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Memorandum

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Subject	**dSedNet model development and results**	**Project Name**	Whaitua te Whanganui-a-Tara
Attention	Mark Heath, Brent King, James Blyth	**Project No.**	IZ130500
From	Stuart Easton, Lydia Cetin		
Date	7 February 2020		
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1. Overview

Jacobs have been engaged by GWRC to develop a daily hydrological and sediment model for whaitua te Whanganui-a-Tara (‘whaitua’) to support the water quality limit setting process under the National Policy Statement for Freshwater Management (NPSFM). The model replicates the architecture and utilises parameter sets from the previously developed and calibrated Porirua whaitua eWater Source and dSedNet models. Limited calibration has been possible due to data scarcity and condensed project timeframes. Model results are therefore somewhat uncertain in providing reliable absolute daily load or suspended sediment concentration (SSC) values, but the model is useful in providing information on relative differences in sediment loading between whaitua sub-catchments and runoff events and to assess changes in loading rates under potential catchment planning and mitigation scenarios.

2. Hydrological model

The developed model for whaitua te Whanganui-a-Tara replicates the architecture established for the Porirua whaitua modelling programme. The following sub-sections provide a brief overview of the methods adopted to develop the hydrological and sediment model; see Jacobs (2019) for detailed model development description.

2.1 Model architecture

The eWater Source platform is a semi-distributed catchment modelling framework designed for exploring a range of water management problems (Welsh et al., 2012). It conceptualises a range of catchment processes using sub-catchments which are composed of Functional Units (FU) that represent areas of similar hydrology and constituent generation, typically characterised through land use or rainfall-runoff response. Daily rainfall-runoff modelling calibrated using spatially-distributed historical climate data enables the representation of spatial and temporal variability in runoff and water quality generation from different land uses across the catchment. Flows and pollutants are routed through a node-link representation of the stream network.

Source provides a library of rainfall-runoff models for hydrological model development. The GR4J (Perrin et al., 2003) model was selected based on its strong performance in numerous settings around the world (Perrin et al., 2003; Vaze et al., 2011), its parameter parsimony, and previous rainfall-runoff modelling with GR4J for the Porirua stream catchments that produced a well calibrated model. Rainfall-runoff model parameters from the calibrated Porirua model were adopted for the whaitua te Whanganui-a-Tara model.

2.1.1 Sub catchments

Sub-catchment boundaries were derived using aggregated River Environment Classification (REC) v2.3 boundaries. A sub-catchment area of around 600 ha was adopted for the rainfall-runoff modelling, although smaller sub-catchments were delineated for some coastal streams. The node-link network was drawn within the Source software based on the REC 2.3 river network and the direction of surface water drainage. The resulting sub-catchment delineation and node-link network as represented within Source is illustrated Figure 1.

