in the upper catchment, shown in white in Figure 38.

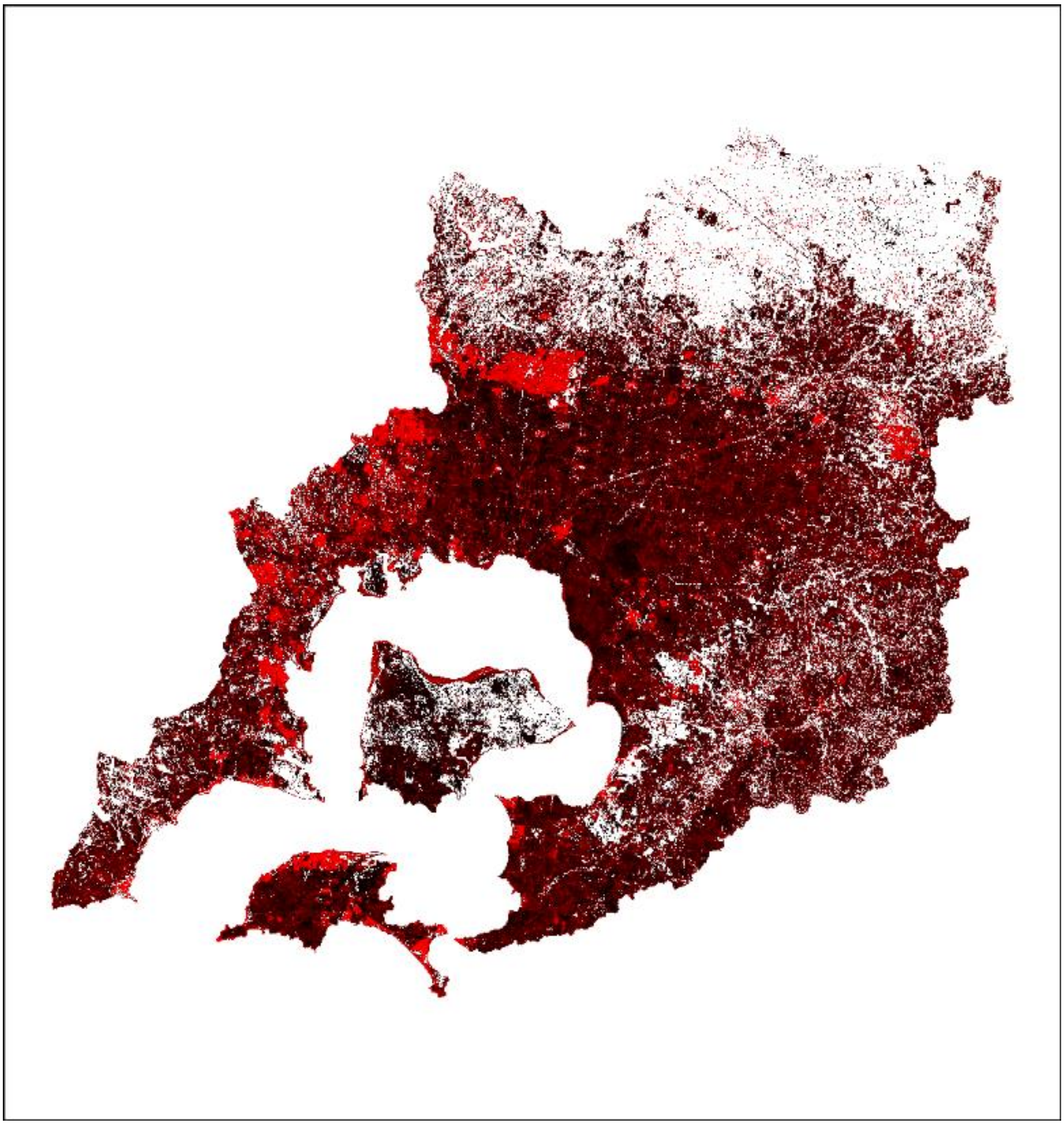


Figure 38 Overlaid 3-monthly Landsat data from 2016 and 2017 (8 grids total) where white areas within the catchment indicate spatially coinciding data gaps (data source TERN AusCover, 2018b)

These cover maps are project data products and are available on request from Melbourne Water.

Static vs dynamic cover

The values of the three parameters *KLSC*, *C* and *KLSCdynamic* alter the behaviour of the model to determine what value is used in the calculations. The options are:

1. As a played timeseries (*KLSCdynamic*), possibly generated by the spatial parameteriser from a series of spatial layers
2. As a constant in full (*KLSC*)
3. A mixture, where *KLSC* is static and *C* is dynamic (*KLS* portion is static and *C* is played as a timeseries input). Note: in this case, *KLSC* is only made up of *K*, *L* and *S*, *C* is the variable.

Note: If you have previously applied a constant value to *KLSC* (or *C*) and are changing to use a timeseries *KLSCdynamic* (option 1 above), you will need to set the static value back to 0 (zero).

The decision process is captured in Figure 39.

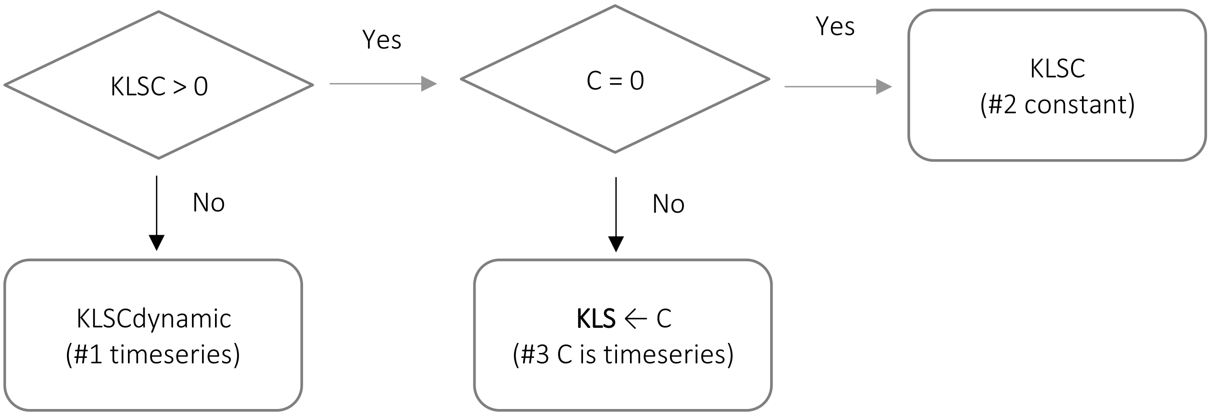


Figure 39 *KLSC* Flowchart for the three input parameters

B.3 Gully erosion model

Gully erosion represents ongoing incision and enlargement of hillslope drainage lines and streams which have smaller contributing areas than the upstream extent of the model stream network (Wilkinson et al, 2014). For modelling purposes, gullies represent lower order watercourses than those represented in the model stream network.

An input map of the current areal density of gullies, their age and cross-section, together with relevant soil properties are used to calculate volume. Eqns 3 and 4 are from Wilkinson et al (2014).

Eqn. 3

$$G_x = \frac{1}{365}\frac{p_G \rho_G a_G L_G f_G M_G}{\bar{t}} f_{RO}$$

Eqn. 4

$$f_{RO} = \left(\frac{1}{\frac{1}{n}\sum RO_{LT}^{b}}\right) RO^{b}$$

Proportion fine sediment (Pf)

Proportion of fines is spatially parameterised using a grid input format. Proportion of fines on a scale of 0-1 represents the fraction of clay and silt in the upper soil layer. The Soil and Landscape Grid of Australia provides National Soil Attribute Maps that are generated by combining Australia-wide digital soil attribute maps derived using consistent data mining-kriging models and regional maps for parts of Australia, derived using disaggregation and regression modelling (Viscarra Rossel et al, 2014). These National scale grid data are available at 30 arc second resolution (~90m) and estimate parameters for 6 defined depth intervals (0-5cm, 5-15cm, 15-30cm, 30-60cm, 60-100cm and 100-200cm). Attributes include clay (< 2 um mass fraction of the < 2 mm soil material) and silt (2-20 um mass fraction of the < 2 mm soil material) for soil layers. Data for the 0-5cm depth for both clay and silt were extracted for the study area. These were added to give total proportion of fine sediment, resampled to 20 m resolution (matching the DEM grid used in the model) and interpolated and extrapolated using an average nearest neighbour technique to fill gaps and extend to the catchment boundary. The resulting grid was exported as a text format for input to the model (see Figure 40).

Soil bulk density (Pb)

Soil bulk density is spatially parameterised using a grid input format. Soil bulk density represents the dry bulk density of the gully subsoil expressed in t/m^3. The Soil and Landscape Grid of Australia provides this attribute as a measure of the whole soil (including coarse fragments) in mass per unit volume (as $g/cm^3 = t/m^3$) by a method equivalent to the core method for upper soil layers (Viscarra Rossel et al, 2014). Data for the 0-5cm depth were extracted for the study area, resampled to 20m resolution (matching the DEM grid used in the model) and interpolated and extrapolated using an average nearest neighbour technique to fill gaps and extend to the catchment boundary (Figure 40). The resulting grid was exported as a text format for input to the model.

