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Flood Hydraulics and Impacts on Invasive Vegetation in a Braided River Floodplain, New Zealand

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Abstract

This study evaluates the effects of floods and their hydraulic characteristics on invasive vegetation in the Ahuriri River floodplain, a braided gravel-bed river in the eastern high country of the South Island, New Zealand. Invasive vegetation alters the natural braiding tendency of rivers such as the Ahuriri and has severe negative impacts on threatened and endangered native wading birds and floodplain ecology. Aerial photographs for a 10-year period (1991 to 2000) that includes the largest flood on record in 1994 (recurrence interval of almost 50 years) based on a 46-year record were analysed to determine changes in aerial cover of water, bare substrate, and several different vegetation classes. This was complemented by hydraulic modelling using HEC-RAS software for a representative 1.1-km reach to evaluate flood hydraulic characteristics that can impact vegetation, including water inundation area, depth, velocity, and shear stress. The 1994 flood (570 m^3/s) removed up to 25% of the invasive vegetation in the study reach, with preferential removal of lupin and less removal of willow and grassland. However, flood effects varied considerably with overall minor effects on total vegetation cover over the entire lower 21-km reach. The spatial distribution of vegetation cover changed considerably in response to this flood event, in a pattern resembling a shifting-mosaic steady state model. Modelling showed that a 600 m^3/s (50-year) flood is likely to result in almost total inundation of the study reach floodplain and significant velocities and shear stresses on floodplain vegetation. Over the study reach linear models approximate the relationships between flood peak magnitude with average water area, depth, velocity, and shear stress. Depth and velocity do not increase as fast as flow area or shear stress, and differences between hydraulic characteristics for the 600 and 155 m^3/s floods ranged from 37% for velocities to 179% for flow inundation areas. Much of the vegetation appeared to recover relatively quickly after flood events so that vegetation removal effects are short-lived. Although large floods can remove a considerable amount of invasive vegetation in some reaches of the river, natural flood events are unlikely to significantly reduce invasive vegetation cover throughout the river.

Keywords: braided rivers, floodplain, riparian, invasive vegetation, hydraulic modelling, New Zealand

1. Introduction

Braided gravel-bed rivers are complex due to their constantly changing morphology and numerous interacting variables which make them a challenge both for scientific understanding and practical river management calling for a multidisciplinary approach (Morisawa, 1985; Bristow & Best, 1993). They are characterised by highly variable flows and multiple alluvial channels in wide floodplains which divide and rejoin in a similar fashion to braids (Mosley, 1983; Bristow & Best, 1993). Such rivers are very difficult to measure and model accurately due to their high spatial and temporal variability (Mosley, 1983; Morisawa, 1985; Davies, 1987). Management and restoration of these rivers after human impact, or as part of flood protection of adjacent land, is also challenging (Piégay et al., 2009). In addition, floodplain riparian vegetation complicates braided river behaviour because different vegetation types affect flow resistance and channel morphology by increasing the resistance of river banks to erosion and sediment entrainment. In turn, a river affects its riparian vegetation through processes such as seed dispersal, scouring and removal during floods (Murray & Paola, 2003; Corenblit et al., 2007). The concept of 'fluvial biogeomorphic succession' describes the two-way interactions between fluvial landforms and riparian vegetation communities (Corenblit et al., 2007). Large floods that can inundate the floodplain, as well as high flow pulses that may not overtop primary channels, can have substantial effects on riparian vegetation and are the key drivers of ecological processes in many rivers, especially braided river systems (Junk et al., 1989; Tockner et al., 2000; Tockner et al., 2009; Bertoldi et al., 2009; Welber et al., 2012). However, most braided river studies have focussed on analysing the relationships between high flow pulse and small flood (up to the approximate 2-year return period) water levels and vegetation. Very few studies have evaluated the impacts of large flood flows and hydraulic characteristics on invasive vegetation.

In the South Island of New Zealand, braided river floodplain ecosystems are complex mosaics with shifting surface water-groundwater interactions in deep gravel hyporheic zones; side channels, springs and adjacent wetland interactions; plant and animal species highly adapted to extremely variable flows and morphology; and exotic/invasive plants in newly-formed substrates outcompeting some native species (Figure 1) (Gray & Harding, 2007). Braided gravel-bed rivers flowing east from the Southern Alps provide critical, unique habitat for numerous threatened and endangered native bird species, including the black stilt (*Himantopus novaezelandiae*) and wrybill (*Anarhynchus frontalis*). However, these rivers have been impacted by hydroelectric power (HEP) development and other anthropogenic stressors (Peat & Patrick, 2001; Caruso, 2006). The Upper Waitaki Basin (UWB, also known as the MacKenzie Basin) in South Canterbury on the South Island has approximately 13% of New Zealand's braided river habitat and is critically important to a number of threatened native wading and shore birds (Caruso, 2006). Nine power stations in Median Energy's Upper Waitaki HEP scheme generate approximately 7600 GWh annually, around 18% of New Zealand's electricity generation and more than 30% of all its hydroelectricity. However, a number of rivers have been impacted by dam and reservoir construction (raising levels of glacial lakes) and diversion of rivers for HEP generation. The Ahuriri River on the southern boundary of the basin (Figure 2) is one of the last remaining free-flowing rivers unimpacted by HEP. Although the river is unregulated, vegetation in the lower reaches of the river is characterised by a higher prevalence and diversity of exotic and invasive plants than many other rivers in the UWB as a result of land use impacts, including major seed sources in a primary tributary (Longslip Creek) near the upper portion of the lower catchment. Deeper surface layers of finer material and a higher groundwater table providing moist soil conditions in some locations also contribute to a predominance of exotic vegetation in the Ahururi River floodplain (Woolmore, 2011). Invasive vegetation such as crack willow (*Salix fragilis*), Russell lupin (*Lupinus polyphyllus*), and sweet briar (*Rosa rubiginosa*) can stabilise banks and islands, encouraging the development of a single channel instead of the dynamic braided river patterns that form in the presence of native plant species (Nadler & Schumm, 1981; Murray & Paola, 2003). This vegetation also has severe negative impacts on birds and other fauna that rely on bare, shifting gravels for habitat, including providing cover for introduced pest mammalian predators such as ferrets (*Mustela furo*), stoats (*Mustela ermine*) and feral cats (*Felis catus*) that have decimated bird populations in many areas of New Zealand (Figure 1) (Peat & Patrick, 2001; Caruso, 2006). Invasive vegetation in some UWB rivers, including the Ahuriri River, are currently controlled by herbicide applications and manual removal, which is costly and sometimes very controversial (Woolmore, 2010, Pers. Comm.). For example, lupins are considered aesthetically pleasing to many people and willows are appreciated by anglers and provide shade and temperature moderation for introduced sport fish species such as trout.

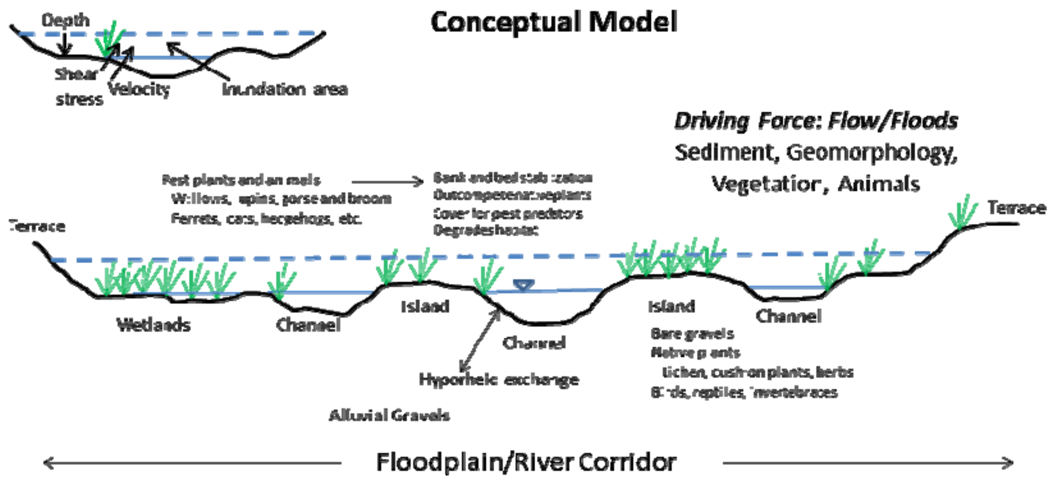

Figure 1. Conceptual model of the Ahuriri River floodplain, a braided gravel-bed river floodplain ecosystem including invasive vegetation. The dashed horizontal line is a flood event inundating much of the floodplain and vegetation. The smaller inset shows potential flood hydraulic characteristics that could affect or remove vegetation