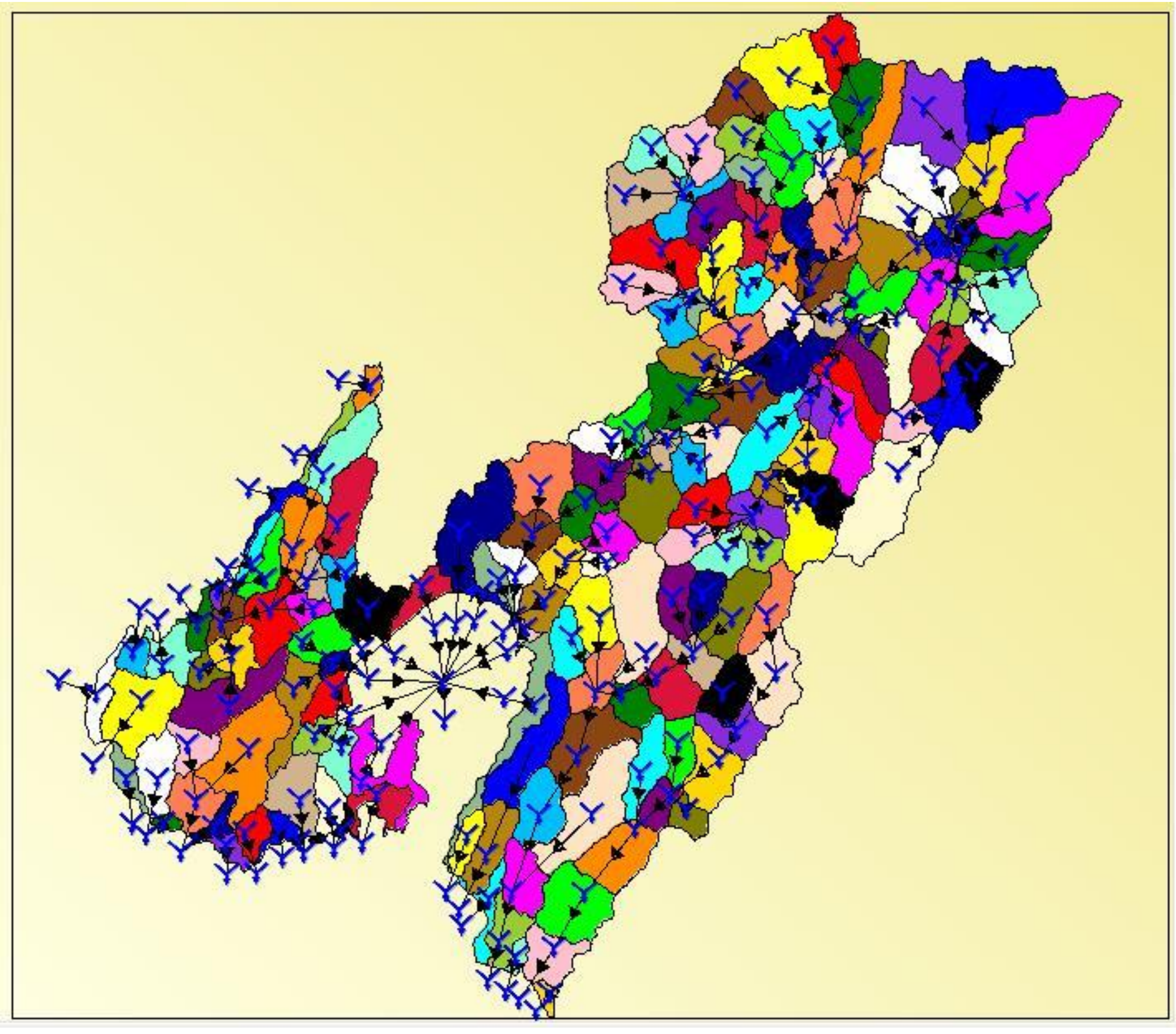

Figure 1 Source sub-catchments and node-link network

2.1.2 Functional Units

Functional Units (FUs) have been defined based on land use and follow those as defined for the Porirua model. In the urban zone, FUs were defined based on detailed land cover mapping previously undertaken for the development of the whaitua Contaminant Load Model (CLM). Rural FUs are derived from the Landcover Database (LCDB) version 4.1 following Table 1.

The detailed FU mapping represents a ‘snapshot’ of current land use that is held static during each model run, while historical climate is simulated at a daily time-step.

Table 1 Mapping of Functional Units

LCDB Category	CLM Category	Source Functional Unit
Indigenous Forest	Stable forest*	Natural Forest
Broadleaved Indigenous Hardwoods	Stable forest*	Natural Forest
Deciduous hardwoods	Stable forest*	Natural Forest
Manuka and/or Kanuka	Retired Pasture*	Scrub
Mixed Exotic Shrubland	Retired Pasture*	Scrub
Sub alpine shrubland	Retired Pasture*	Scrub
Gorse and/or Broom	Retired Pasture*	Scrub
Fernland	Retired Pasture*	Scrub
Tall Tussock Grassland	Retired Pasture*	Scrub
Exotic Forest	Exotic Production Forest*	Plantation Forest
Forest - Harvested	Farmed Pasture*	Scrub
High producing exotic grassland	Farmed Pasture*	Farmed Pasture
Low producing grasslands	Farmed Pasture*	Farmed Pasture
Surface Mine or Dump	Farmed Pasture*	Retired Pasture
Built-up Area (settlements); Transport infrastructure	Paved surfaces other than roads, Commercial	Paved surfaces other than roads, Commercial
	Paved surfaces other than roads, Industrial	Paved surfaces other than roads, Industrial
	Paved surfaces other than roads, Residential	Paved surfaces other than roads, Residential
	Road surface, < 1000	Road surface, < 1000
	Road surface, 1000-5000	Road surface, 1000-5000
	Road surface, 5000-20000	Road surface, 5000-20000
	Road surface, 20000-50000	Road surface, 20000-50000
	Road surface, 50000-100000	Road surface, 50000-100000
	Roof, Commercial	Roof, Commercial
	Roof, Industrial	Roof, Industrial
	Roof, Residential	Roof, Residential
	Urban grasslands and trees*	Urban grasslands and trees
Urban Parkland/Open Space	Parks*	Parks
Gravel or rock	Other	Other
Herbaceous freshwater vegetation	Other	Water
Herbaceous saline vegetation	Other	Water
Lake or pond	Other	Water
River	Other	Water

LCDB Category	CLM Category	Source Functional Unit
*Further split into 3 slope classes in the CLM		

2.1.3 Climate information

Spatially gridded daily rainfall and potential evapotranspiration (PET) data at 5 km x 5 km resolution was obtained from NIWA's Virtual Climate Station Network (VCSN) (Tait et al., 2012). VCSN data has been reformatted into ASCII grids for input to the Source model. The Source model then calculates the spatial average daily rainfall and PET from the VCSN grids for each sub-catchment. The input VCSN time-series is between January 1, 1990 and October 28, 2019, inclusive.

2.2 Validation

Given that calibrated GR4J model parameters for the Porirua River catchment have been adopted in the whaitua te Whanganui-a-Tara model, hydrological validation was undertaken to assess model performance is representing the measured streamflows. Validation statistics for four sites are shown in Table 2. The model generally predicts total flows and flow magnitude well. Low flow statistics were not analysed as the priority of the model was to match medium to high flow events that generate and transport the vast majority of total sediment load. 7-day rolling average NSE scores for all validation sites were 'satisfactory' (< 0.5 NSE ≤ 0.7) for all sites following the criteria in Moriasi et al. (2015). PBIAS scores for all sites were also satisfactory (±10%≤ PBIAS <± 15%) except Mangaroa River at Te Marua which was +16%.

Flow duration curves for the validation sites are given in Figure 2, Figure 3, Figure 4, and Figure 5. Modelled flows are comparable to observed flows for medium to large events. High flows are best predicted for The Hutt River at Taita Gorge and Mangaroa River at Te Marua sites while high flows at the Whakatikei at Dude Ranch site are underpredicted in the model.

In agreement with GWRC, flow results were deemed to be satisfactory for the purposes of sediment load estimation, and further calibration was not undertaken.

Table 2 Flow Validation statistics

Hutt River at Taita Gorge (1/01/2000 - 22/01/2019)		
Statistic	**Observed**	**Modelled**
MAF (ML)	775,643	882,358
95th Percentile (m³/s)	78.2	84.1
NSE (7-day rolling average)	0.63	
NSE (FDC)	0.91	
PBIAS	+14%	
10-year ARI (m³/s)	494.0	454.5
20-year ARI (m³/s)	563.1	532.7
50-year ARI (m³/s)	652.6	633.8
Mangaroa River at Te Marua (1/01/2000 - 12/09/2018)		
Statistic	**Observed**	**Modelled**
MAF (ML)	102,133	115,732