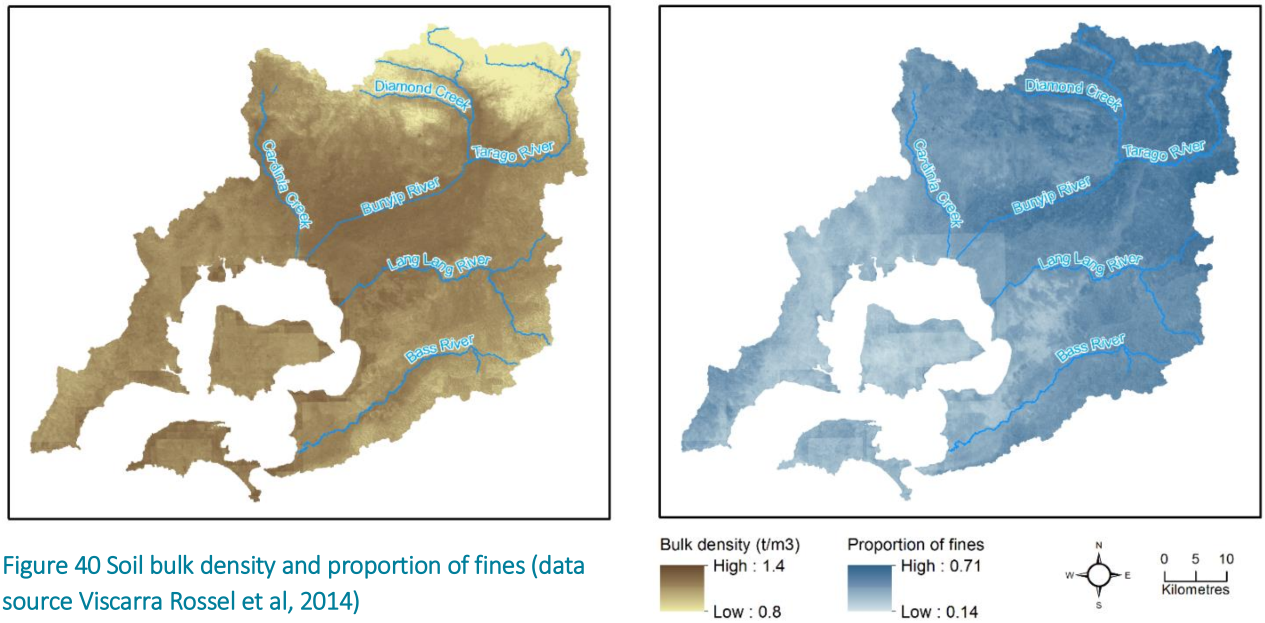


Figure 40 Soil bulk density and proportion of fines (data source Viscarra Rossel et al, 2014)

Gully cross sectional area or depth (aG)

Gully cross sectional area is a globally set parameter representing the contemporary gully cross sectional area (aG in m^2). In the absence of detailed gully surveying information or very high resolution (e.g. sub-metre) elevation data from which actual values could be estimated, a value of 10 m^2 was determined to be appropriate for the study area. Previous studies of gully morphology indicated a reasonably uniform value of 10m^2 for gullies mapped in Australia; spatial variation in aG is generally overshadowed by variations in overall gully density (Prosser et al, 2001b).

Gully density or gully length (LG)

LG is spatially parameterised using a grid (ascii) format. It can be expressed as gully length (product of FU gully density and FU area) or simply as gully density (length of gully within FU grid in km/km^2) (Wilkinson et al, 2014). In this study the density expression of LG was used. Data from gully mapping of the Westernport catchment conducted by Hughes et al (2003) were acquired for the current study and checked against current (typically within 3-5 years of currency) aerial base maps from ESRI World Imagery (2018) using visual interpretation of images at a viewing scale of about 1:5000. High resolution aerial imagery tiles captured in 2014 and 2017 were later supplied by Melbourne Water and visually compared very closely to images sourced from ESRI World Imagery (2018). The following revisions to the original geometry and attributes of the 2003 gully mapping were made and saved to a new vector file:

- Spatial correction of entire dataset moving all features 220m to the north-east to align with terrain relief visible in a 10m DEM.
- Added field 'Active' to record 0 where a gully was determined inactive and 1 where active.
- Gully Active was determined through visual interpretation of current aerial imagery from ESRI base layers.
- 1 was assigned where the gully had sharply incised banks and/or presence of bare ground at base or edges.
- 0 was assigned where the gully had rounded banks with partial or complete vegetation cover at base or edges.

- Some gullies were deleted where land use had changed and gully was no longer visible, e.g. urban development, agriculture.
- New gullies were identified through the process of checking 2003 gully mapping.

The gully density grid was created from the new vector file using the following work flow:

1. Created 100m grid across the Westernport catchment
2. Selected active gullies from the gully polyline mapping and save separately
3. Summed length of all active gullies within each grid cell and divided by cell area (km/km2)
4. Created final gully density grid (km/km2) at 10m resolution projected in GDA94 MGA55 in ascii format for the Westernport catchment.

The revision of the 2003 gully mapping revealed 22% (95 km) of previously mapped gullies remained active. Gully activity and density is shown in Figure 41.

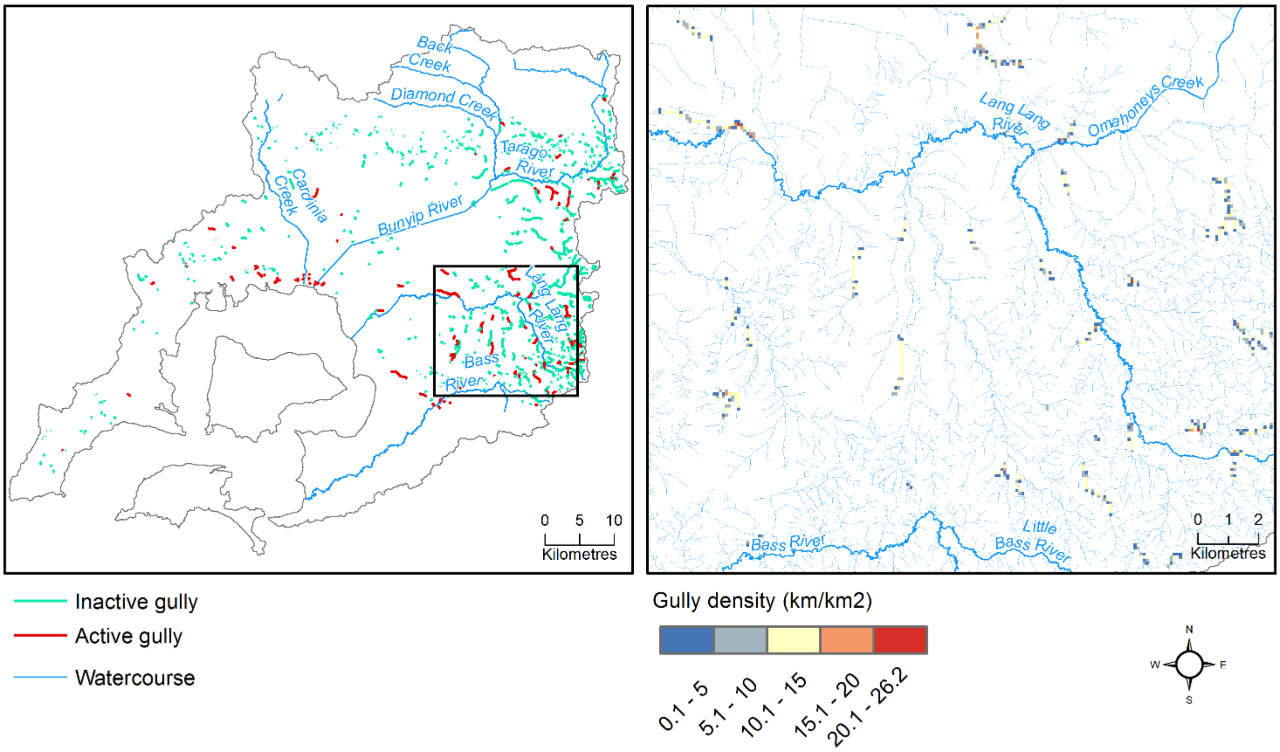


Figure 41 Gully activity and density based on revision of previous mapping (Hughes et al, 2003)

The revised gully density map is a project data product and is available on request from Melbourne Water.

Gully age (T)

Gully age (T) is a globally set parameter representing the mean age of the gully network. Wilkinson et al (2014) cite studies referring to gullies being initiated largely through landscape intensification occurring during European settlement in the late 19th and early 20th centuries. For this reason, gully age has been estimated using this period as the start date. Gully age in the model is inversely linearly proportional to sediment generation potential, i.e. the older the gullies the less sediment generation is predicted however, sensitivity in the model is relatively low. In the Hughes et al (2003) study of Westernport, a gully age of 100 years was applied, this study mapped those remaining active gullies and assumed a contemporary age of 120 years (1900-2018). Of the 95km of active gullies in 2018, 13% were not mapped in 2003. This could be as a result of recent land use changes e.g. urban developments, or due to data limitations in the 2003 gully mapping exercise, these gullies may have been missed.