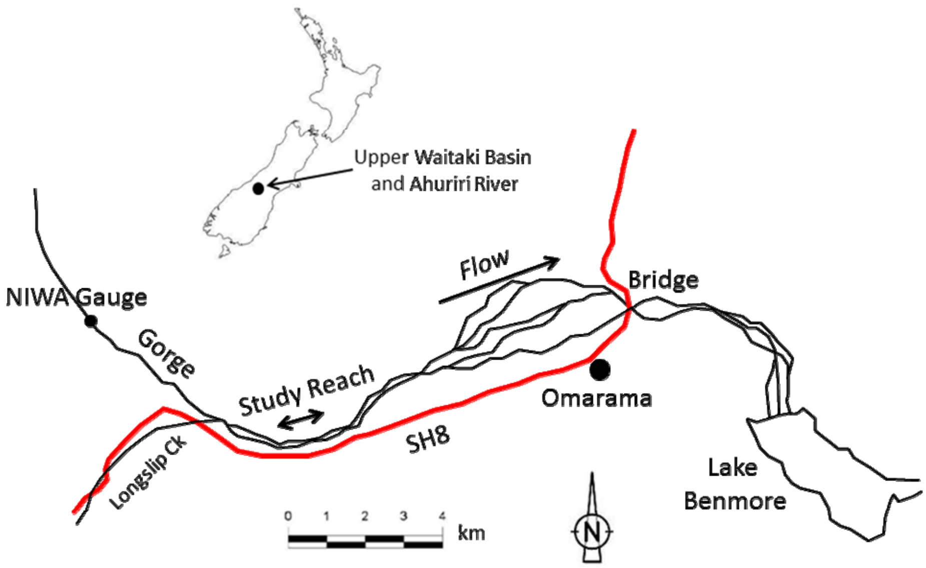

Figure 2. Location of the lower Ahuriri River, NIWA flow gauging station, and 1,100 m model reach where floodplain cross sections are located, and aerial photograph analysis for changes in invasive vegetation and hydraulic modelling of the floodplain were performed

In 1991 Meridian Energy entered into a Compensatory Funding Agreement with the New Zealand Department of Conservation (DOC) and initiated Project River Recovery (PRR), a braided river and wetland restoration programme developed to mitigate impacts of HEP development on river ecosystems in the UWB (Peat & Patrick, 2001; Caruso, 2006). PRR includes four primary components: predator and pest plant control, wetland construction, education and outreach, and a research component. A review of PRR suggested that objectives could be expanded and the project could benefit from a more holistic approach to understanding and incorporating information on the physical aspects of the rivers and floodplains, including their hydrology and geomorphology (Caruso, 1996). However, little is known about the hydrology and hydraulics of the Ahuriri River and other high country braided rivers under flood conditions, nor their interactions with floodplain invasive vegetation. Furthermore, although invasive vegetation is a major problem in the lower reaches of the

Ahuriri and for neighbouring braided rivers, no known studies have been conducted which examine the effect of floods on invasive vegetation in these rivers.

The primary objective of this study is to evaluate the effects of large flood peaks and their hydraulic characteristics on invasive vegetation in the lower Ahuriri River floodplain. The study has two main components: (1) analysis of aerial photographs of the river to determine whether the extent of floodplain invasive vegetation has changed over time as a result of a major flood, and (2) hydraulic modelling of the river floodplain to simulate different flood peaks and link hydraulic characteristics to observed changes in vegetation cover.

2. Methods

2.1 Study Area

The Ahuriri River rises in the Southern Alps and is 70 km long, flows past the township of Omarama near State Highway 8 (SH8), and discharges to Lake Benmore, a man-made HEP reservoir near the UWB outlet upstream from the Waitaki River (Figure 2). Annual precipitation varies significantly from as little as 350 mm near Omarama to 6400 mm in the highest headwaters near the main divide of the Southern Alps, and parts of the lower catchment are semi-arid with potential evapotranspiration rates ranging up to 925 mm. There is some permanent snow and ice in the upper reaches and several small glaciers, the largest of which is the Thurneysen Glacier (approximately 2 km^2). The upper catchment area is 560 km^2 and ranges in elevation from approximately 600 m to 2200 m above sea level (asl). Land cover in the upper catchment is 46% tussock grasslands, 31% low and high producing grasslands (with some pastoral sheep grazing), and 17% alpine gravel and rock (Landcare Research, 2011).The lower catchment ranges in elevation from 380 to 600 m asl, and is approximately 752 km^2 in area. It is a mix of low-producing grassland/pasture and high–producing exotic grassland/pasture for sheep and beef cattle grazing, exotic shrubland, and some native tussock grassland. Mean annual flow is approximately 23 m^3/s based on a period of record of 46 years (1963-2009) at a National Institute of Water and Atmospheric Research (NIWA) flow gauging station (Ahuriri at South Diadem) located in a gorge at the upstream end of the study reach (Figure 2). Although the river has some braiding in the upper catchment above the gorge, braiding becomes much more substantial and prevalent, along with invasive vegetation, downstream of the gorge. A study reach downstream from the gorge was used for analysis of invasive vegetation cover and modelling flood events (Figure 2). This reach was selected because it was typical of the lower sections based on channel sinuosity, braiding, and extent of vegetation cover. The accessibility of the river from the highway and the availability of safe crossing points on the main channel were also important selection criteria. The study reach is approximately 1100 m long with an average floodplain width of roughly 500 m (Figure 3). This reach has one main channel and several secondary channels displaying some braiding. The flowing channels are separated by a wide area of patchy vegetation, bare gravels and stagnant water. Willows, lupins, and grasses are present on many islands in the study reach, with some areas of very dense vegetation. During floodplain surveying, the NIWA flow gauge recorded flows between 15 and 20 m^3/s.

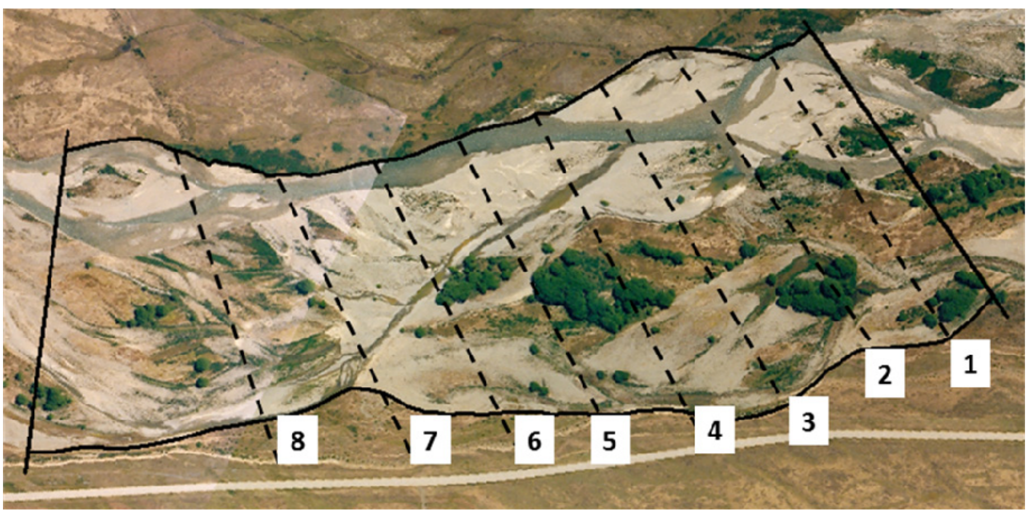

Figure 3. Aerial photograph (1991) of Ahuriri River floodplain study reach with approximate locations of surveyed cross-sections overlayed with HEC-RAS river station (R.S.) numbers. The river flows from left to right

2.2 Aerial Photograph Analysis

Aerial photographs were obtained from PRR records and comprised seven sets of photos of the lower reach (Table 1). Most were obtained as printed copies, except for the most recent set taken in 2000 obtained in electronic format (Terralink, 2000). Mean and maximum daily flow records at the gorge from 1963-2009 were obtained from NIWA, and the annual maximum (flood) flow was determined for each year (Table 1). The largest flood on record had a peak discharge of 570 m^3/s in January 1994, with a return period of almost 50 years (Caruso et al., in press). Therefore three sets of aerial photos were chosen to analyse the changes in vegetation cover: photos taken in 1991, 1995 and 2000 (Table 1). The 1991 and 1995 photos bracketed the January 1994 flood. The 1995 photos were taken in February, approximately 13 months after the largest flood. Another large flood (509 m^3/s) occurred in December 1995. The most recent aerial photos from 2000 were also included in the analysis to evaluate recovery of invasive vegetation over a 5-year period, after the two large floods. Each aerial photograph from the 1991 and 1995 sets was scanned at 300dpi, and all photos were georeferenced to the NZGD 1949 Lindis Peak Circuit coordinate system. Resolution of the photos was approximately 0.3 m^2, which was adequate for delineating vegetation class boundaries.