95th Percentile (m³/s)	10.3	12.1
NSE (7-day rolling average)	0.59	
NSE (FDC)	0.997	
PBIAS	+16%	
10-year ARI (m³/s)	80.0	76.6
20-year ARI (m³/s)	92.4	88.8
50-year ARI (m³/s)	108.5	104.5
Wainuiomata River at Leonard Wood Park (1/01/2000 - 5/02/2019)		
Statistic	**Observed**	**Modelled**
MAF (ML)	75,907	84,126
95th Percentile (m³/s)	7.9	8.2
NSE (7-day rolling average)	0.60	
NSE (FDC)	0.87	
PBIAS	+12%	
10-year ARI (m³/s)	69.5	50.3
20-year ARI (m³/s)	83.2	59.2
50-year ARI (m³/s)	101.0	70.7
Whakatikei River at Dude Ranch (1/01/2000 - 15/03/2018)		
Statistic	**Observed**	**Modelled**
MAF (ML)	50,100	44,809
95th Percentile (m³/s)	4.8	4.15
NSE (7-day rolling average)	0.64	
NSE (FDC)	0.87	
PBIAS	-12%	
10-year ARI (m³/s)	43.6	22.8
20-year ARI (m³/s)	51.1	26.9
50-year ARI (m³/s)	60.8	32.1