Gully activity factor (fG)

The gully activity factor (fG) is a globally set parameter representing changes in gully sediment supply over the modelling period, relative to the long-term average over the entire life of the gully features e.g. in regions where gullies are now mature and less active. This parameter is highly sensitive in the model. Hughes et al (2003) did not apply this parameter in the earlier build of the Westernport SedNet model. The Burdekin basin dynamic SedNet study ignored the parameter (set to 1) due to a lack of data on gully maturity (Wilkinson et al, 2014). In the current study, fG was set to 0.5 initially to represent that most of the gullies in Westernport catchment are mature (age ~120 years) and less likely to generate sediment (Wilkinson pers. comm.). This parameter can be used to calibrate against observed water quality data where available.

Management factor (Mg)

The management factor (Mg) is a globally set parameter representing gully activity changes through land management practices as a proportion of historical rates. Practices to improve gully management include contour banks, check-dams, or revegetation. This parameter was not applied in the previous Hughes et al (2003) Westernport study or by Wilkinson et al (2014) for the Burdekin basin. In the current study, the Mg value was initially set to 1 (i.e. ignored) but could be reduced upon evidence of management practices such as revegetation programs, or as a lever in scenarios where practices are implemented.

B.4 Streambank erosion model

Streambank erosion is modelled along the model stream network, while channel erosion upstream of the network is represented by gully erosion. Thus, the threshold catchment area used to define the upper limit of the stream network should include all streams having significant streambank erosion that are not represented in the gully density grid (Wilkinson et al 2014).

Streambank erosion is modelled along the stream network, while channel erosion upstream of the network is represented by gully erosion. Thus, the threshold catchment area used to define the upper limit of the stream network should include all streams having significant streambank erosion that are not represented in the gully density grid. The suspended sediment supply from streambank erosion along a link (t/day) is derived by multiplying the mean-annual SedNet function of stream power and bank erodibility (Wilkinson et al, 2009).

Eqn. 5
$$B_f = \frac{1}{365} p_f \rho_s h L_l \left(k \rho_w g S_l Q_{bf} \right) \overline{E}_i f_Q$$

Eqn. 6
$$E_i = [1 - \min\{(RipVeg, MaxVegEffectivness)] \times SoilErod$$

Link stream bed slope (Sl)

Link stream bed slope (Sl) is spatially parameterised at link level through model calculation based on the link network and underlying DEM.

Bank full discharge (Qbf)

Bank full discharge (Qbf) is a manually input parameter applied at link level that represents a discharge of defined recurrence interval (m^3/s) based on long term hydrograph analysis and is a sensitive parameter. Hydrographs from a long-term hydrological model run of the Westernport Source model revealed the appropriate flow discharge rate to be the 5 year ARI. This was used in the application at corresponding links.

Proportion of fine sediment in bank subsoil

Spatially parameterised at link level and represents proportion of fine sediment in bank subsoil. This uses the same data as applied in the gully module (Pf).

Streambank subsoil dry bulk density

Spatially parameterised at link level and represents streambank subsoil dry bulk density (t/m^3). This uses the same data as applied in the gully module (Pb).

Bank height (h)

This parameter is spatially parameterised at link level and represents the height of the bank surface exposed to erosion and is not necessarily the full channel height or depth (Ellis and Searle, 2014). Uniform values for a river network can be used e.g. values of 1.5–3m are common (Wilkinson et al, 2008). Alternatively, height (h) can be varied according to a function of upstream catchment area and slope or some other coefficient where a relationship can be established (Wilkinson et al, 2014). In this application, point buffer estimations were evaluated directly from the 1m LiDAR DEM data across the main stream lines to evaluate height.

Victorian government Index of Stream Condition (ISC) data giving reach averaged stream width and bank height were available for part of the Westernport catchment for high order streams. It was beyond the scope of the current study to extend the ISC mapping methods across the catchment and a simplified approach was developed for the purposes of deriving the bank height parameter. The statistics of the ISC data were used to approximate stream widths to apply for estimation of bank heights from recently acquired 1m elevation data (Melbourne Water 2017/18 LiDAR data). 90% of the ISC stream bank full width values were below 53m, median width was 17m (Figure 42).

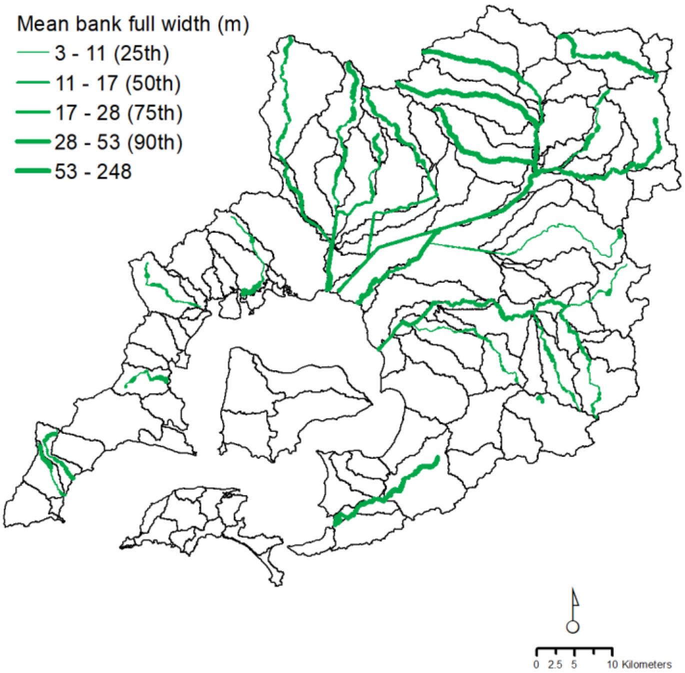


Figure 42 Reach averaged stream bank full widths from Index of Stream Condition data within Westernport catchment

The workflow for generating bank height estimates from 1m LiDAR data was set up in Model Builder within the ArcGIS (version 10.2) environment. This method is subsequently referred to as buffer-point. Following mosaicking the original 3940 1m DEM tiles (total size 63GB) into four rasters in separate file geodatabases (each mosaic file size ~4GB from ~1000 tiles) the following steps were applied to each dataset:

- Resample DEM raster to 5m (bilinear) to increase processing efficiency and retain acceptable stream feature precision.

- Pit fill resampled DEM, generate flow direction raster, flow accumulation raster (min 4000*5m cells or 10 hectares) and stream order raster.
- Convert stream order raster to polyline (no line simplifying) filtering out first order streams (and second order for mosaic #1) to create a stream network that represents drainage paths of the Source model stream link network.
- Generate points along stream centrelines every 100m including start/end (resulted in ~6000 points per mosaic).
- Buffer points by radius of 10m and add surface information (min z, max z) from 1m DEM within circles, calculate bank height (h) for each circle (zmax – zmin).

Bank height estimates may be between zmax and zmin points anywhere within the buffer, there is a degree of error through elevation differences upstream/downstream within the buffer and from differences between heights of opposing banks.

The resulting stream network from which bank heights were sampled is shown in Figure 43. As the stream order network was generated separately for each mosaic (1-4) the result is not hydrologically accurate. It is used in the bank height calculation workflow as a way to filter out lower order drainage paths that are not representative of the SOURCE stream link network.

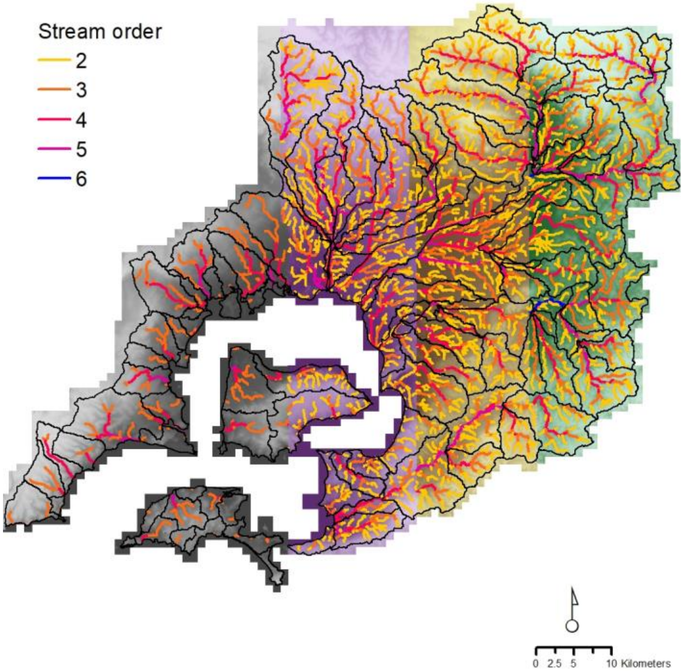


Figure 43 1m DEM mosaic extents indicated by different colour ramps and resulting ordered stream network

Bank height estimates were compared against Victorian government Index of Stream Condition (ISC) data where they spatially coincided. The metrics are not directly comparable as ISC metrics are summarised at reach level. ISC methods calculate the difference between stream bed elevation and that of the lower of the two stream banks tops (Figure 44), whereas the method applied here simply calculates the difference between stream centreline elevation and the highest point within the buffer area.