Table 1. Annual maximum flow (annual flood) for 15 years and timing of aerial photography available and used for analysis. The 1994 flood of 570 m3/s (bold italics) was the largest on record (1963-2009, n = 46)

Year	Maximum flow (m^3/s)
1985	154.7
1986	181.7
1987	260.9
1988	212
1989	220
1990	164.6
1991	220.7
	Aerial photographs taken 4/12/1991
1992	170.9
1993	204.9
1994	***570***
	Aerial photographs taken 13/02/1995
1995	508.9
1996	151.9
1997	110
1998	183.8
1999	376.2
	Aerial photographs taken 5/03/2000

The boundary of the active floodplain for each aerial photo was delineated and digitised using ArcGIS 9.3 based on extent of gravel floodplain seen in the images. Floodplain classes included water, bare substrate, and vegetation classes for willow, lupin, and grassland. Crack willow, Russell lupin, and grasses comprise >90% of all vegetation in much of the study reach floodplain (Woolmore 2011). Grassland was defined as pasture grasses and all other herbaceous species at ground level to fill in gaps and complete mapping of the floodplain. The vegetation was classified based on visual assessment of the aerial photos. Criteria used to assign vegetated patches to classes included the approximate percentage of species (>50% willow, lupin, or grass) within an area in combination with the percentage of total vegetation cover (>50%) in that area. For example, if a given area exhibited approximately 60% vegetation cover (and the other 40% was bare substrate), and 60% of that vegetation was willow, the area was assigned to the 'willow' class. These classifications based on visual interpretation of the aerial photos were also checked using ground truthing of more recent 2011 photos using the same procedure. The class boundaries were then manually delineated and digitised for each aerial photo. The areal cover of each floodplain class in the study reach, and the proportion of each class relative to the total active floodplain area, was then calculated for each photo. Using aerial photos for the entire lower Ahuriri river (21-km), the aerial cover for water, bare substrate, and all vegetation classes (total vegetation), and the proportion of each relative to the floodplain area, were also determined for each of the three years analysed. In addition, the proportion of active floodplain width covered by total vegetation was estimated at 10 cross-sections approximately evenly spaced along the lower reach. To compare each dataset at the same locations, transects were drawn at landmark points and the cross-sections of vegetation polygons intersected by these lines were measured and summed, then taken as a proportion of each total width.

2.3 River Cross-Section Surveying

The 1.1-km study reach was surveyed during two field visits in August 2010. Eight floodplain cross-sections were surveyed using a total station and reflective staff, and the location of each set-up was recorded using a Global Positioning System (GPS). Cross-sections were spaced at intervals of approximately 100 to 150 m in the downstream direction and were measured approximately perpendicular to the flow direction in the main channel (Figure 3). Each cross-section consisted of approximately 50 separate survey points, spaced at intervals of 5-20 m across the floodplain. At each survey point the horizontal and vertical distance and the type of vegetation cover and bed material were noted. More survey points were recorded at points of significant elevation change, with fewer points on flat terrain. For most cross-sections it was not possible to survey the bed of the main channel as the river was too deep and swift to cross safely, but visual observations of shape and depth were made. The location of each survey point was converted to New Zealand Transverse Mercator coordinates. The location of each base-station point was available as a GPS measurement and as two survey measurements (a forward bearing and a back-bearing). The base-station coordinates obtained by surveying were compared to the coordinates obtained using GPS to provide an estimate of the positional error included in surveyed points.

2.4 Hydraulic Modelling

The U.S. Army Corps of Engineers Hydrologic Engineering Center River Analysis System (HEC-RAS) Version 4.1 was used to model Ahuriri River floodplain hydraulics and provide initial estimates of water surface profiles and velocities for floods that could result in vegetation removal. HEC-RAS is a 1-dimensional steady and unsteady flow software package for river hydraulics calculations (Brunner, 2008a). Water surface profiles are computed between adjacent cross-sections by solving the 1-D energy equation. The energy head loss between two cross-sections includes friction losses (calculated using Manning's equation) and losses from contraction or expansion (Brunner, 2008a). For preliminary modelling of flood peak effects on vegetation we only needed the characteristics of the peak flow, so we assumed the peak was steady and did not analyze the rising and falling limbs of the hydrograph. This is a reasonable assumption given our objective of evaluating the potential effect of peak flood flows on invasive vegetation. For steady-flow analyses, HEC-RAS assumes that flow is gradually varied, as a hydrostatic pressure distribution is assumed to exist at each cross-section, and the river channels have slopes of less than 0.1 m/m (Brunner, 2008a).

Data from the topographical floodplain survey were entered into a geometric input file in HEC-RAS. Each cross-section was assigned a river station (R.S.) identifier, with R.S. 1 corresponding to the cross-section at the downstream end of the study reach. Additional points were added to represent the thalweg of the main channel, using a maximum channel depth of 1 m below the riverbanks and modelling the main channel as parabolic in shape based on field observations. Downstream reach lengths were calculated separately for the left bank, main channel and right bank, by assuming a straight line between subsequent points and finding the difference in the coordinates. The river longitudinal slope was calculated by finding the sum of elevation changes between points on the left bank and right bank, respectively, and dividing by the total horizontal distance between these points. The average of the left bank and right bank slopes gave a slope of approximately 0.009 m/m.

Manning's n roughness values can vary depending on surface roughness, vegetation, channel form and alignment, and water stage (Brunner, 2008a). Values of 0.04 for the main channel and 0.05 for the floodplain were taken from Chow (1959, quoted in Brunner, 2008b) and Hicks and Mason (1998) and used to reflect a clean, winding natural channel with some pools and shoals, and a floodplain dominated by scattered brush and heavy weeds, respectively (Brunner, 2008b). Several different geometric input data files were created in HEC-RAS to test the sensitivity of the model to channel and floodplain roughness values, including using different values of Manning's n for every change in vegetation or bed material type across the floodplain. For all geometry files, contraction and expansion coefficients were set at the default values of 0.1 and 0.3, respectively. These values are typical for small topographical changes between subsequent cross-sections and for sub-critical flow (Brunner, 2008a). A normal depth boundary condition was used, with the energy slope approximated by the river longitudinal slope of 0.009 m/m. The flow regime for each analysis was subcritical only, based on the assumption that a self-formed channel will only have very localised areas of supercritical flow (Grant, 1997).

A flow of 10 m^3/s was used to simulate base or low-flow conditions. Four different flow analyses were run for flood peaks of different magnitudes: 155, 285, 500, and 600 m^3/s, representing floods with approximate annual recurrence intervals (ARIs) of <2, 5, 25, and 50 years. The model outputs of interest for each cross section were the flow areas of inundation, hydraulic depths, flow velocities, and shear stresses in the channel and floodplain overbank areas during different flood peaks, as these parameters affect the ability of the river to remove vegetation from the floodplain. In addition, local velocity values were obtained for up to 45 points along two of the cross sections (R.S. 2 and 4) using the flow distribution option in HEC-RAS to provide a more detailed analysis and better characterization of hydraulic properties at key locations. These data were used to compute probability distributions and develop cumulative distribution plots for depth, velocity, and shear stress at these sections. No adequate data on flood flows, velocities, or levels have been collected in braided sections of the Ahuriri River for calibration or validation of the hydraulic modelling. As for many flood hydrologic and hydraulic modelling studies, calibration and validation of the model can be difficult or impossible due to a lack of gauged monitoring data during flood or high flows in key river locations resulting from inaccessibility and dangerous conditions. In some cases, any relevant gauged or observed flow, velocity or level data collected in a river or nearby/similar rivers can be used to the extent possible, or qualitatively to compare to model output and evaluate results. Therefore, in this study any available data collected during high flows or results from other modelling studies in the Ahuriri or similar rivers (Mosley, 1982, 1983; Nicholas, 2003; Duncan & Bind, 2009) were used for comparison and evaluation.