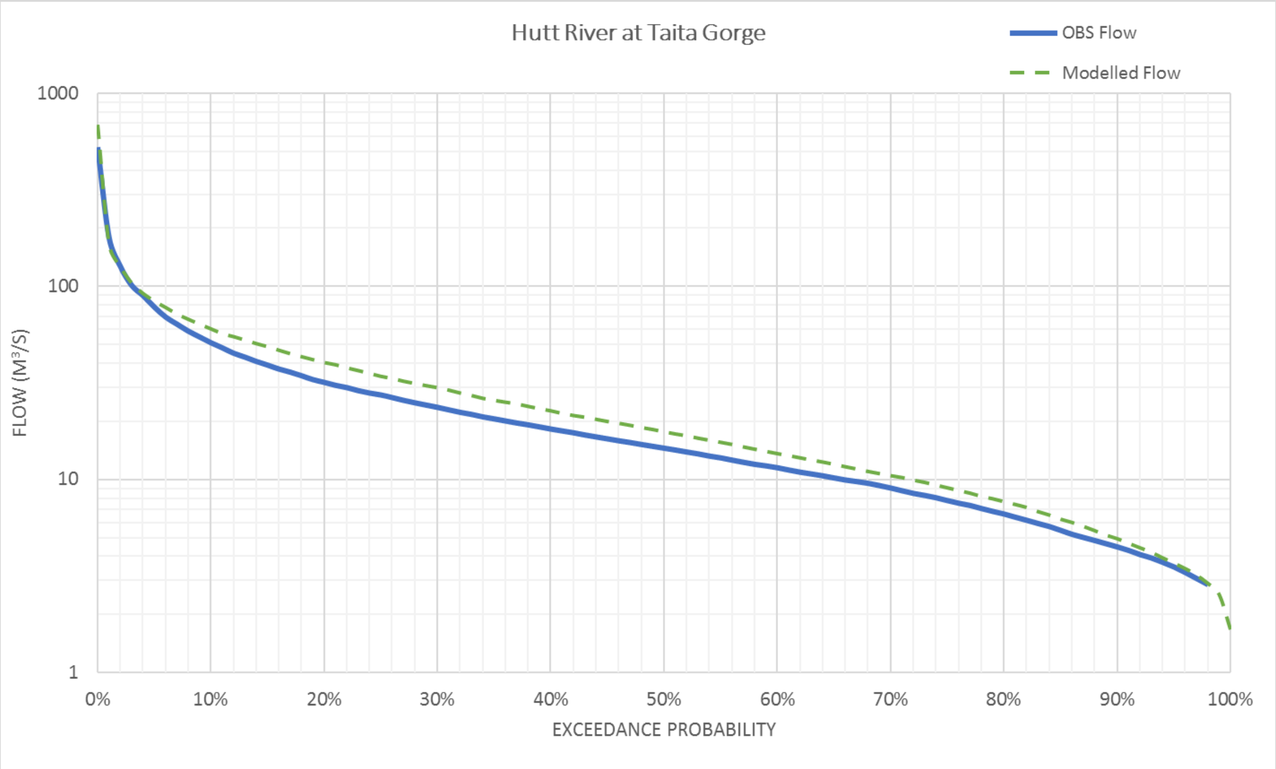

Figure 2 Flow duration curve for Hutt river at Taita Gorge

Figure 3 Flow duration curve for Mangaroa river at Te Maruia

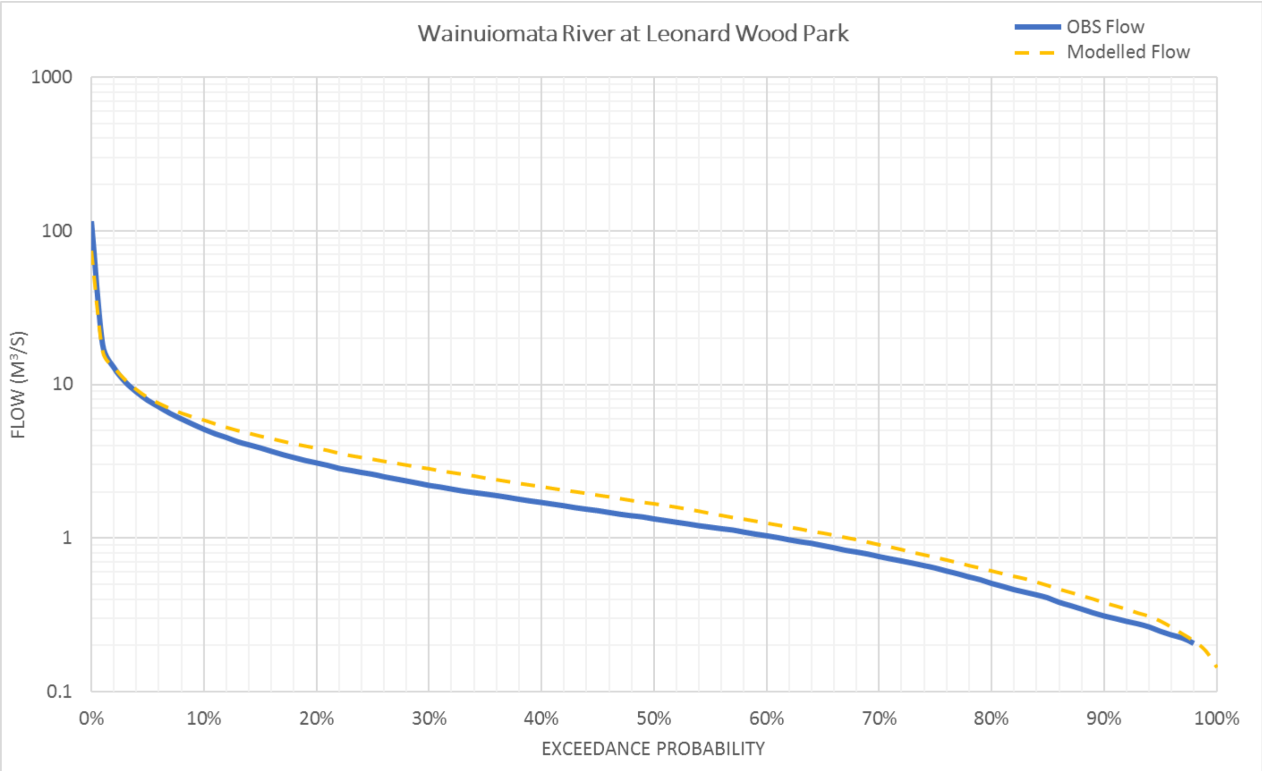

Figure 4 Flow duration curve for Wainuiomata River at Leonard Wood Park

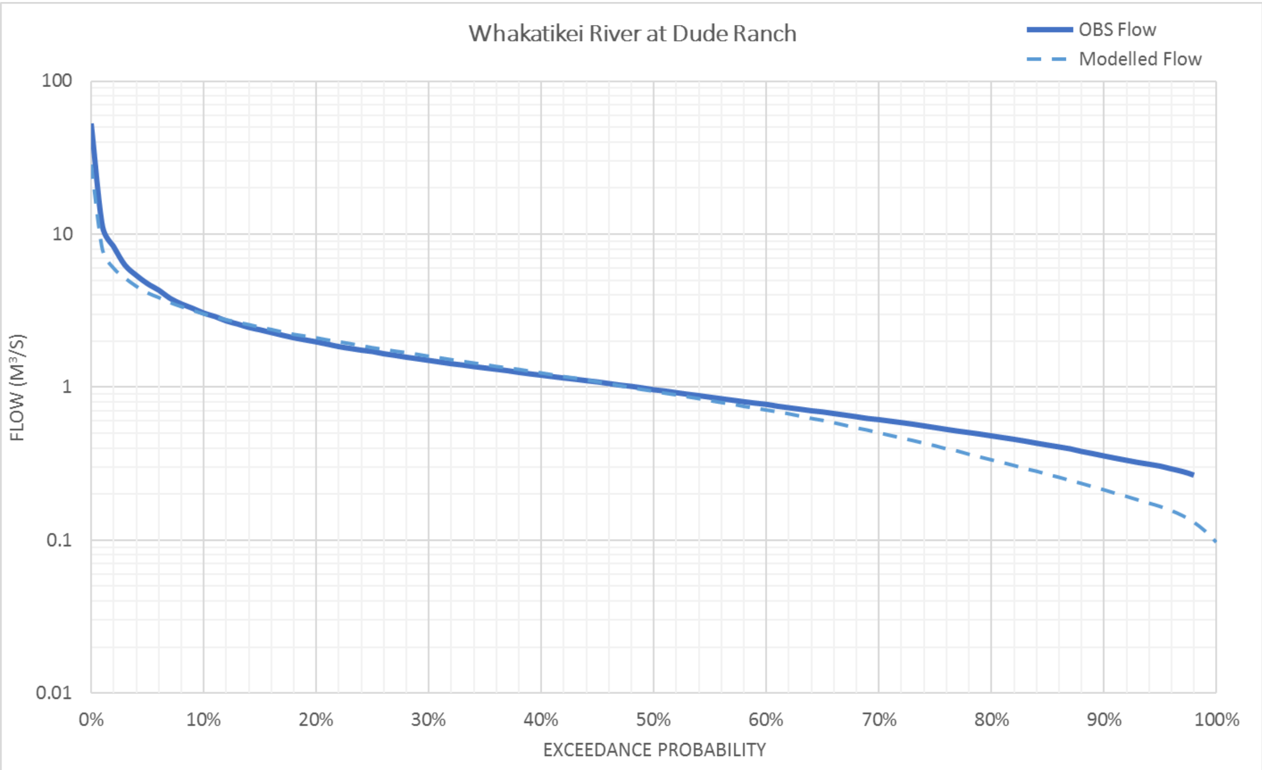

Figure 5 Flow duration curve for Whakatikei at Dude Ranch

3. Sediment model

3.1 Model development

As for the hydrology, modelling of sediment generation and transport follows the architecture and methodology for the Porirua sediment model (Jacobs, 2019). Suspended Sediment (SS) load generation has been simulated for surficial erosion (hillslope erosion), streambank erosion, and shallow landslide processes.

3.1.1 Surficial erosion

Surficial erosion is simulated using the Source dSedNet plugin (Freebairn et al., 2015). The dSedNet hillslope module implements a spatially distributed form of the Revised Universal Soil Loss Equation (RUSLE), which predicts surficial erosion according to:

$$E = R \times K \times S \times L \times C \times P$$

Equation 1

where *E* is the soil erosion per unit area (t/ha/year);

R is the rainfall erosivity (EI30) (MG.mm/ha.h.day);

K is the soil erodibility (t.ha.h/ha.MJ.mm);

S is slope steepness (dimensionless);

L is slope length (dimensionless);

C is cover management factor (dimensionless); and

P is the practice factor (conservation measures) (dimensionless).

K factor values are based on soil texture following the NZUSLE approach described in Dymond (2010):

- sand 0.05
- silt 0.35
- clay 0.20
- loam 0.25

Jacobs have applied the K-factor values above to the NZLRI soils GIS layer (S-map is currently unavailable for the project catchments), with Silt Loam given a value of 0.30, and stony sandy loam or sandy loam a value of 0.20. The class ‘Town’ is assumed to be loam (0.25). Following Renard et al. (1997), the K factor values from Dymond (2010) have been converted to SI units (multiplied by 0.1317).