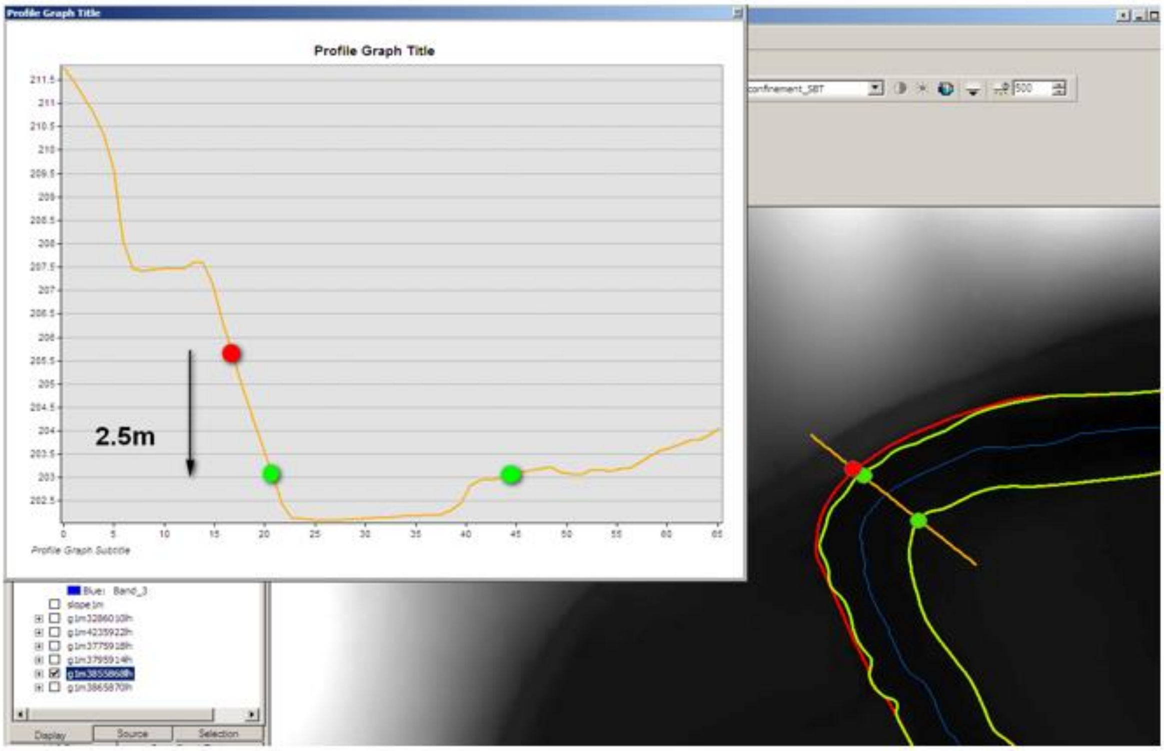


Figure 44 Opposing bank height difference correction method applied in the Index of Stream Condition bank height metric

The buffer-point method is therefore likely to overestimate bank height. This was reflected when 10m buffer-point height distributions were compared with ISC data (Table 17). Applying a scalar of 0.7 to the 10m buffer-point estimates adjusted percentile values to with 19cm of ISC heights.

Table 17 Spatially coinciding bank height estimation comparison with ISC metric (n=17309)

Percentile	10m buffer-point bank height (m)	ISC reach averaged bank height (m)	Rescaled buffer point height (m)
25th	1.51	0.87	1.06
50th	2.28	1.50	1.60
75th	3.61	2.50	2.53
90th	4.76	3.42	3.34

The buffer-point method was also applied using 15m, 20m and 25m buffer distances. Larger buffer distances increased bank height estimates. Aggregated at subcatchment level, using a buffer distance of 25m compared to 10m increased mean bank height by 83%. Larger buffer distance also increases potential error due to differences in elevation upstream/downstream within the buffer area and differences between heights of opposing banks.

Rescaled 10m buffer-point estimates were converted to grid format for input to dSedNet. Centres of buffer circles were converted to raster format (matching the cell size and extent of the 20m Source model reference grid) taking the mean value where more than one point fell within a cell. The spatial parameteriser in *dSedNet* reads the bank height grid and calculates a mean from values within each sub catchment (one link per subcatchment).

Note that active bank height was estimated across an average of streams, including those of lower order. An alternative would be to estimate based on only the higher order streams represented by the Source link network. It may be that the bank height method also affects the spatial pattern, since there will be more 'streams' (ie lower order streams) in wetter areas. This cannot be assessed without further testing.

Link length (Ll)

Simply the length of the stream network represented at the link level. The Ll is spatially parameterised at link level through Source model calculation based on the node-link network.

Erodibility exponent (b)

The erodibility exponent (b) is a globally applied parameter used to scale erodibility and applied as a calibration parameter against observed loads. An initial value of 1 was applied and if the streambank model is found to overestimate loads compared to observations, then b can be reduced during calibration and vice versa.

Erodible soil extent (SoilErod)

Erodible soil extent (SoilErod) is spatially parameterised using a raster grid of soil properties. SoilErod represents the extent of erodible area along streams. The grid contains either 1 or 0 values where 1 indicates the cell is erodible. Areas inundated in major flood events are likely to have erodible soil. Melbourne Water provided flood inundation models (FIMs) for 5-, 10-, 20-, 50- and 100-year recurrence intervals. Due to the channelized nature of the Westernport catchment in low lying areas, Recurrence Intervals below 100 years had extremely limited extents. The 100-year inundation extent was used to represent the extent of streambanks from which sediment could be mobilised.

Riparian vegetation proportion (RipVeg)

Riparian vegetation proportion (RipVeg) is spatially parameterised at the link level using gridded values representing the proportion of riparian vegetation cover.

Seasonal fractional vegetation cover data available from the Terrestrial Ecosystem Research Network provides vegetation and bare ground cover on a 30m grid across Australia (TERN, 2018). However, these data contained gaps where tree cover exceeds ~15% as estimates of ground cover become unreliable (TERN, 2018). This resulted in very patchy coverage across the study area. For example, the bare ground fraction data (band 1 for Dec 2017 to Feb 2018) covered 43% of the Westernport catchment, with extensive areas of no data particularly in riparian zones and in the upper catchment areas where there is a higher density of tree cover.

Moderate Resolution Imaging Spectroradiometer (MODIS) derived data (Guerschman et al, 2009) provides vegetation indices for 8, 16 day, monthly and annual with complete coverage but at ~500m resolution is too coarse for riparian cover estimates.

Given the above limitations, Melbourne Water provided 2016 tree canopy polygon data for riparian zones (0-200m stream buffer) in Westernport catchment. These data represented presence/absence of tree canopy and did not capture vegetation with low vertical projection e.g. grasses and shrubs. Tree canopy was mapped at a fine scale (~1: 5000) from remote sensing and aerial image digitisation and captured considerable detail. The proportional area of tree canopy occurring within 1ha grid cells was calculated across Westernport catchment and resampled to the 20m grid for input to the model (Figure 45).

While tree cover alone is not necessarily representative of riparian vegetation that stabilises streambanks that also includes low standing types, it is indicative of intact streambank vegetation occurrence and is a useful indicator of where stable streambanks may be present. It should also be noted that areas of engineered stream works would be present in the catchment (such as armouring). During the project, this issue was discussed and there was the potential to use the riparian vegetation proportion as a surrogate for stream interventions, but this was not adopted due to not having access to a data layer identifying the locations of these interventions.