3. Results

3.1 Changes in Cover

Within the Ahuriri River study reach, the area of active floodplain at the time of the 1991 aerial photos was approximately 458406 m^2 (Table 2). Vegetation covered approximately 38.6% of the active floodplain, bare substrate covered 46.7% and water accounted for 14.6% of the area. Most of the vegetation was comprised of grassland (24.1%), followed by willow (10.4%) and lupin (4.1%) (Table 2, Figure 4). By 1995, the area of active floodplain increased approximately 3.3% (to 473601 m^2), after the largest flood on record of 570 m^3/s in January 1994. It increased a further 0.3% by 2000, almost five years after another large flood of 509 m^3/s in December 1995. These changes equate to a rate of increase of active floodplain area of 0.8% per year during the first period, and 0.06% per year for the second period, with an overall increase of 0.4%. In 1995 total vegetation cover decreased almost 25%, with the largest decrease of 70% for lupin and the smallest for willow (3.8%). Bare substrate cover increased almost 30%, and water decreased 6.3%. By 2000 there was a further decrease in total vegetation cover of 19.5%, with the greatest decrease for grassland (32.5%) followed by willow (14.4%). However, lupin increased dramatically by approximately 128%. Bare substrate increased another 4.7% and water increased 23%.

Table 2. Summary of cover area (m^2) for floodplain classes and percent of total area, changes between aerial photographs, and averages over period

Floodplain	1991		1995		Δ1991-1995		2000		Δ1995-2000		Avg 1991-2000	
Class	m^2	%	m^2	%	m^2	%	m^2	%	m^2	%	m^2	%
Boundary	458,406	100.0	473,601	100.0	15,195	3.3	475,168	100.0	1,567	0.3	469,058	100.0
Water	67,156	14.6	62,930	13.3	-4,226	-6.3	77,383	16.3	14,453	23.0	69,156	14.7
Willow	47,600	10.4	45,813	9.7	-1,787	-3.8	39,211	8.3	-6,602	-14.4	44,208	9.4
Lupin	18,810	4.1	5,680	1.2	-13,130	-69.8	12,943	2.7	7,263	127.9	12,478	2.7
Grassland	110,615	24.1	82,056	17.3	-28,559	-25.8	55,403	11.7	-26,653	-32.5	82,691	17.7
Vegetation Total	177,025	38.6	133,549	28.2	-43,476	-24.6	107,557	22.6	-25,992	-19.5	139,377	29.8
Substrate	214,225	46.7	277,122	58.5	62,897	29.4	290,228	61.1	13,106	4.7	260,525	55.4

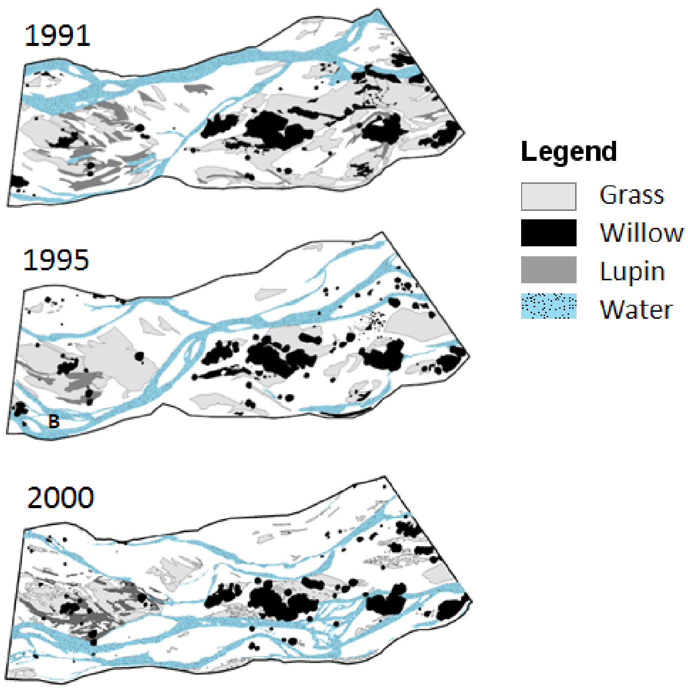

Figure 4. Ahuriri River study reach invasive vegetation cover and changes over time. The river flows from left to right

Results for the entire lower 21-km reach showed that in some areas floodplain and channel morphology and vegetation patterns changed significantly between aerial photographs. Overall the active floodplain area decreased roughly 2% (from 878 ha to 862 ha) between 1991 and 1995, and then increased 7% between 1995 and 2000 to 924 ha (rate of loss of 0.5% per year during the first period and increase of 1.4% per year for the second period, with an average gain of >5% per year). Vegetation covered 42% of the active floodplain in 1991, but decreased to 38% by 1995. There was negligible change in vegetation cover between 1995 and 2000, with the percentage of cover remaining constant at 38%. However, some sections gained vegetation cover from 1991-2000, while other sections lost cover or remained relatively constant (Figure 5). The 2000 dataset showed the least variability in vegetation cover longitudinally along the channel, with a 43% difference between the highest and lowest values of vegetation cover. Both the 1991 and 1995 datasets demonstrated greater longitudinal variability in vegetation coverage, with differences of 59% and 45%, respectively.

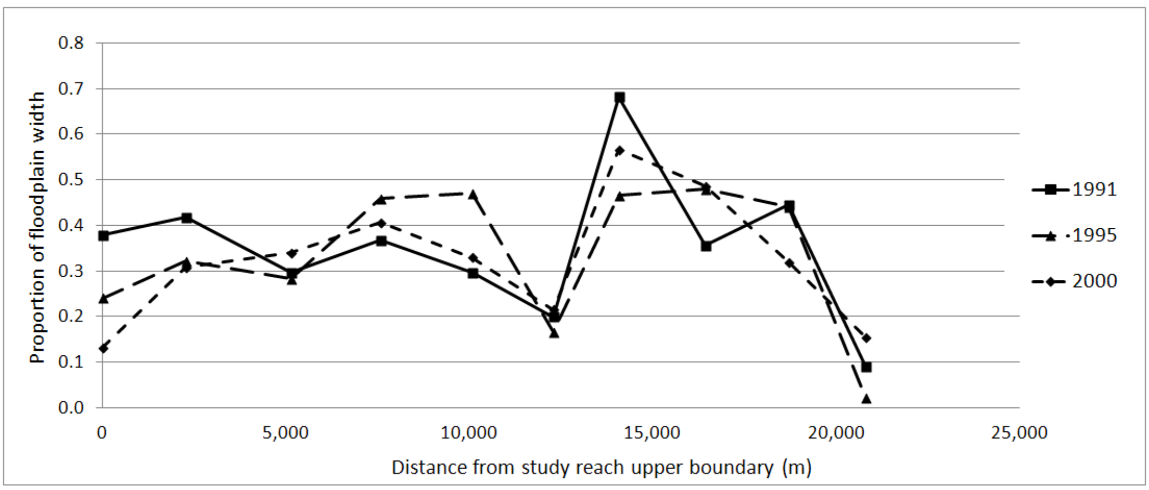

Figure 5. Vegetation cover as a proportion of active floodplain width along the lower 21-km reach of the Ahuriri River

3.2 Hydraulic Modelling

The hydraulic modelling showed that flow was restricted to the primary channels at a low flow of 10 m^3/s. However, a flood of 155 m^3/s (<2-year return period) resulted in some channel overtopping and inundation of parts of the floodplain (Figure 6). Although water occupied some of the floodplain, numerous islands remained above the water surface at specific cross sections. During the largest flood of 600 m^3/s (50-year return period), almost all islands were inundated, but a few of the highest or largest islands remained above water (Figure 6). The flow area of inundation for different size flood peaks varied with distance along the study reach based on floodplain width, presence and heights of islands, and number and sizes of channels (Figure7a). On average over the reach the area of inundation ranged from 133 - 354 m^2 for a 155 and 600 m^3/s flood, respectively, with a maximum of 459 m^2 at one cross section during the 600 m^3/s flood. The average area was 166% greater for a 600 m^3/s flood than a 155 m^3/s flood, and a linear relationship between flood peak and inundation area has an R^2>0.99 (Figure 8a).