The LS factor encompasses the slope length (L) factor and the slope steepness (S) factor. Jacobs have adopted the GIS-ready approach of Moore & Burch (1986) and Moore & Wilson (1992):

$$LS = \left(\frac{A_S}{22.13}\right)^{0.4} \times \left(\frac{\sin\theta}{0.0896}\right)^{1.3}$$

Equation 2

Where:

LS is the combined length and slope factors,
A_s is the specific catchment area,
θ is the slope angle.

Equation 2 has been calculated using the national 15m resolution digital elevation model (DEM) developed by the Otago University, School of Surveying. A_s is calculated for each cell as the number of upstream contributing cells multiplied by the cell resolution. An upper limit of 300m (Renard et al., 1997), and a lower limit of 1 cell (15m) were specified. Slope angle is calculated from the same DEM.

C factor values have been adapted from NZUSLE, which applies the following (Dymond et al. 2016):

- 0.005 for plantation forest, native forest, and scrub;
- 0.01 for pasture, urban areas;
- 1.0 for bare earth.

The product of the K, L, S, and C factors are imported into dSedNet as a raster grid (4 m resolution). The P factor is related to farm management practices (contouring, terracing etc.); because there is negligible arable farmland in the project catchments, the P factor is assumed to be equal to 1.

The rainfall erosivity factor (R) is calculated within Source for each day using NIWA VCSN rainfall data:

$$EI30 = \propto \times (1 + \eta \times TimeOfYearFactor) \times R^{\beta}, when\ R > R_0$$

Equation 3

Where *EI30* is daily rainfall erosivity (MJ.mm/ha.h);

R is daily rainfall amount (mm);

R_0 is the threshold rainfall amount (12.7 mm);

η is time of year scaling factor;

β is an erosion scaling factor;

α is a calculated constant – utilised as a calibration factor; and

Time of Year Factor determines the peak intensity.

A sediment delivery ratio (SDR) is commonly used to account for the proportion of eroded sediment that reaches the stream network. In New Zealand, an SDR of 0.5 is generally accepted (ARC, 2014), and has been adopted for the whaitua te Whanganui-a-Tara model.

3.1.2 Streambank erosion

Streambank erosion is related to high-flow events and has been modelled in a simple manner using a custom function that relates streambank SS load to flow. The custom function calculates streambank erosion as:

$$SE = aQ^b, when\ Q \geq MF$$

Equation 4

where *SE* is streambank suspended sediment load (kg/day);

a is the calibrated constant;

b is the calibrated exponent;

Q is the modelled link flow (m^3/s); and

MF is the 2.33 ARI flow for the modelled reach.

Equation 4 has been applied to all links for catchments containing second-order or higher streams. Streambank erosion load is calibrated to annual loads calculated following Dymond *et al.* (2016). Mean annual flood for each link is estimated as the 99.8th percentile flow. The adopted *a* and *b* parameters are 1.5 and 1.4, respectively.

Reduction of streambank erosion to account for stabilisation from existing stock exclusion (fencing) and riparian vegetation has been applied in a spatially weighted manner. Riparian managed proportions for each model link were estimated based on average riparian management implemented in the Porirua whaitua for each land use. Native bush and plantation forest stream lengths are assumed 100% riparian managed, and the main Hutt river stem below Te Maruia is also assumed to be 100% riparian managed with bank protection that forms part of the flood control system. This riparian managed length has a load reduction of 80% applied to the generated streambank load (Equation 4) following Mueller & Dymond (2015).

3.1.3 Shallow landslide erosion

Observed data shows that landslides are a significant contributor to sediment delivery in the Wellington region. Work in New Zealand shows that landslides are generally confined to steep slopes greater than 26 degrees (DeRose 1995, 1996, 2013; Dymond et al. 2016), with the highest number of landslides per area occurring in pastureland (Glade, 1998). A simple approach has been adopted in the model as a rainfall-triggered power function to represent shallow landslides. The landslide function is applied to all grassland (urban and rural) and scrub FUs that occur over steep land as defined by the NZLRI (> 26 degrees), with a minimum area of 1000m^2:

$$LE = aQ_{quick}{}^{b}, when\ R_3 \geq threshold$$

Equation 5

where *LE* is the Landslide Erosion SS concentration generated (mg/l);

a is the calibrated constant;

b is the calibrated exponent;

Q_{quick} is the modelled FU generated quick flow (m^3/s);

R_3 is the average rainfall over the preceding 3 days;

threshold is the rainfall threshold; 30 mm has been adopted.

Parameterisation of Equation 5 follows that derived for the Porirua stream; 1.5 and 1.9 have been adopted across the project catchments for the *a* and *b* parameters, respectively.

3.2 Validation

Limited sediment load and concentration data is available within the project catchments to validate the dSedNet model results. This section compares model results to the long-term annual loads estimated by the Suspended Sediment Yield Estimator (SSYE, Hicks et al., 2011) and the New Zealand Empirical Erosion Model (NZEEM, Dymond et al., 2010). Peak SSC values are also discussed.

3.2.1 Validation to annual sediment load models

Annual sediment loads for major whaitua streams and rivers as predicted by dSedNet, SSYE, and NZEEM are shown in **Figure 6**.