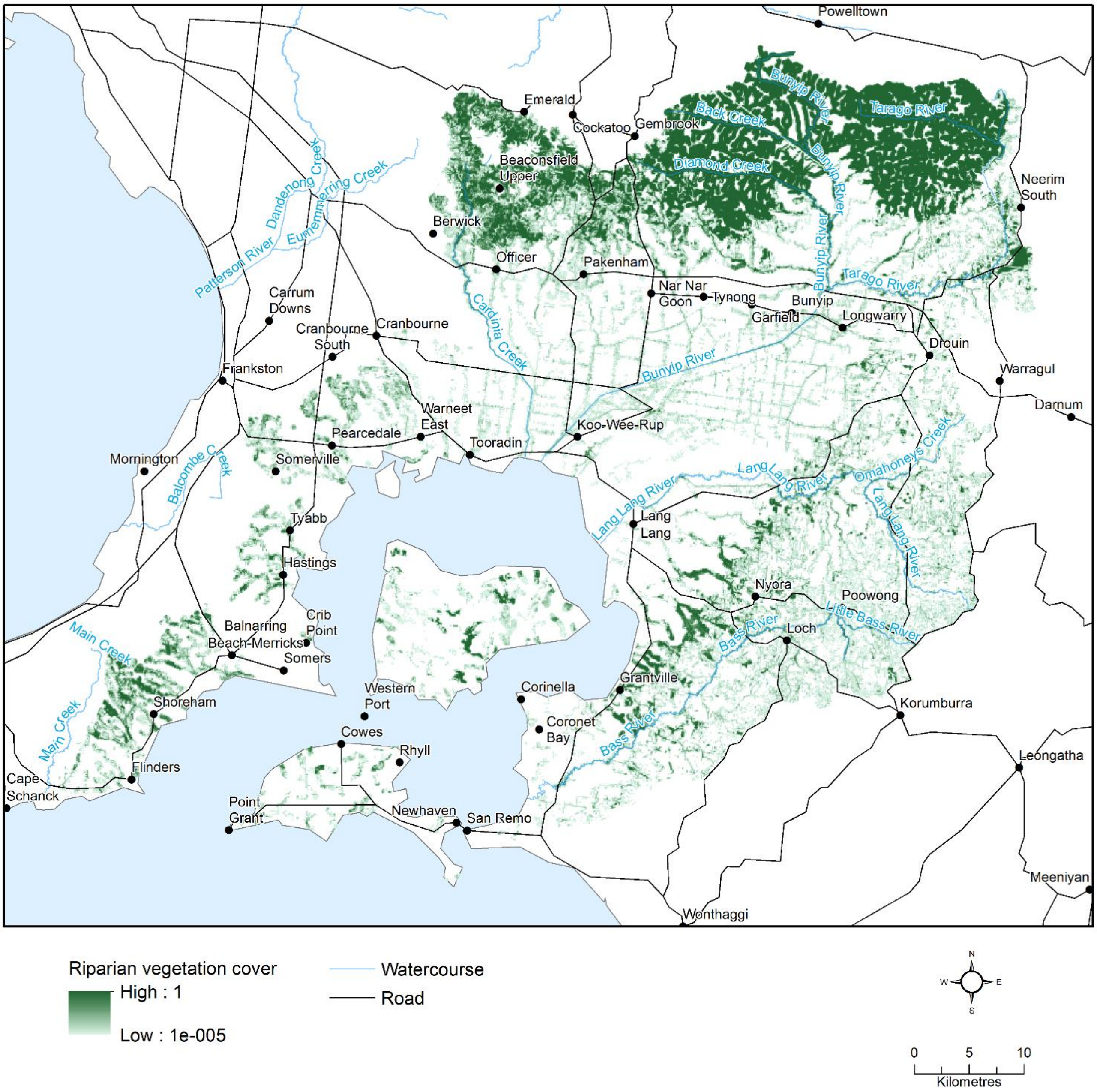


Figure 45 Riparian vegetation cover based on 2016 tree canopy mapping within 200m of streams (data source: Melbourne Water)

Maximum vegetation effectiveness (MaxVegEff / MaxVegEffectiveness)

Maximum vegetation effectiveness is a globally set parameter with low model sensitivity that represents the maximum effectiveness of vegetation to prevent erosion. It is assumed to never reach 100%; it caps values of RipVeg to <1. A value of 0.95 was set based on previous studies (Wilkinson et al, 2009; 2014).

B.5 Floodplain deposition model

The mass of fine sediment deposited on floodplains adjacent to a link is estimated as a proportion of the incoming load, based on the proportion of discharge flooding overbank and the likelihood of settling on the floodplain considering particle size and floodplain residence time (Prosser et al, 2001b).

Eqn. 7

$$F_f = I_f\left(Q_f/Q_L\right)\left(1 - e^{-\left(v_p A_f/Q_f\right)}\right)$$

Eqn. 8

$$(Q_f/Q_L) = \frac{Q_L - Q_{bf}}{Q_L}\ if\ Q_L > Q_{bf}$$

$$(Q_f/Q_L) = 0\ if\ Q_L \leq Q_{bf}$$

Floodplain area (Af)

Floodplain area is the area available for deposition of sediment for a defined flood recurrence interval inundation extent. Melbourne Water provided flood inundation models (FIMs) for 5, 10, 20, 50 and 100 year recurrence intervals. Due to the channelised nature of the Westernport catchment in low lying areas, Recurrence Intervals below 100 years had extremely limited extents. For this reason, the 100 year inundation extent was used to represent the total area of floodplain where sediment could be deposited during overbank flow, although this would only be present during extreme events.

B.6 Mass transformation model

The Mass transformation module applies a multiplier (the only parameter) to the total inflow constituent mass to increase or decrease the mass by a specific factor. It is used to emulate a storage that extracts a portion of the incoming sediment and allows the remainder to flow downstream.

Table 18 Parameters and their description as encoded in the Mass transformation module

Parameter name as appears in Source	Description	Type
Factor	Multiplier factor to adjust the constituent mass	X

The total mass is calculated by summing four Source link properties:

- InitialStoredMass
- UpstreamFlowMass
- CatchmentInflowMass
- AdditionalInflowMass.

The output value is the total mass multiplied by the ‘Factor parameter.

Note: at the time of writing there are no constraints on the value of the Factor.

B.7 Summary

The above information is synthesised in Table 19 to Table 22. In these tables:

- the ‘parameter’ column refers to the terms used in the equations from Wilkinson et al (2014). Note: the terms are documented here without subscripting to improve legibility in this document. For example, here we use QL and it appears in the paper as QL.
- Ƒ(x, y) means that a parameter’s value is calculated via a function of parameters x and y.
- ‘[0,100%]’ means the parameter is a percentage, entered as a floating number between zero and 100, inclusive.
- ‘[double]’ means the parameter’s value is a number with no restrictions.
- ‘>0’ is number greater than zero.
- ‘[a, b]’ is a number between a and b, inclusive.
- ‘[year]’ is a specific year selected by the project (e.g. a start or end date).

Table 19 List of *dSedNet* parameters – Hillslope erosion

Parameter	dSedNet plugin	Description	Units/format	Default	Sensitivity	Data sources	Method/comment
HSDR	USLE HSDR – Fine	Hillslope sediment delivery ratio, 5% is an appropriate value for hillslope delivery in southern Australia (Prosser et al 2001)	Global Fraction 0-1	0.05	very high	Prosser et al (2001)	Global, set at FU level, literature value for area e.g. 5% is an appropriate value for hillslope delivery in southern Australia (Prosser et al 2001). Apply 0.05 unless strong case is made to use higher value (S. Wilkinson pers. comm.).
R	R See Alpha, Beta, Eta, RainThreshold, P and S below	Rainfall erosivity factor (based on rainfall for the given timestep, limited by the threshold value	Global		Medium	ƒ(Alpha, Eta, **DAY**, **RAIN**, Beta)	Alpha calculated from mean annual rainfall and summer rainfall (done in temporal parameteriser), others calibrated against daily turb/TSS in NZ model, current study uses scaled up value from southern hemisphere value to represent higher intensity rainfall.
K	See KLSC, C and KLSCdynamic below	Soil erodibility	Fraction Gridded	0.027	Low	After Teng et al (2016)	Value taken from study at Australian continent scale, values generally low in study area. Applied with L and C in grid
L		Slope length factor	Fraction gridded	1.0	Low	S. Wilkinson pers. comm	Global set by expert (applied with L & C in grid) Low influence and safe to ignore in context of current study (S. Wilkinson pers. comm.).
S		Slope steepness factor, represents the influence of slope gradient on erosion	Fraction, gridded		high	Calculated based on 20m DEM	Calculated from DEM using QGIS/TIME plugin based on Renard (1997) equations, also refer to similar equations in Teng et al (2016) and Rosewell (1993).
C		Cover factor, represents effect of vegetation cover presence of mulch, organic matter in soil etc.	Fraction, gridded		med	MODIS bare ground index monthly data http://data.auscover.org.au/thredds/catalog/auscover/modis-fc/v3.0.1/catalog.html	Invert raw data and apply equations based on Rosewell 1993 tables D-3 and D-5, produced a monthly time series from Feb 2000 to May 2018 Grid, applied with L and L
P	P	Practice factor	Fraction Gridded	1.0	low	S. Wilkinson pers. comm	Input at FU level. Set as 1 initially, lever to simulate improved land management practice for different land uses.
	KLSC	KLS(C)	Fraction Gridded	-1			Averaged for all cells in a FU; used in conjunction with C and KLSCdynamic to determine the source the KLSC values (global vs. grid)
	C	C factor (static)	Fraction Gridded				Averaged for all cells in a FU; calculated by temporal parameteriser
	KLSCdynamic	KLS where C is dynamic	Fraction, gridded	0.0		Calculated in the model	Calculated by temporal parameteriser. See note below for method
	Alpha Beta Eta	Rainfall erosivity factors used to calculate R	f(P,S) (0.1,10) (0.1, 10)	0.56 1.49 0.389		Monthly EI30 Parameter (Equation 4 - page 152)	Alpha calculated from mean annual rainfall and summer rainfall (done in temporal parameteriser), others calibrated against daily turb/TSS in NZ model, current study uses scaled up value from southern hemisphere value to represent higher intensity rainfall.
	R Factor RainThreshold	R Factor Rainfall Threshold	Mm Global	12.7			Threshold set by expert; If daily rainfall > threshold, R is set to zero, in the current time step
	P	Mean annual rainfall used to adjust R factor value for seasonality	Mm				