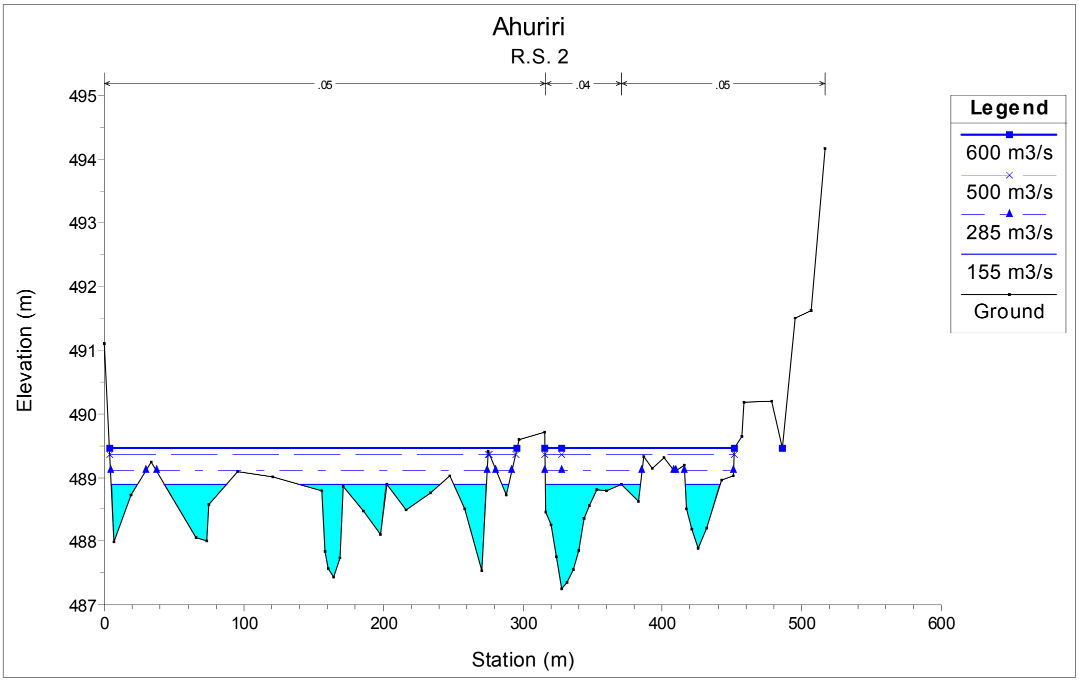

Figure 6. Ahuriri River study reach cross-section R.S. 2 hydraulic depths and areas at modelled peak flows

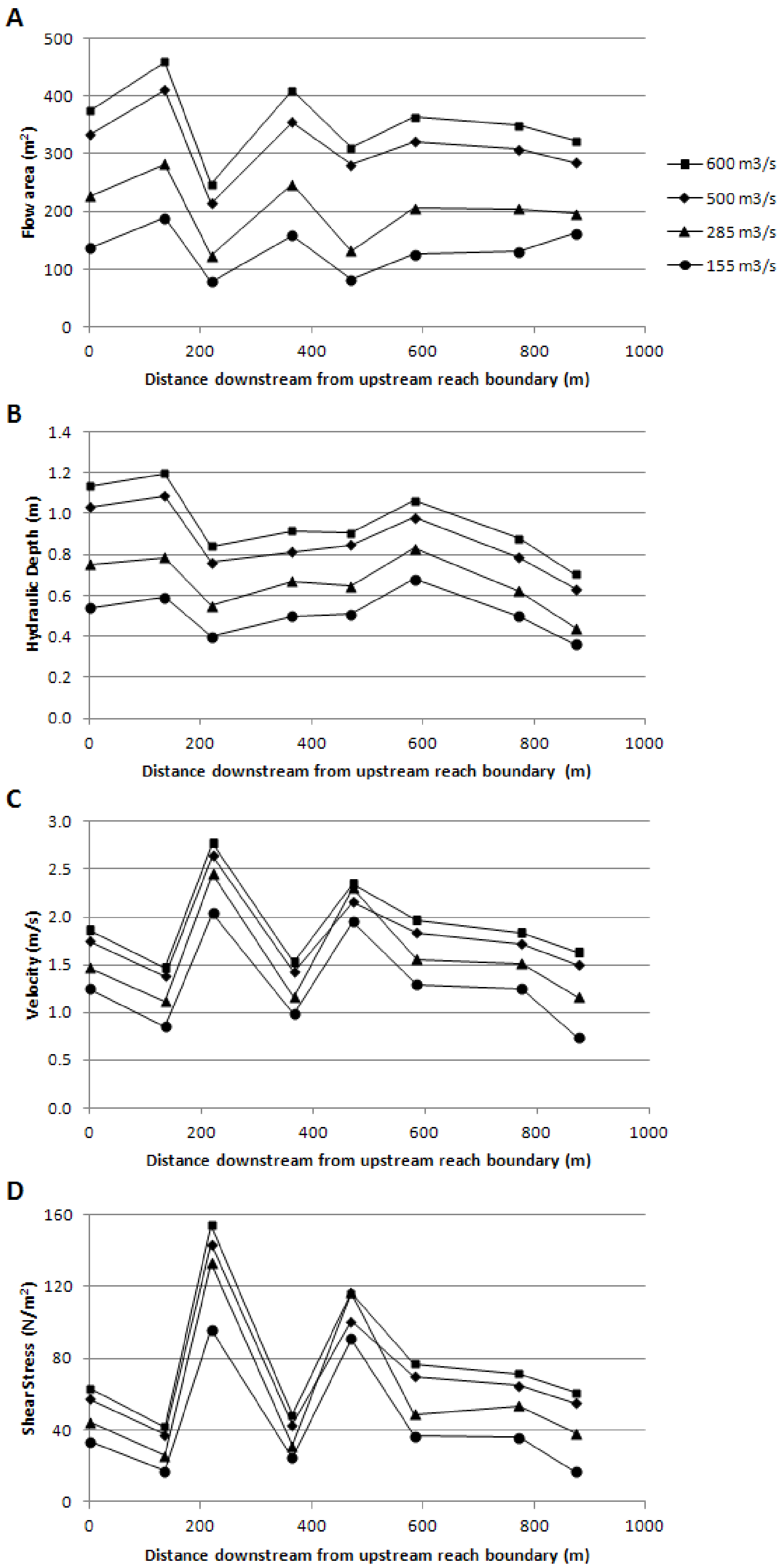

Figure 7. Ahuriri River study reach modelled (A) cross-sectional area of flowing water, (B) average water depth, (C) average flow velocity, and (D) average shear stress across the floodplain for different flood peaks

The depth of water in the floodplain increased from an average of 0.51 m during the 155 m^3/s flood to 0.95 m during the 600 m^3/s flood (Figure 7b). For all cross sections the 600 m^3/s flood had an average depth 87% greater than the 155 m^3/s flood, and a linear correlation exists between flood peak and depth with an $R^2>0.99$ (Figure 8b). In the main channel, the average depth increased from 0.66 m during the 155 m^3/s flood to 1.3 m for the 600 m^3/s flood. Based on the more detailed flow distribution analysis for two cross sections, shifts in the depth cumulative distribution plots to the right occurred (smaller probability of not exceeding a certain depth for high flows versus lower flows), with smaller shifts for greater depths for some sections (R.S. 2) and larger shifts for greater depths in other sections (R.S. 4) (Figure 9a).