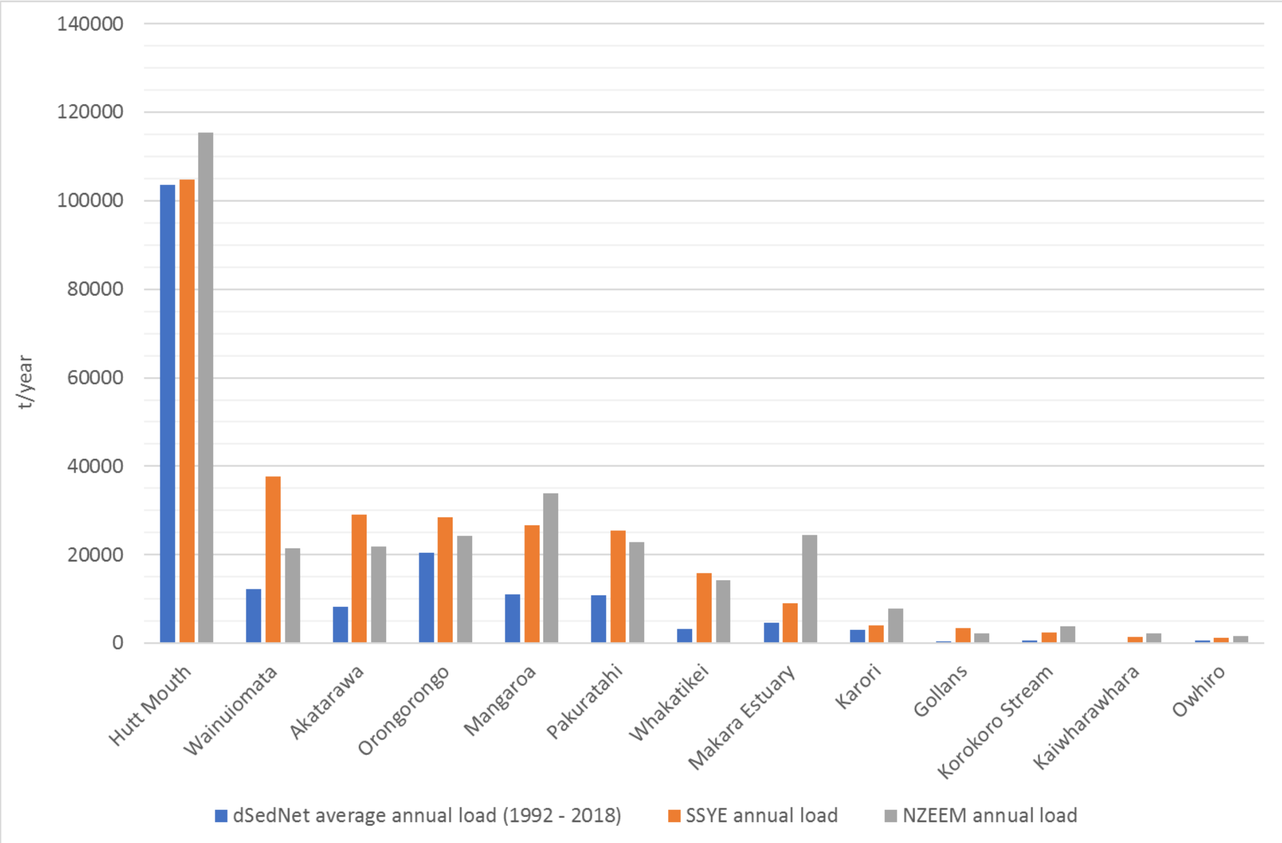

Figure 6 Annual sediment load comparison for major streams and rivers in whaitua te Whanganui-a-Tara

In comparison to the annual sediment loads estimated by the SSYE, the dSedNet model matches well for the Hutt river. For other main rivers such as the Wainuiomata, Akatarawa, Mangaroa, and Pakuratahi, the dSedNet model under-predicts annual loads in comparison to the SSYE. One driver of this difference is the general over-prediction of loads by the SSYE GIS layer compared to the SSYE calibration sites in the Wellington region. The published predicted/observed ratios are 2.20, 1.78, 1.88 for the Hutt river at Kaitoke, Mill Creek at Papanui, and Pauatahanui at Gorge sites respectively (Hicks et al., 2011), indicating that the SSYE may generally over-predict sediment yields in the Wellington and Porirua catchments. Furthermore, the SSYE does not explicitly account for the effect of landcover on sediment generation. The discrepancy between dSedNet predicted and SSYE predicted loads was also present for some catchments for the Porirua whaitua modelling, particularly for the Horokiri at Snodgrass site.

As for the SSYE, the long-term mean annual erosion predicted by the NZEEM GIS layer (Dymond et al., 2010) predicts loads greater than those predicted by the developed dSedNet model. While landcover is explicitly accounted for in NZEEM, the difference in sediment yield is likely to be driven by the lack of sediment delivery ratio applied in NZEEM, which the authors recommended to be applied at a local scale depending on dominant erosion processes and the time-scale of analysis which was not possible within the constraints of this project.

In general, it is difficult to compare sediment load estimates between average annual models and dSedNet due to the different representation of erosion processes, time-scale of the rainfall driving factor (daily vs annual), and time periods analysed (recent climate vs long-term). However, the dSedNet model results are within the same order of magnitude for major whaitua streams and rivers, indicating general agreement with previous modelling.

3.2.2 Suspended sediment concentration

As for sediment loads, there is limited SSC data available for whaitua rivers and streams during high flow events. Automatic sampler-collected SSC data for Hutt River at Melling has been supplied by GWRC for two events in 2019. The lab analysed samples returned a maximum SSC of 722 g/m^3 and an average of 348 g/m^3 across 11 samples during an event on the 30th and 31st May 2019. For these dates, the dSedNet model predicts daily SSC concentrations of 427 and 210 g/m^3, indicating generally reasonable agreement with the observed data. A good match was achieved for the 13th May 2019, where an average of 47 g/m^3 was observed across 6 samples (range 31-76 g/m^3), compared to the daily concentration of 57 g/m^3 predicted by dSedNet.

4. Results and conclusion

4.1 Model results

Results for major rivers and streams in the whaitua are provided in Table 3. Reported streams are displayed in Figure 7. Daily SSC and sediment load timeseries have also been extracted and provided to GWRC.

Table 3 Statistical summary of dSedNet results for major whaitua rivers and streams for 1992-2018.