Parameter	dSedNet plugin	Description	Units/format	Default	Sensitivity	Data sources	Method/comment
	S	Mean Summer Rainfall used to adjust R factor value for seasonality	Mm	0			
	DWC	Dry Weather Concentration	mg/L	0		Fletcher et al (2004)	Global, Used for urban runoff calculation. DWC and EMC values taken from Fletcher
	DoYOffSet	Number of days that are subtracted from the current day of year	[0,365]	15			Global

Table 20 List of *dSedNet* parameters – Gully erosion

	Parameter in plugin	Description	Units/format	Default	Sensitivity	Data sources	Method/comments
P_F Pf	Gully_SDR_Fine	Fine sediment fraction	[0,1] Gridded global	100	Med	http://www.clw.csiro.au/aclep/soilandlandscapegrid/ProductDetails-SoilAttributes.html	clay + silt 0-5cm, resampled to 20m, extrapolated to catchment boundary
	Gully_SDR_Coarse	Coarse sediment fraction		100			
P_S Ps	Soil_bulk_density	soil bulk density	[0,100%] Gridded	0	med	http://www.clw.csiro.au/aclep/soilandlandscapegrid/ProductDetails-SoilAttributes.html	data already in g/cm3 (=t/m3), resample to 20m DEM, extrapolated to catchment boundary
p_G	Gully_Percent_Fine	Gully Clay + Silt Percentage	[0,100%) gridded	30	med		Set by expert user
a_G aG	Gully_Cross_Section_Area	Contemporary gully X-section area	m^2 global	10	med	use 10m2 after Wilkinson et al 2009	Set by expert user; used to calculate volume
L_G LG	Gully_Density [km/km^2]	Gully density or gully length	km/km^2 or km^2/km^2 gridded	0	med	Revised gully mapping from Hughes (2003) using current ESRI base map aerials	Active gullies mapped and gully density 20m grid produced (km/km2) as using cross section area
ρ_G ρG	Gully_Soil_Bulk_Density	Spatially uniform dry soil bulk density	Tonnes/m3 global grid			Soil Landscape Grid Aust (http://www.clw.csiro.au/aclep/soilandlandscapegrid/ProductDetails-SoilAttributes.html)	Set by expert user
	Gully_Year_Density_Raster			2003			
T	Gully_Year_Disturb	Gully age: starting year for calculations	[year] global	120 1900	low	Hughes (2003) assumed 100 years	Set as 120 years across all, there are a few new gullies mapped but small proportion of total. Plugin returns zero for all years before this value.
	Gully_End_Year	Year of gully maturity	[year] Global	1970			Apply activity factor **AFTER** this year
f_G fG	Average_Gully_Activity_Factor	Reduces (<1) or increases (>1) sediment supply, over the modelling period, from the long-term average rate	Fraction	0.2	high	S. Wilkinson pers. comm	Set by expert user; initially set as 0.2 and potentially adjusted compared to observed loads (S. Wilkinson pers. comm.) Set to one (1) **if** year < Gully_End_year

	Parameter in plugin	Description	Units/format	Default	Sensitivity	Data sources	Method/comments
M_g Mg	Gully_Management_Practice_Factor	Rate of gully activity in future management scenarios as a proportion of historical rates, associated with gully management practices	[0,1] global	1	low	S Wilkinson pers. comm.	Set by expert user; if land use changes e.g. revegetation, could reduce by half (S. Wilkinson pers. comm.)
f_{RO}	Gully_Annual_Average_Sediment_Supply	Mean-annual fine gully sediment	tonnes/year	0		(Source::quickflow ^ b) / ROLT	Internally calculated (temporal parameteriser); used by plugin as part of calculations, but no clear relationship to equation 3.
B	Gully_Daily_Runoff_Power_Factor	Gully Daily Runoff Power Factor	[0.5,2]	1.4			Set by expert user; Global; used for calibration to fit to a sediment rating curve, or to match sediment yield to catchment runoff
ROLT	Gully_Long_Term_Runoff_Factor	Gully long-term runoff	[double]	1			Internally calculated (temporal parameteriser)

Table 21 List of *dSedNet* parameters – Streambank erosion module

	Parameter in plugin	Description	Units/Format	Default	Sensitivity	Data sources	Method/Comment
S_L Sl	LinkSlope	Average slope of the streambed in the link	m/m	0.005	low		Calculated in the spatial parameteriser, based on DEM and links
Q_{bf} Qbf	BankFullFlow	Bank full discharge (m3/s) based on the selected ARI	m^3/s	0 1.58	high	Prosser et al (2001)	A long hydrological model run was used to determine the ARI representing the long term mean annual flood recurrence interval for the main stream links, resulting in the use of the 5 year ARI discharge. A value of 1.58 years was applied to all other stream links following the convention suggested by Prosser et al 2001
	BankFullFlowARI	Recurrence interval of the flow when bank full	integer	5			Set by expert
Pf p_F	SoilPercentFine	proportion of fine sediment in bank subsoil	[0,1] Gridded	.5	med	http://www.clw.csiro.au/aclep/soilandlandscapegrid/ProductDetails-SoilAttributes.html	same data as for gully model [eqn 5 error in description: “pB”]
ρS	SedBulkDensity	streambank subsoil dry bulk density	tonnes/m^3 gridded		med	http://www.clw.csiro.au/aclep/soilandlandscapegrid/ProductDetails-SoilAttributes.html	same data as for gully model [eqn 5 error in description: “ρB”] grid within 200m buffer of streams
h	BankHeight	bank height	M gridded	2.0	high	Melb Water 1m LiDAR 2017/18	Calculated using methods described in §B.4. *dSedNet* spatial parameteriser calculates average h at link level.
L_L Ll	LinkLength	link length	M	1	high	DEM and links	Calculated in the spatial parameteriser
K		Long term average daily flow raised to the daily flow power factor	[0.00001, 0.0001]				Calculated in the temporal parameteriser, used for calibration
Pw		Density of water	kg / m^3 global constant	1000			Global constant

	Parameter in plugin	Description	Units/Format	Default	Sensitivity	Data sources	Method/Comment
G		Gravity	m / s^2	9.81			Global constant
b	SoilErodibility	exponent set to scale erodibility	[0,100%]	1	med		Set as 1 initially and if under cf. gauged +, if over then -
SoilErod	SoilErod	Erodible soil extent	[0, 1] gridded		high	Melbourne Water 100 year flood extent	Coded as 1 within flood inundation extent and 0 outside.
RipVeg	RiparianVegPercent	Represents proportion of vegetation in riparian zone on a scale of 0-1	[0,100%] gridded	0.5	high	Melbourne Water tree cover mapping from Lidar, created by Jasper Kanapo of Grace GIS for Melbourne Water, canopy presence for 200m buffer either side of all waterways.	Method to produce input data is given in §B.4. Vic gov stream condition data (2010 Index of Stream Condition - River Centre Lines at the 100 Section Level) did not contain riparian veg attributes. TERN data is too patchy. MODIS data is too coarse. Grid within 200m buffer of source stream network
MaxVeg Effectiveness	MaxRiparianVegEffectiveness	Represents fact that vegetation is never 100% effective at stopping erosion	[0,100%] global	0.95	low	After Wilkinson et al (2009)	Set by expert user as 0.95
Ei	(calculated)	Mean erodibility				Wilkinson et al (2014), eqn 6	Calculated in the model Ei = [1 – min(RipVeg, MaxVegEffectiveness)] x SoilErod
	DailyFlowPowerFactor	Daily Flow Power Factor	>0	1.4			Ref gully model

Table 22 Parameters and their description for the floodplain deposition module

	Parameter in plugin	Description	Units/format	Default	Sensitivity	Data sources	Method/Comment
Af	FloodPlainArea_M2	Floodplain area M^2	m^2	0			Calculated based on extent of 100 year ARI
Vp	fineSedSettVelocityFlood	Sediment Settling Velocity m/s (floodplain)	m/s	0.0007			
QL	LongTermAvDailyFlow	Long Term Average Daily Flow raised to the Daily Flow Power Factor	m^3/day	0			Calculated in the plugin

Appendix C Scenarios – requirements elicitation

This Appendix documents the requirements gathered from stakeholder workshops held during the project. It includes information that was presented to stakeholders, prior to requirements elicitation, to inform (and constrain) the scope of requirements (Table 23).