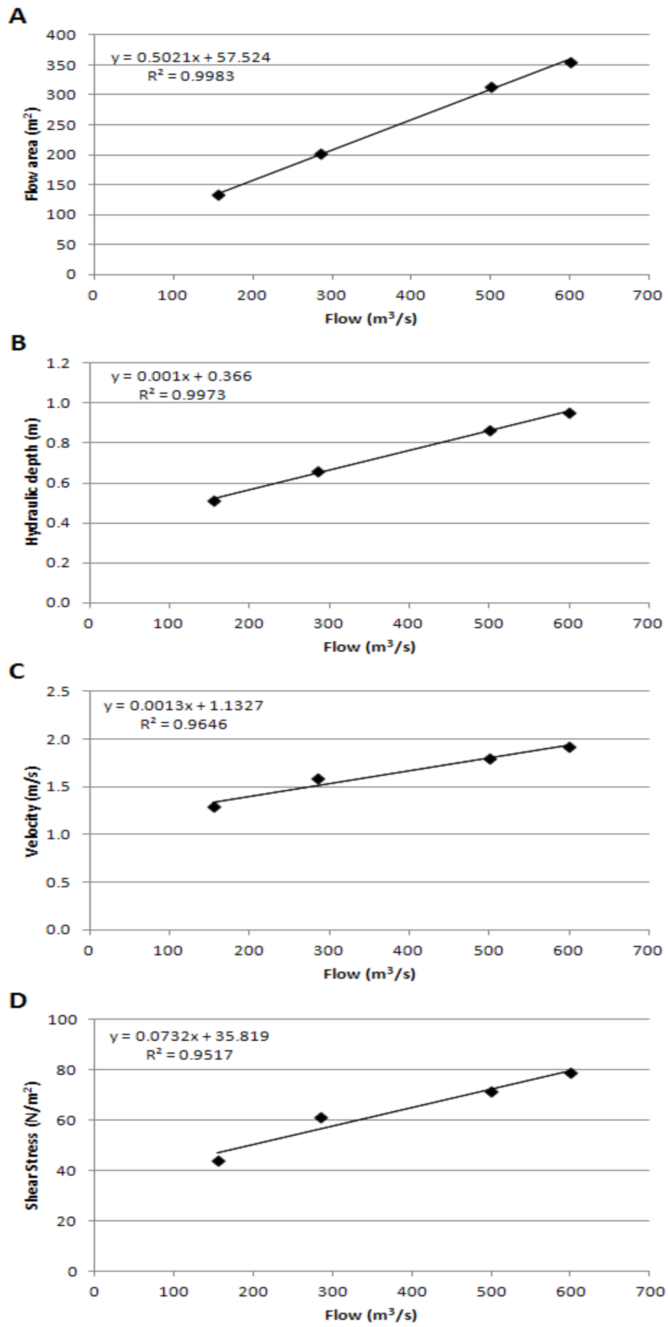

Figure 8. Ahuriri River study reach linear regression of modelled (A) cross-sectional area of flowing water, (B) average water depth, (C) average flow velocity, and (D) average shear stress across the floodplain vs different flood peaks

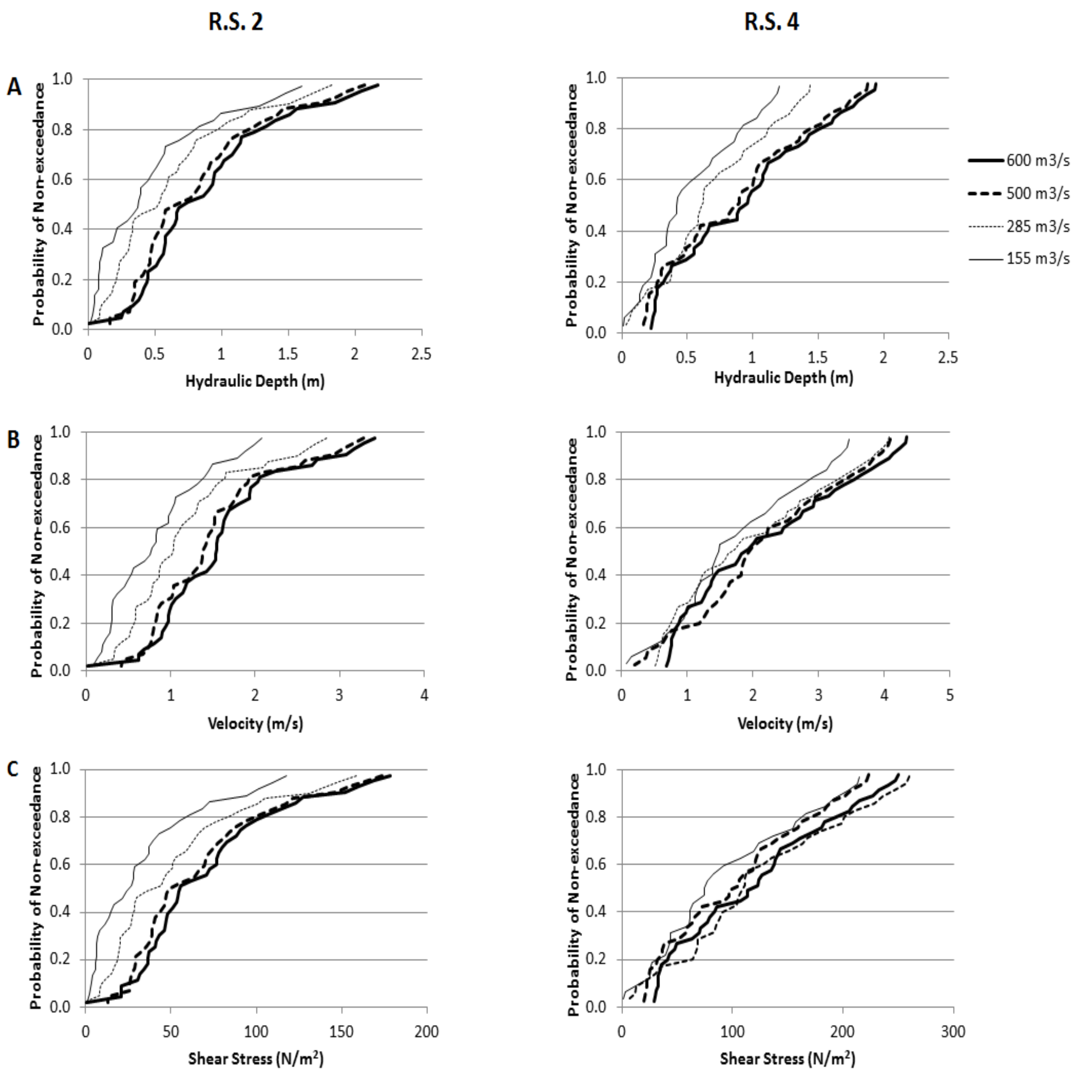

Figure 9. Cumulative distribution plots of Ahuriri River study reach cross sections R.S. 2 and R.S. 4 for modelled (A) hydraulic depth, (B), velocity, and (C) shear stress

Flow velocity across the floodplain increased with increasing flood peak, ranging from approximately 0.7 - 2 m/s during the 155 m^3/s flood to 1.6-2.8 m/s for the 600 m^3/s flood (Figure 7c). However, at R.S. 4. a slightly higher velocity occurred during the 5-year flood (approximately 285 m^3/s) than during the 50-year event. This was due to an incised thalweg and overtopping of the primary channel between the 5-year and 20-year flood flows with water spreading out across a flat area of the floodplain at this cross section. On average, however, velocities were 49% greater for the 600 m^3/s flood compared to the 155 m^3/s flood. A linear relationship between flood peak and velocity has an R^2 of 0.96 (Figure 8c). The average floodplain flow velocity, calculated as the average of the velocity left and right of the main channel, was 1.1 m/s during the 155 m^3/s flood. This increased to 1.5 m s^{-1} for the 600 m^3/sflood. In the main channel, average velocity was as high as >3.7 m/s during the largest flood. The detailed flow distribution analysis showed local velocities <1 m/s in some areas of the floodplain, and local values in the main channel >4 m/s at some sections (Figure 10). The velocity cumulative distribution plots generally showed shifts to the right with increasing flows, with some sections (R.S. 2) exhibiting large, consistent shifts with greater flows. However, other sections had smaller and more inconsistent changes with greater flows, such as those shown in greater detail at R.S. 4 due to overtopping of the primary channels with flow spreading across a flat floodplain area (Figure 9b).

Average shear stresses across the floodplain increased from approximately 44 N/m^2 for the 155 m^3/s flood to 79 N/m^2 for the 600 m^3/s flood, with a maximum of approximately 153 N/m^2at R.S. 6 during the largest flood

(Figure 7d). Shear stress changes with flood magnitudes were similar to those for velocities at R.S. 4 due to overtopping of the primary channels with flow spreading across the floodplain. On average, shear stresses were 80% greater for the 600 m^3/s flood compared to the 155 m^3/s flood, and a linear relationship exists between flood peak and shear stress with an R^2 of 0.95 (Figure 8d). Shifts to the right with increasing flows were also observed in the shear stress cumulative distribution plots, with similar results to velocities. Some sections (R.S. 2) had large, consistent shifts with higher flows, while others (R.S. 4) had smaller, more inconsistent changes with higher flows due to overtopping of primary channels (Figure 9c).