Stream	SSC median (mg/l)	SSC 95th percentile (mg/l)	SS load median (kg/day)	SS load 95th percentile (kg/day)	Annual average load (t)
Owhiro	3.37	110.73	22	2050	629
Karori	3.48	131.79	69	6479	3012
Makara Estuary	N/A	N/A	143	16546	4567
Makara Stream	3.96	285.69	129	14998	4437
Ohariu Stream	4.06	284.23	71	9303	2632
Kaiwharawhara	3.18	63.51	49	2978	290
Korokoro Stream	3.22	126.04	64	3777	658
Hutt Mouth	9.51	250.25	18226	918136	103572
Waiwhetu Stream	3.15	31.43	58	2379	293
East Harbour	3.18	74.54	35	1774	215
Whakatikei	3.27	139.91	659	26281	3189
Akatarawa	3.52	154.84	1557	68479	8147
Mangaroa	3.98	186.86	1047	72306	10965
Upper Hutt	5.57	501.02	3758	592568	58576
Pakuratahi	3.88	190.11	1324	80712	10896

Stream	SSC median (mg/l)	SSC 95th percentile (mg/l)	SS load median (kg/day)	SS load 95th percentile (kg/day)	Annual average load (t)
Wainuiomata	3.81	173.73	1185	61895	12243
Gollans	3.29	117.29	64	2831	442
Lake Kohangapiripiri	3.58	146.62	6	461	42
Orongorongo	4.66	267.09	2049	143240	20419
Wellington Harbour	N/A	N/A	18727	934604	105297

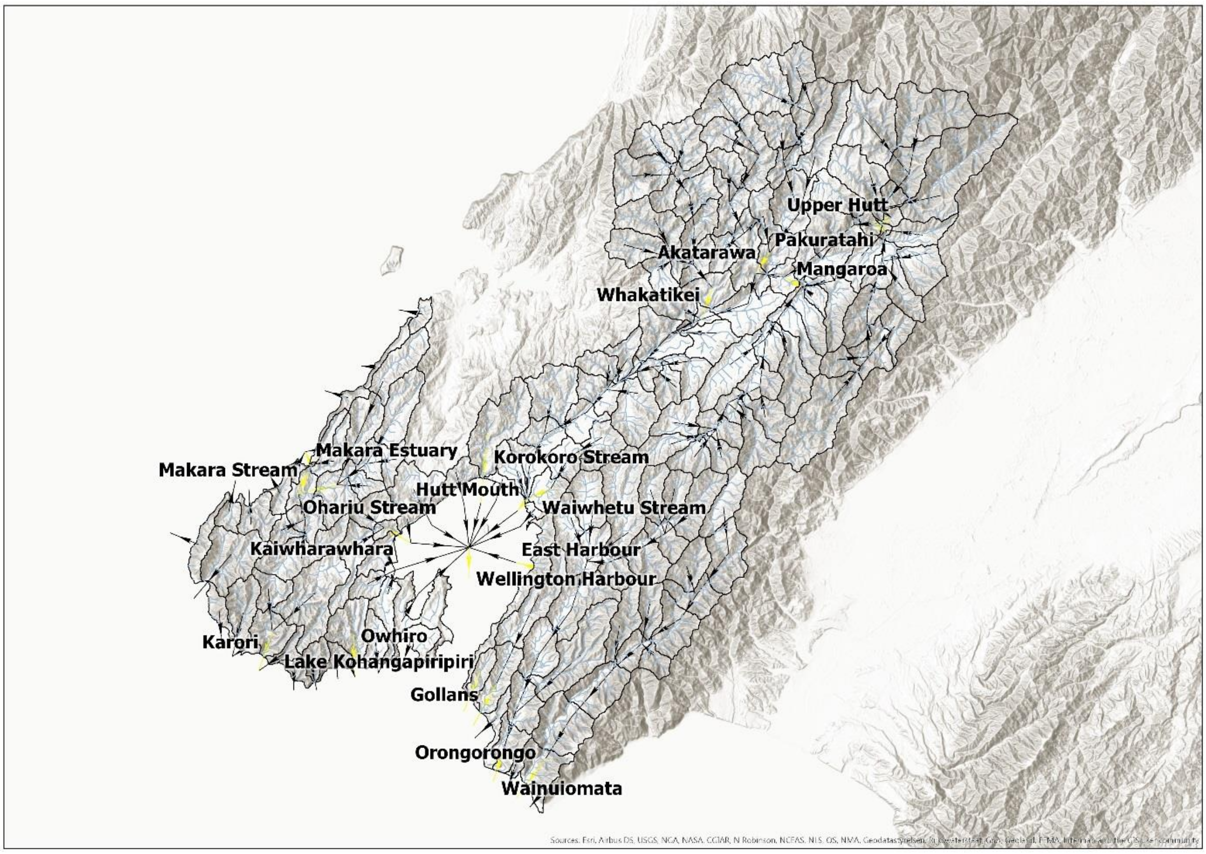

Figure 7 Model reporting links

To aid identification of sediment ‘hotspots’ in the whaitua, the daily sediment load generated by each unique FU / sub-catchment combination was extracted from dSedNet (Figure 8). The load generation is the sum of the hillslope and landslide simulated sediment load, it does not include streambank erosion generated sediment which is simulated at each model link and is not associated with a specific FU. Figure 8 shows the highest sediment-yielding areas are those in the Hutt river headwaters and Orongorongo catchment, where high rainfall and steep slopes contribute to increased rates of sediment loss.