Table 23 Constraints/limitations presented to stakeholders prior to requirements elicitation

	Constraint
C-01	Scale – we are working on a 20m resolution – however Source (and thus *dSedNet*) is a semi-distributed lumped model. This means that we know the % of area in a sub-catchment that is described as a particular land-use, or soiltype, but we do not know exactly where in the sub-catchment they occur. We are also constrained through having to balance runtime against resolution – the finer the resolution, the longer the runtime. We believe we have settled on a robust and workable compromise.
C-02	Water quality data – while the WQ index confirms that turbidity is consistently poor throughout Westernport, we are constrained by the quality of the monitoring data. There are not a lot of data that discriminates fines (silts, clays) from coarse (sand), and sampling points are sparse.
C-03	Contextual data – While the land use map has been updated, it then becomes a static layer. We are implementing a seasonal cover factor within *dSedNet* which will allow us to provide some discrimination based on % ground cover
C-04	Limitations in the model formulation– more generally, there are limitations in the model – while run at daily timestep, we know that most sediment moves in events and doesn't move daily.
C-05	Source (and thus *dSedNet*) is a lumped (semi-distributed) model. For example, it records the % of gully density within a functional unit, but it does not record exactly where the gullies are.
C-06	Uniquely identifying the contribution of existing management practices/interventions to loads. We still have very scant data on the efficacy of management practices/interventions, and thresholds for performance. This would require long-term monitoring of catchment trails. Modelling of base case obviously includes the impact of existing interventions. These cannot be separated from the modelled loads. Our approach will be to allow the user to 'experiment' with % efficacy of interventions. We will work with Melbourne Water to identify the efficacy/load reduction shape.

Table 24 Design principles

	Principle
D-01	Adopt a minimum viable product (MVP) approach - this describes a product with sufficient content and functionality to be accepted by early adopters, providing a testbed for learning. (This approach reduces up-front over-design while still being user-centric; it reduces overheads and stakeholder fatigue that can come from running a large and prolonged user engagement campaign; and can provide for gradual build of in-house interest and capacity to support the emergence of new, and better, ideas during the life cycle of the product.
D-02	Maintain alignment with wider Port Phillip-Westernport (PP-WP) Source model conceptualisation, characterisation and hydrological calibration, except where this may not give the best outcome for the modelling. An example of this is the disaggregation in the land use classifications where we are using a finer scale to provide for likely scenarios
D-03	Consider each and every step in the context of the latest science. To this point, this has meant revisiting the calculation of RUSLE parameters.
D-03	Where possible, generalise the design when coding the plugin (and the next phase of development - the Catchment Planning Tool). While this has an overhead in terms of time (compared to just writing the code to meet the immediate need), it provides flexibility in being able to adapt to changes and introduce new features.

Use assumptions (Table 25) and user profiles (Table 26) were developed to assist with design of the system (and prioritising for scenario implementation). On discussion, it became apparent that there were two distinct user groups (not one):

During the planning workshop, two distinct sets of users of the CPT were identified:

- Catchment managers who are interested in likely impact of management interventions, combinations of locations and type thereof, all aimed at improving/stabilising catchment condition
- Policy/planners who are interested in likely impact of development and other pressures within the catchment.

Identifying these different user groups assisted in tailoring software navigation, documentation and reporting of results

Table 25 Use case assumptions

ID	Use cases
U-01	For internal use only, i.e. not designed as a communication device for the public – for planning, could be used with partners (e.g. EPA, DEWLP) looking at priorities; major decisions around S/w management
U-02	Used by individuals on desktop or possibly in a group setting
U-03	Not used every day, but when have an issue – perhaps used for exploring the catchment in a group setting
U-04	Custodianship of the CPT sits with Melb Water. No updating of the CPT is planned, i.e. this is a one-off development. (An alternative could be that the CPT is updated, with new information, as part of an annual investment strategy)
U-05	Reporting regions are to be the same as for Healthy Waterways strategy (if possible and doesn't compromise the integrity of the sediment modelling and reporting of results)

Table 26 User profiles - initial assumptions

ID	User attribute
UP-01	Technically skilled with sound analytical skills, but not necessarily model savvy
UP-02	Understands sediment generation and transport processes at a catchment scale
UP-03	Does not know the details (e.g. algorithms or methods) of the *dSedNet* model. Those who care will read the References
UP-04	Has diverse interests in the 'well-being' of Westernport, driven by scientific curiosity and roles and responsibilities at Melbourne Water
UP-05	Well-connected into Melbourne Water strategies, and those of the government (i.e. DELWP)
UP-06	Use will be sporadic and driven by individual interest and priority of issues. May even drop back into business-as-usual, i.e. using other tools (e.g. spreadsheets) or relying on consultants
UP-07	Understand and accept the use of 'pre-run[10]' scenarios' (ie the CPT does not run simulations on the fly) (see further discussion under Deployment)
UP-08	Interested in being involved in testing over the period Feb-May 2019, depending on other work commitments
UP-09	Thinks that written documentation (help) is good, but prefers to learn by doing
UP-10	Some knowledge of hydrology modelling, and may be actively involved in the revision of the Source modelling for Port Phillip Bay/Westernport
UP-11	Immediate focus is on 'baseline', i.e. understanding the current situation – would then be interested in moving to exploratory analysis

C.1 Requirements

Sediment is the biggest water quality issue, but not the biggest waterway health issue which is the change in hydrology caused by urban development

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[10] Original term of 'pre-canned' was replaced by 'pre-run' as canned has two meanings – ie rejected (as in thrown out); already processed (ie in the can).

The requirements listed here focus on 'levers' available to Melbourne Water and partners that can affect the water quality, some or all of which can be captured in a simulation model such as Source+*dSedNet*. We have used a Status code to capture how we have been able to respond to these requirements:

- I = Implemented
- Ip = partially implemented
- NA = science and/or data not available
- O = Outstanding
- P = possible but not prioritised in this implementation
- X = Source+*dSedNet* can't adequately model.

Table 27 'Final' list of requirements as elicited from stakeholders during the period 2017-2018. These reflect management 'levers' available to Melbourne Water

ID	Management/infrastructure intervention available to Melbourne Water	Status
M-01	Urban stormwater management	I
M-02	Gully management/stabilisation on Melbourne Water land, and private land through Rural Land Program	I
M-03	Bank stabilisation on Melbourne Water land, and private land through Rural Land Program	I
M-04	Farm track management (and drainage effluent design) (designed by accredited organisations)	P
M-05	Plant vegetation along streams	Ip
M-06	Fencing waterways and wet areas	P
M-07	Dairy and other stock containment areas (to preserve cover and reduce sediment generation)	P
M-08	Stormwater harvesting in priority areas– [HOW TO REPRESENT/CAPTURE THIS IN AN USLE MODEL; gully is disaggregated by runoff]	NA
M-09	Ground cover management – grazing management BMP	I

So as not to lose the large list of requests, they are captured for future reference in Table 28.

Table 28 Specific requests from stakeholders during the period 2017-2018

R-ID	Request = requirement	Requestee	Status
R-01	Systematic identification of high risk reaches for loss of physical form; and impacts on d/s reaches (as part of annual works planning)	Project brief	Ip
R-02	Potential use for stormwater quality offset schemes that are based on sediment targets – to identify suitable offset options	Project brief	P
R-03	Understanding sediment loads generated from the Koo Wee Rup drainage district (as well as others)	Project brief	P
R-04	Spatially and temporally linking catchment loads to the receiving water model for Western Port	Project brief	Ip
R-05	Prioritising reaches for riparian revegetation and other rural land management activities to reduce sediment inputs	Project brief	Ip
R-06	Managing (in order of priority) (1) impacts on the Bay; (2) stream health; (3) interventions to target (e.g. impact of revegetating parts of Lang Lang) which requires understanding role of catchments and conduits	Rhys	Ip
R-07	Incorporate some broad rotational principles? e.g. (an entirely made up example) asparagus crops/fields have 50% bare soil between March and August and are generally fallowed every third year when they are bare for the entire year	Tom H	O
R-08	Be able to test effectiveness of programs		Ip
R-09	Be able to discriminate contributions from rural vs urban		I

R-ID	Request = requirement	Requestee	Status
R-10	Test BPEMT (best practice environmental management targets). And if can't meet targets, where is best place to locate an 'offset'	David	Ip
R-11	Sediment sources, targeting of remediation to support design works programme & prioritisation	Penny & Leigh	Ip
R-12	Linkages between modelling and incentives program (how results might interpret into on-ground project, at waterway and farm scales	Louise	Ip
R-13	Consistency in approach and answers with Source modelling by Jacobs	Trish	I
R-14	Integration of understanding to direct Melbourne Water programmes around sediment	Rhys	I
R-15	Discover sources of sediment to the Koo Wee Rup drainage system; and then how to manage – channel stability works, more vegetation, stabilising catchment gullies, etc	Tom	O
R-16	Contribute to monitoring around loads	Rhys	Ip
R-17	Would like to have $ (i.e. investment) – then could use as a prioritisation tool – the greater the spatial resolution, the more we would use it	Penny	O
R-18	Are we investing in the RIGHT places, can we target better?	Louise	Ip
R-19	Want to handle dairies and containment areas better –intensifying and people transferring to beef; both result in increased herd size – handling sediment movement off animal tracks	Louise	O
R-20	Understand the relative benefit of different practices (it's not about efficacy of the practice, but about adoption/compliance and area under the practice)	Rhys	Ip
R-21	Scenarios – change from one land use/practice to another; put on management practices (e.g. BMPs filters)		Ip

Table 29 Reporting/visualisation preferences expressed by stakeholders

ID	Reporting/visualisation preferences	Status
AV-01	Reporting as annual (and potentially seasonal) loads acceptable	I
AV-02	Always report load to the Bay, in addition to loads generated within and exiting selected (reporting points selected by the user) sub-catchments (also meets AP-01, ie focussing on understanding the catchment)	I
AV-03	Reporting required by source (e.g. gullies, hillslope) and location	I
AV-04	Quite like the idea of using slider bars to explore the impact of changing some of the input parameters (e.g. size of interventions)	-
AV-05	Expose contextual information (e.g. land uses, vegetation), hydrology, as well as sediment loads	I
AV-06	Report total, and coarse and fine fractions (check modelling assumptions for fractionation)	O
AV-07	Use graph/chart styles that are commonly used within Melbourne Water	I

Appendix D Model Notebooks

Several Python Notebooks[11] were written to automate the configuration the Source project. The notebooks allowed bulk changes to be made to the project, as well as fine-grain changes to specific objects. Some of these automated changes are:

- Assign Gully and Hillslope models to functional units (FU)
- Assign default parameters to all models
- Change parameters for links upstream of gauges
- Assign observation data to catchments, functional units and reaches.