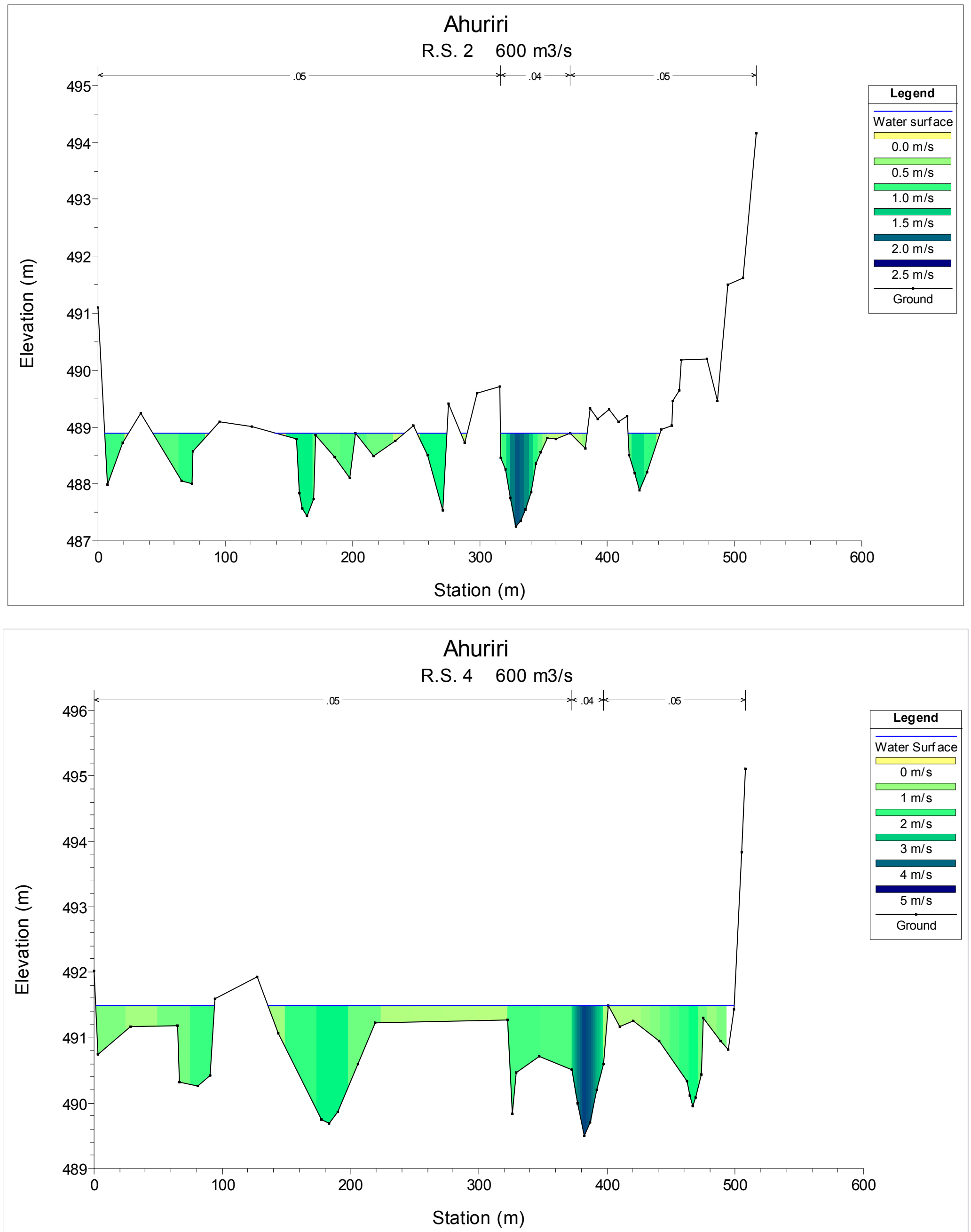

Figure 10. Ahuriri River study reach cross sections R.S. 2 and R.S. 4 water area at a peak flow of 600 m^3 s^{-1} showing velocity distributions used for cumulative distribution plots

4. Discussion

4.1 Changes in Cover

Our results for the whole lower 21-km reach showed a loss of active floodplain area of 0.5% per year, followed by 1.4% gain per year, which is consistent with erosion rates of between 0.17% and 3.3% per year calculated by Latterell et al. (2006) in their study of the Queets River in the Olympic Mountains of Washington, U.S.A. Few studies have evaluated vegetation removal by large floods in braided river floodplains, particularly impacts on invasive vegetation in these environments. Hickin and Sichingabula (1988) found significant geomorphic changes in a braided reach of the Squamish River (Canada) after a 30-year recurrence interval flood. The flood was able to re-instate the braided character of the reach by removing vegetated bars and islands, but the amount or type of vegetation removed was not quantified. A 100-year flood in a mountain floodplain removed up to 22% of pioneer vegetation on floodplain areas that became unvegetated gravel bars, but did not remove larger amounts of older successional vegetation like willows, demonstrating considerable resilience (Hering et al., 2004). In their analysis of the Upper Gila River in Arizona, USA, Dick and McHale (2006) found losses of emergent wetland area as large as 56% immediately after a significant flood event, but on average for all wetland types the loss was 11% and for all riparian areas was only 1%. The return period of the flood was not quantified, but the discharge was 1104 m^3/s compared to the largest flood on record of 3738 m^3/s, and was the 5th largest flood on record. Our results appear to be somewhat similar to these studies since approximately 25% of invasive vegetation was removed in the Ahuriri River study reach between 1991 and 1995 after the largest flood on record of 570 m^3/s (slightly less than the 50-year flood), but there was only a 4% decrease in vegetation cover over the whole lower 21-km reach during that period. We also found that there was preferential removal of lupin in the study reach after the largest flood, but that willow was preferentially removed after a somewhat smaller flood the following year with lupin recovering rapidly within five years.

Our data suggest that any vegetation removed by the large floods was likely replaced by growth of new vegetation in other parts of the floodplain, leading to minimal change in total vegetation coverage over the 10-year time period analysed. However, different vegetation types shifted spatially in the floodplain over time, with some areas losing vegetation cover and other areas gaining vegetation. This is consistent with the shifting-mosaic steady state model, which describes how river valleys resemble ‘dynamic mosaics’, with many ‘patches’ at different stages of development (Latterell et al., 2006). These patches are ‘transient features’ which are formed by the river and by patterns of vegetation succession which may occur over long time periods. Over time patches shift spatially, but the total proportion of each patch type in the riverbed remains constant at large scales, for example at the scale of a river valley (Latterell et al., 2006). Longitudinal variations in vegetation cover along the 21-km lower reach may be explained by differences in floodplain width, channel form, and vegetation type. Some parts of the reach are relatively narrow and contain many islands heavily-vegetated with willow, which are likely to resist erosion during floods (Blom, 1999; Hering et al., 2004; Gurnell et al., 2012). Other sections are very wide (up to 3 km) and display a more typical braided river pattern, with large expanses of bare gravels or with pioneer lupins or grasses. These areas may be more prone to disturbance during flooding events, and may consequently display greater variations in vegetation cover. This is consistent with the results of Latterell et al. (2006), who found that type of vegetation cover determines the erosion rate of a patch, with forested patches typically the most resistant to erosion and bare gravel bars the most susceptible to erosion. The spatial variation in vegetation cover with time is a key feature of the shifting-mosaic steady-state concept.

Anthropogenic factors may have affected the extent of vegetation cover and change in the floodplain between 1991 and 1995 to a limited extent. Sheep and cattle are allowed to graze in parts of the active floodplain, so browsing and trampling of vegetation may reduce the extent of vegetation cover in the floodplain. Conversely, animals might encourage the spread of exotic vegetation by transporting seeds and depositing nutrient-rich faecal matter. Although these influences may act as confounding factors which obscure the relationship between floods and vegetation cover, it is believed that these effects are likely to be small compared to influences of floods and discharge. Other high flow events between 1991 and 1995 may have also contributed to the decrease in vegetation cover during these years. However, no other floods greater than the 2-year event (>220 $m^3 s^{-1}$) occurred during this period, so only high flow pulses less than the 2-year flood could have contributed to the observed changes (Caruso et al., submitted). There are many contrasting views in the literature concerning the relative importance of floods of different magnitudes and frequencies to channel morphology. A common view is that annual floods are largely responsible for shaping river form and pattern, with floods both smaller and larger than the annual flood being relatively less effective at shaping the river channel (Hickin & Sichingabula, 1988; Davies, 1988). Hickin and Sichingabula (1988) also suggest that the most significant channel adjustments are made in response to large, infrequent flood events. Large flood events result in the largest areas of terrain being scoured and readied for colonization by plant species (Corenblit et al., 2007), and therefore may be the most important determinants of total vegetation cover. Perhaps the most holistic view is that channels integrate processes over a range of timescales, therefore a range of flood magnitudes and frequencies are likely to be important in shaping a river and its vegetative cover (Hickin & Sichingabula, 1988).

