

MEASURES OF PHYSICAL HETEROGENEITY IN APPRAISAL OF GEOMORPHIC RIVER CONDITION FOR URBAN STREAMS: TWIN STREAMS CATCHMENT, AUCKLAND, NEW ZEALAND

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Abstract: This investigation created and tested a template to rapidly assess geomorphic river condition in urban settings. This extension to the River Styles Framework® (Brierley and Fryirs, 2005) entailed mapping the heterogeneity in bed material, habitat, and flow characteristics for different types of rivers, integrating parameters from geomorphology, ecology, and hydrology. Analysis was carried out at 27 sites in the Twin Streams catchment in West Auckland, New Zealand. The method successfully recorded the extent of degradation of physical structure following European settlement of the catchment. With the exception of one subcatchment, streams were found to be largely intact in the headwaters. Many of these headwater streams were found to be of exceptional quality, with high physical heterogeneity. Geomorphic condition is more degraded in downstream areas. Fine-grained sediment has smothered stream courses in the lower half of the catchment, covering bed material and creating homogenous structure and flow, decreasing quality of habitat for biota. In this more urbanized area, with more stormwater drains, riparian vegetation is limited and of poor to moderate quality. Understanding of geomorphic responses to human disturbance is critical in the design and implementation of effective management strategies that seek to improve the ecological condition of urban streams. [Key words: Heterogeneity, river health, urbanization, geomorphic condition, aquatic habitat.]

INTRODUCTION

Rivers are of paramount importance to life, whether considered in terms of human health, ecosystem health, or spiritual health (Karr and Chu, 2000). Riparian corridors contain a high proportion of the total biodiversity of a given region (Ward et al., 2001). Rivers and terrestrial ecosystems have suffered degradation owing to long-term anthropogenic changes to the landscape and direct channel alterations (Maddock, 1999; Hardy, 2005). Despite recent progress in mitigating pollution of waterways, the worldwide decline in the health of aquatic ecosystems continues (Karr and Chu, 2000; Wohl et al., 2005). Enhanced understanding of the human imprint on river systems is needed to reduce this impact and to inform rehabilitation procedures.

River degradation is particularly dramatic in urban environments, where a decline in stream health has been directly related to the extent of urban development (Bravard and Petts, 1996; Karr and Chu, 2000). Urban areas now contain more than half the world's population, presenting a challenge for river managers worldwide (Feminella and Walsh, 2005). As cities increase in size and density, the

magnitude of effects on river ecosystems is also expected to increase (Chin, 2006). Given the range of disturbance processes in urban areas, it is difficult to unravel the specific drivers that determine changes to the ecological structure and function of urban streams (Walsh et al., 2005). Multiple and complex changes to stream hydrology, geomorphology, and water chemistry make monitoring and understanding of urban effects problematic (Petts et al., 2002; Suren and Elliott, 2004). Effects vary greatly, with variable responses in different catchments and at different locations within a catchment, reflecting the geomorphic make-up of the system, land-use history, and cumulative responses to the suite of disturbance events (Gregory et al., 2008).

Development of urban areas alters the hydrologic regime, triggering changes to the sediment balance of the system, the pattern/rate of erosion/deposition (i.e., degradation and/or aggradation), and the sequence of channel adjustments. Effects include an increase in runoff and a decrease in travel time to the channel owing to the high percentage of impervious surfaces and stormwater drainage systems, respectively, resulting in faster and higher flood peaks, and lower groundwater recharge (Paul and Meyer, 2001; Walsh et al., 2005). Wolman (1967) conceptualized a two-phase pattern of geomorphic responses to urbanization. The initial "construction" phase results in a large increase in sediment flux resulting in net aggradation. The second "erosional" phase reflects increased flood peaks caused by increasing impervious surface area, which results in bank erosion and channel widening. Chin (2006) reviewed geomorphological data collected in urbanizing catchments worldwide to understand the extent of these changes. Effects found included an increase in channel size associated with an increase in both width and depth, increases in bed material size and bedform roughness, greater drainage density and a decrease in sinuosity. In differing reaches, slope either increased or decreased.

In general terms, the primary geomorphic response to urbanization is decreased channel complexity, resulting in a more homogeneous environment with reduced habitat availability (Brierley and Fryirs, 2005; Walsh et al., 2005). Enhanced flood peaks erode channels, decreasing channel roughness and refuge areas, washing biota downstream more frequently (Suren et al., 1998; Allan, 2004). Urbanization also degrades water quality, as run off from impervious surfaces collects organic, chemical, and metal contaminants from multiple sources, delivering them directly to the channel via the stormwater network (Karr and Chu, 2000). These environments also tend to have degraded riparian strips, which, among other effects, reduce the buffering of contaminants in runoff and can lead to increased water temperatures (Paul and Meyer, 2001). Collectively, these factors exert devastating effects on the biota of urban catchments. Sensitive biota may disappear, or be replaced by more resilient and often invasive species. As a consequence, degraded stream ecosystems reduce both the biological integrity and biodiversity of a region (Karr and Chu, 2000; Paul and Meyer, 2001).