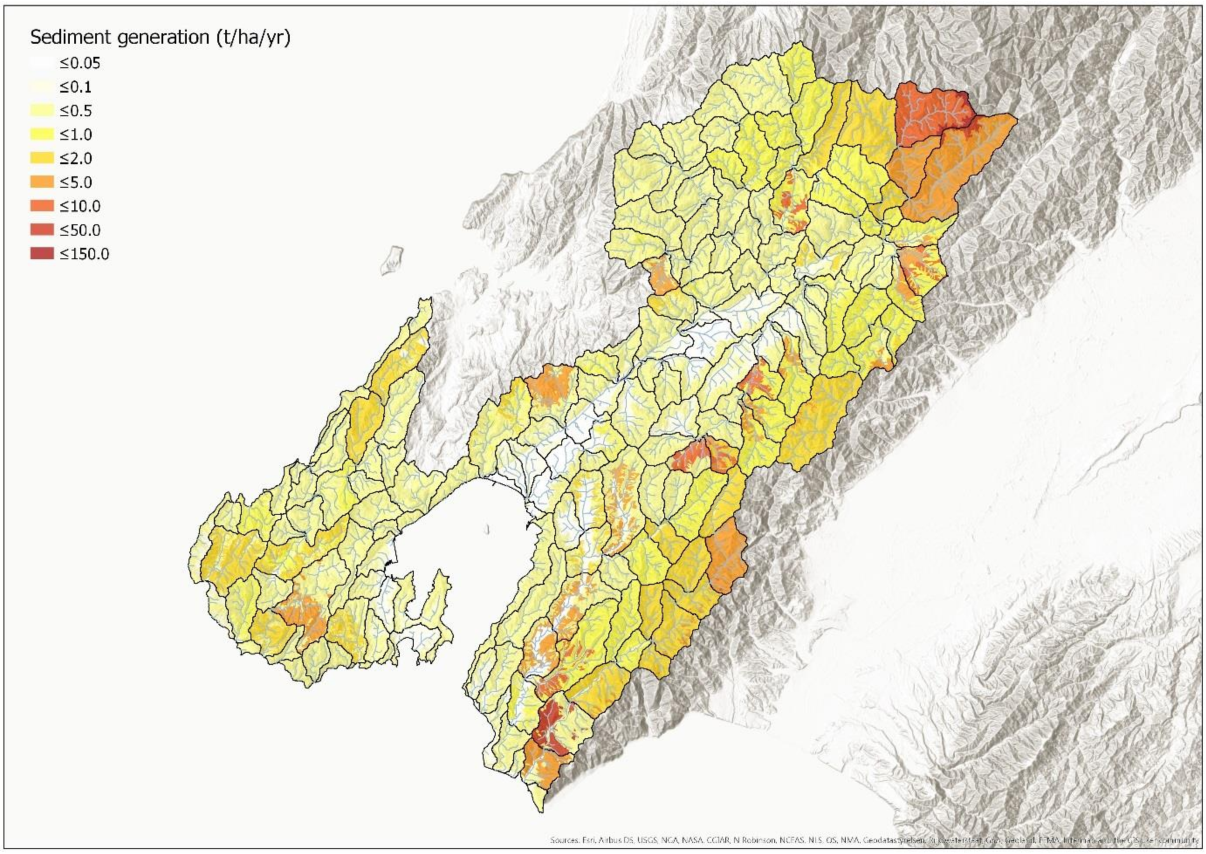

Figure 8 dSedNet simulated surficial and landslide sediment generation from functional units

4.2 Discussion and limitations

The developed model replicates the architecture and utilises parameter sets from the previously developed and calibrated Porirua whaitua eWater Source and dSedNet models. Further model development and calibration has been limited due to data scarcity and short project timeframes. Model results are therefore somewhat uncertain in providing reliable absolute daily load or suspended sediment concentration (SSC) values, but the model is useful in providing information on relative differences in sediment loading between whaitua sub-catchments and runoff events and to assess changes in loading rates under potential catchment planning and mitigation scenarios.

The greatest source of uncertainty in the modelled loads is likely the large, infrequent sediment loading events that have been attributed to landslide and streambank erosion processes. Streambank erosion is calibrated to match the annual average load predicted following NZSedNet across the entire whaitua; streambank erosion yield for a given reach in the developed model may be less- or greater-than that estimated by NZSedNet for that reach. Sediment load contribution from shallow landslides has been estimated based on Porirua information, using a relatively simple power-function approach based on generated quickflow and landcover. The shallow landslide sub-model assumptions may not hold for the different erosion terrains in whaitua te Whanganui-a-Tara, and the model fails to account for deep landslide processes that are independent of landcover where slope failure may occur below the rootzone of forested slopes. Load generation from landslides may also be overestimated where only a small proportion of a FU within a given catchment meets the required ‘landsliding criteria’ of 1000m^2 classified as steep (> 26 degrees), as simulated loads are determined by the total quickflow generated from a FU.

While the dSedNet predicted SSC values agree satisfactorily with the limited in-stream observations available, SSC values for very large events should be viewed with caution due to the lack of calibration data in the project catchments. The maximum SSC concentration predicted by the dSedNet model for the Hutt river at Melling is 3,571 g/m3 which was predicted to occur on February 3, 2013. This value is within the same order of magnitude as the peak events recorded in the Porirua and Pauatahanui streams (3,357 mg/l and 4,552 mg/l, respectively) to which the dSedNet was calibrated during the Porirua whaitua dSedNet model development. Elsewhere, these parameters have resulted in SSC concentrations reaching above 14,000 g/m3, for example on the Hutt river at the confluence with the Pakuratahi during the February 3, 2013 event. Concentrations of this magnitude are not expected to be observed in-stream and indicate that further calibration of the model is required to accurately model sediment concentrations during large events. As such, it is recommended that statistical measures such as 95th percentile concentration, or percent of days above a certain threshold are used, rather than maximum values for analysis of SSC. It is recommended that ongoing sediment event monitoring is carried out across the whaitua to enable further refinement of the developed model.

Counter to the likely over-prediction of SSC during large events is the under-prediction of flow volumes by the hydrological model for some catchments (e.g. Whakatikei, Wainuiomata) due to imperfect hydrological calibration where peak flows are lower than those observed (see section 2.2). This may temper the potential overestimation of daily and total loads driven by anomalous SSC values for some reaches and may be a contributing factor to the underestimation of annual loads in comparison to the SSYE and NZEEM (see section 3.2.1).

4.3 Conclusion

Despite the identified uncertainties, the limited validation data available shows general agreement with model results. The described sediment modelling approach represents a novel methodology that offers increased utility and resolution of erosion processes than annual scale models. The approach allows mitigation options such as pole planting, retirement, and constructed wetlands to be tested in scenario modelling, and provides model outputs expressed as daily in-stream SS concentrations and loads to receiving harbours and estuaries. The comparison of model results as load and concentration time-series provides for wider ecosystem health assessment and linkage to other models, e.g. harbour assessments for sediment deposition and stream habitat assessment.

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