4.2 Hydraulic Modelling

Model results for the Ahuriri River indicate that even during smaller floods or high flow pulses, such as the modelled peak of 155 m^3/s (<2-year flood), some of the floodplain can be inundated. Although the largest flood covered most of the floodplain, however, some small islands still remained. Surprisingly little information on measured inundation areas (or depths and velocities) during floods is available for braided rivers in New Zealand. Mosley (1982) analysed relationships between increasing channel widths with discharge, including during a flow released from hydropower operations approximating the 50-year flood, in the slightly larger Ohau River (immediately north of the Ahuriri), and for a more frequent range of flows in several other South Island rivers (Mosley, 1983). The relationships were nonlinear and cross sectional area of water increased at the greatest rate. Our modelling results for the study reach also showed that the area of water increased with flood peak at the fastest rate, followed by shear stress, velocity, and then depth. However, our data also indicate that on average across all sections, a linear correlation approximates all these relationships well.

The modelled average water depths in the floodplain of 0.51 m during the 155 m^3/s flood to 0.95 m during the largest 600 m^3/s event, and the average depth of 1.3 m in the main channel during the largest event, match field observations that the main channel thalweg was approximately 1-m deep during baseflow (approximately 15 m^3/s during the surveying visit). Although measured depths in braided sections of the Ahuriri River during floods for model calibration and validation are not available, our model results also compare well with very limited results from other studies of New Zealand braided rivers. In the Ohau River, Mosley (1982) recorded some depths up to almost 3 m and a median depth >0.5 m during a roughly 50-year flood flow. In other South Island braided rivers he recorded depths ranging from approximately 0.1 to 1.3 m for more typical ranges of flows (Mosley, 1983). Some results are also available for comparison from other modelling studies of South Island braided rivers using the 2-dimensional model Hydro2de (Beffa & Connell, 2001; Beffa, 1996). Modelled depths in the Avoca River (tributary of the Rakia River) for flood flows up to 100 m^3/s (with a mean annual flood of approximately 110 m^3/s 12 km downstream) ranged up to 1.9 m with a median depth of approximately 0.4 m (Nicholas, 2003). Several other studies using this model focused on a more typical range of flows or low flows for habitat modelling and evaluation of weighted usable area (WUA) for different aquatic biota in braided rivers. Depths under these flow conditions ranged up to approximately 1.9 in the Hurunui (Duncan & Shankar, 2004) and 0.9 m in the Waiau (Duncan & Bind, 2009) rivers, respectively. Some higher flows above the median flow were also modelled to evaluate WUA, but not specifically for evaluation of depths and velocities so were not reported. Because HEC RAS is a fixed bed model (like Hydro2de), the Ahuriri River main channel may be even deeper than modelled during large floods due to mobilisation of the bed.

Although modelled average flow velocity in the main channel increased with increasing flood discharge, the rate of increase was not large (from approximately 0.7-2 m/s during a <2-year flood to 1.6-2.8 m/s for the 50-year event). The rate of increase was slightly greater for the average velocity across the floodplain (from 1.1 to 1.5 m/s). The greatest average velocity of >3.7m/s in the main channel during the largest flood is slightly higher than values of approximately 3 m/s measured by Mosley (1982) in the Ohau River during the approximate 50-year flood. Measured velocities in several other South Island braided rivers for more typical flows ranged from 0.1 to 1.7 m/s (Mosley, 1983). His analysis showed that with the exception of cross sectional area of water, velocity generally increased with increasing discharge at the fastest rate. Our study also indicates that area increased the fastest, but that velocity increased at the slowest rate (both depth and shear stress increased faster) in this reach of the Ahuriri River for larger floods. Modelled velocities using Hydro2de for a flow close to the mean annual flood in the Avoca River approached 4 m/s (Nicholas, 2003). Modelled velocities for more typical flows ranged up to approximately 1.4 m/s for the Waiau River (Duncan & Bind, 2009).

Our modelled average shear stresses across the floodplain increased from approximately 44 N/m^2 for the <2-year event to 79 N/m^2 for the largest flood peak, with a peak of approximately 153 N/m^2 during the 50-year flood. Using Hydro2de, Hicks et al. (2007) reported modelled shear stresses up to 20-40 N/m^2 throughout most of the lower Waitaki River based on a flow of 450 m^3/s (mean annual flow of approximately 350 m^3/s and 100-year flood of 2700 m^3/s), but values ranged up to 60-90 N/m^2 in a few locations. These stresses were generally high enough to move sand throughout the river, but gravel would be mobile in only small patches. Our results are in a similar range as these, but show considerable higher peak values during larger floods.

It is difficult to predict the specific effects the modelled water depths, flow velocities and shear stresses would have on vegetation cover in the floodplain. Species with shallower root systems (e.g. grasses and lupins) are likely to be more at risk of uprooting from the gravels during a flood, compared to species that form a large, deep root mass (e.g. willows). The capacity of a plant to bend and flex without breaking would also increase its prospects for withstanding the shear stresses experienced during a flood (Gurnell et al., 2012). It is likely that vegetation removal would occur through a combination of shear stress on the upper part of the plant and scouring of the bed material in which the plant is rooted. Inundation and "drowning" of plants during floods of long duration may also play a role, as may abrasion by passing bedload. However, further studies are required to clarify these processes and directly link them to the modelled river hydraulics.

The largest flood on record of 570 m^3/s was only 5% less than the estimated 50-year event of 600 m^3/s, so the hydraulic modelling results for the 50-year flood can be used to approximate the hydraulic effects on invasive vegetation observed after the largest flood. Based on comparison of these hydraulic model results with the aerial photograph analysis of changes in vegetation over time, average velocities up to 1.6-2.8 m/s and associated shear stresses of 80-150N/m^2 across the floodplain that could be caused by the 1994 flood are able to remove up to 25% of vegetation in the study reach, with preferential removal of lupin. Increased average inundation areas up to >350 m^2 and depths of almost 1 m across the floodplain also likely played a role in some vegetation removal or drowning. The flood and inundation duration could also cause mortality and ultimate removal of some vegetation, but this was not analysed in this study. Over the entire lower 21-km reach, however, there was considerable spatial variability in removal rates.

The study reach and flood peaks generally conform to most of the assumptions made for a simplified, initial steady-flow analysis using HEC-RAS. For example, the river has a sufficiently small longitudinal slope and gradually varied flow, as there are no major drops in elevation, flow constrictions or hydraulic structures present in the study reach. Peak flood flow in the river can be assumed to be steady for a short time during the flood peaks modelled. Evaluation of floodplain hydraulics can likely be improved using 2-D, 3-D, or cellular models that may also account for sediment movement (Enggrob & Tjerry, 1999; Coulthard et al., 2006: Best, 2008; Schuurman & Kleinhans, 2010). New techniques such as Terrestrial Laser Scanning (TLS) with Light Detection and Ranging (LiDAR) technology and Real Time Kinetic (RTK) GPS may also be used to collect high resolution, topographic spatial data for model input and evaluation of detailed floodplain morphological changes over time (Brasington et al., 2000; Brasington et al., 2012).

5. Conclusions and Recommendations

Aerial photograph analysis indicated that the largest flood on record (570 m^3/s) in January 1994 (almost a 50-yeat event) removed up to 25% of the invasive vegetation in the Ahuriri River floodplain 1.1-km study reach, with preferential removal of lupin and less removal of willow and grassland. However, flood effects varied considerably with overall minor effects on total vegetation cover over the entire lower 21-km reach.The spatial distribution of vegetation cover did change considerably in response to this flood event, in a pattern resembling a shifting-mosaic steady state model. Initial hydraulic modelling showed that a 600 m^3/s (50-year) flood is likely to result in almost total inundation of the study reach floodplain and significant velocities and shear stresses on floodplain vegetation. Over the study reach linear models approximate the relationships between flood peak magnitude with average water area, depth, velocity, and shear stress. Depth and velocity do not increase as fast as flow area or shear stress, and differences between hydraulic characteristics for the 600 and 155 m^3/s floods ranged from 49% for velocities to 166% for flow inundation areas.

It appears that much of the vegetation may recover relatively quickly after flood events so that vegetation removal effects are short-lived. This study indicates that although large floods can remove a considerable amount of invasive vegetation in some reaches of the Ahuriri River, natural flood events are unlikely to significantly reduce invasive vegetation cover throughout the river. The presence of seed sources in tributaries of the river ensures that invasive vegetation will always re-establish over time after flood disturbances. Therefore, until these seed sources are removed, DOC and other land and water management organisations can expect to continually expend resources on managing invasive vegetation in some areas of the active floodplain.

Laboratory-based experiments which investigate the shear forces required to remove different vegetation types from a simulated floodplain, or plant mortality due to inundation from floods of different durations, might help to better understand the link between modelled river hydraulics and vegetation removal. Further evaluation of flood hydraulics using 2- and 3-D dynamic models with bed scour and sediment transport could also be used in future research to account for lateral flow and bank erosion that likely will remove some vegetation.

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