Further changes to specific models/parameters were then made manually based on previous research and/or observations.

The interface between the notebooks and Source was managed by the **Veneer** library developed by Flow Matters Pty Ltd. The library is described later in the section, § D.1.

D.1 Veneer – interface to Source

The Veneer system developed by Flow Matters allows Source to be scripted using languages such as Python. The Veneer system comprises two main components:

1. A plugin to eWater source which provides a web server to receive and process requests; and
2. A Python library which provides an interface to the "backend" server. The library is a façade to the Source project: providing classes that represent Source objects such as links and nodes.

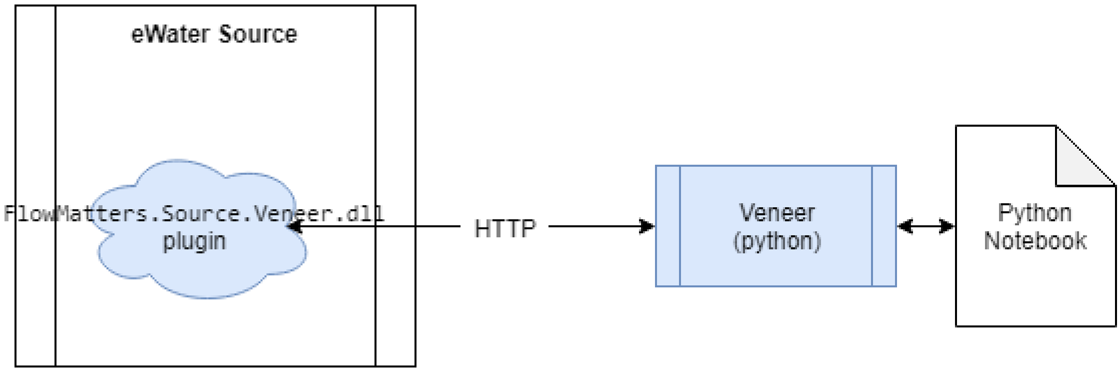

Figure 46 Veneer Source plugin

Veneer is freely available from https://github.com/flowmatters

D.2 Installation

It is recommended that you install Python via the **Anaconda** platform. It provides the latest version of Python Language as well as numerous support libraries for scientific computing. The steps to install Veneer are:

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[11] See Jupyter Notebooks at https://jupyter.org/

a) Install Anaconda Python (https://www.anaconda.com/)

b) Start the Anaconda command line (Windows: Start Menu / Anaconda 3 / Anaconda Prompt)

c) Install Veneer from its Github repository:

```
pip install https://github.com/flowmatters/veneer-py/archive/master.zip
```

The Veneer Source plugin is supplied by eWater as part of Source community plugins. It can be found in the 'plugins' folder such as:

```
C:\Program Files\eWater\Source 4.1.1.5280 (public version)\Plugins
```

The plugin is installed via Source's 'Plugin Manager' found in the menus: *Tools/Plugin Manager*.

D.3 Workflow notebooks

There are two groups of notebooks, as described in Table 30 to Table 32.

Table 30 High level description of notebook groups

Group	Notebook workflow
1	Relate to setting up the model (the baseline) with all the plugins, input data, parameters, etc to run *dSednet*. The starting point is the original Source with catchments defined, landuses applied, climate data loaded, calibrated hydrological parameters configured.
2	Relate to running the scenarios and post-processing the results

Table 31 Group 1 notebooks

Order	Notebook name	Notebook workflow
1	RenameFUs	Renames some functional units that cause problems for Veneer - because they have things like '?' and ',' in the names
2	ConfigureModels	Applys the relevant *dSednet* plugin model to every appropriate Subcatchment/FU and link in the model
3	ZonalStats	Calculates spatial parameters required by the *dSedNet* modules[12] • sub-catchment/FU level stats that are applied to hillslope and gully • subcatchment level stats that are applied to reach (streambank and floodplain) • subcatchment/FU level timeseries stats for cover (bare ground index, BGI)) These are stored in CSV files used by the next notebook (LoadParameterTable)
4	LoadParameterTable	Loads the spatial parameters from CSV files into Source, including • assigns the data-source to the 'C' parameter for all Hillslope FUs from **cover.csv** • Sets parameters (Gully_Soil_Bulk_Density, Gully_Density, Gully_Percent_Fine) from **fu_generation_parameters.csv** for sub-catchment/FUs where ConstituentSource = 'Gully' • Repeats this update for KSLC parameters where ConstituentSource = 'Hillslope' • Sets parameters(BankHeight, FloodPlainArea_M2, RiparianVegPercent, SedBulkDensity, SoilErodibility, SoilPercentFine) from **link.csv** • Sets fineSedSettVelocityFlood = 0.0007
5	RunTemporalParameterisers	Run the 'temporal parameterisers', which are components within the *dSednet* plugins themselves - ie these notebooks don't do much other than automate a process that has created as part of the software development.

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[12] Generation of these zonal statistics (e.g. averages over areas, and over time in the case of BGI) is also available through the dSedNet plugin's spatial parameteriser. They were done separately here, using Python scripts, for convenience.

Table 32 Group 2 notebooks

Sequence	Notebook name	Notebook workflow
1	RunScenarios	Includes the scenario definitions at the top of the notebook. Runs all the combinations and extracts raw results from Source, saving those raw results to disk. Fun fact, for our 24 simulations, this saves our 480Gb of data. (Large in part due to the JSON format that Veneer uses for convenience).
2	PostProcess	Extracts the summary information, required by the CPT, from the previously saved raw results. Final data is 234M - for the Source results. Excludes image data, such as the ground cover, landuse and topography layers
3	GeneratingMaptiles and GeneratingThumbnailsOfMeanMonthlyBGI	Includes the process for generating the map images used in the CPT (topography - the shaded relief map, landuse and BGI). These notebooks are more notes on how to generate those maps, with small Linux shell scripts copied to the shell for generating the images.

Appendix E Key activities

The project team met every fortnight (telemeeting Wednesday afternoons), and came together every 3 months or so in 'Hothouses' – for these, the team sat in one room and worked together, discussing assumptions/solutions, building models, working on data, writing code and/or reports, etc. This proved to be a very efficient way to progress the work as the team was physically separated (Canberra, Brisbane, Adelaide, Melbourne).

Date	Activity	Outcome
February 2017	Initial planning meeting, Melbourne	Project proposal
June 2017	Contract details finalised and staff secured	Contract signed
July 2017	Meeting #1 with key MWC stakeholders	First set of requirements elicited
20-22 March 2018	Field trip, meeting with MWC, followed by Hothouse in Melbourne	Requirements tightened
June 2018	Hothouse #1, Canberra	Bunyip model underway
28 August 2018	Presentation to key MWC stakeholders – covered the plugin, data, Bunyip catchment	Good questions, and continuation of discussion re requirements for CPT, identified potential users for the CPT
28-29 August 2018	Hothouse #2, Melbourne	Build testbed for testing plugin functionality, worked through data layers, continued with setting up of the Bunyip application, land use categorisation explored
September 2018	Hothouse #3, Canberra	Continued with Bunyip application parameterisation, testbed for functionality testing constructed, Progress report writing
September 2018	Delivery of Progress Report to MWC	Description of technical progress, and implementation in WesternPort
19 December 2018	Meeting #2 with key MWC stakeholders	Introduced the concept of the CPT, and worked through some design guiding principles
March 2019	Hothouse #4, Canberra	First set of scenarios sketched, and CPT architecture in place
June 2019	Hothouse #5, Canberra	Writing workshop & in-depth CPT testing
July 2019	Meeting #3 with key MWC stakeholders	Presented on CPT to gauge utility – some changes requested
August 2019	Completion of project	Delivery of Technical Report and CPT to MWC, with actions for archiving of datasets underway

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