Pronounced spatial and temporal variability in responses to disturbance reflect differing catchment characteristics and urbanization processes (Chin, 2006). For example, Grable and Harden (2006) highlighted a mix of erosional and depositional patterns within their study catchment, with no linear trends observable. The high degree of process complexity indicates that the relatively simple conceptual

two step model proposed by Wolman (1967) described above is not always observed, and variable responses to urbanization may be evident in differing settings or at different positions within any given catchment. Wolman's model also assumes that urbanization is a fixed stage in the development process that has a finite end. In reality, urbanization is an ongoing, dynamic process. As the types and intensity of development changes, so too does the pattern and intensity of effects seen in the system (Keen-Zebert, 2007). This emphasizes the need for management actions to be framed in relation to catchment-specific understanding of responses to land-use changes, rather than generalized relationships.

River Health and Geomorphic Assessment

River "health" is now a well discussed and integral concept in river analysis and management (Boulton, 1999; Karr, 1999). Brierley and Fryirs (2005, p. 1) defined the term as "the ability of a river and its associated ecosystem to perform its natural functions." Maddock (1999) suggested that river health is a function of a variety of factors including ecological status, water quality, hydrology, geomorphology, and physical habitat. This holistic view of rivers provides a critical platform with which to analyze river condition. The notion of river and environmental health also provides an integral link to human health (Karr and Chu, 2000), prospectively aiding awareness and knowledge transfer about underlying causes of degradational influences on rivers (Brierley and Fryirs, 2008).

In the past, measures of river condition focused primarily on water quality and ecological data, with physical variables of aquatic systems considered as characteristics of secondary importance to stream ecosystems (Newson et al., 1998; Suren et al., 1998; Karr and Chu, 2000; Graf, 2001). However, this trend is changing and geomorphic measures are now recognized as fundamental in assessments of river "health" (Newson and Newson, 2000; Fryirs, 2003). Geomorphic studies provide insight into both historic and contemporary processes acting within the catchment, and the type and extent of adjustments that can be expected in the future (Newson et al., 1998; Clarke et al., 2003; Brierley et al., 2008). The importance of incorporating geomorphology into restoration projects has also been recognized, and a high failure rate of projects can be related, in part, to its omission (Wohl et al., 2005). Understanding key processes that fashion sediment and water fluxes are vital to creating self-sustaining systems (Clarke et al., 2003). As noted by Cooper et al. (1997), spatial datasets are required to better understand patterns and the distribution of factors that affect biota. Geomorphological studies provide a fundamental spatial context for river research (Montgomery, 2001). Such investigations must extend beyond the site/local scale, analyzing controls at the catchment scale (Brierley and Fryirs, 2005; Wohl et al., 2005) or beyond (Wishart and Davies, 2003).

A wide variety of techniques to analyze river condition already exist. Some of the more widely used procedures include the British macroinvertebrate multivariate analysis tool, RIVPACS (River InVertebrate Prediction And Classification Scheme; Wright, 1995), the Urban Stream Habitat Assessment (Suren et al., 1998), the Index of Stream Condition (Ladson et al., 1999), the River Habitat Survey (Raven et al., 2000), and the Index of Biological Integrity (Karr and Chu, 2000). These schemes

analyze a suite of ecological, physical, and chemical indicators, creating a score as an output. However, many of these systems fail to identify controls on river health at the catchment scale, as they are frequently based on a limited number of aspects at a limited number of sites (Fryirs, 2003). All too often, monitoring programs focus on water-quality standards and simple habitat analyses, failing to consider the geomorphic character and behavior of the system being analyzed, and its geomorphic condition (Newson and Newson, 2000; Montgomery, 2001; Fryirs, 2003; Fryirs et al., 2008). These considerations are particularly important in urban systems, owing to the magnitude of changes.

Tools to appraise geomorphic condition are needed to improve and sustain rivers through more comprehensive management. Ultimately, management applications need to relate the physical structure and heterogeneity of river courses to biotic associations. Analysis of the physical integrity of a river is critical to these exploits. The physical integrity of a river can be defined as "a set of active fluvial processes and landforms wherein the channel, near-channel landforms, sediments, and overall river configuration maintain a dynamic equilibrium, with adjustments not exceeding limits of change defined by societal values" (Graf, 2001, p. 1). Graf extends this idea by highlighting diversity of geomorphology and hydrology as key considerations in appraising the naturalness of running waters. Heterogeneity is a key concept in understanding the variation, complexity, and diversity that is inherent to "natural" systems, as it is linked to the diversity of habitats and, therefore, biota (Pickett and Cadenasso, 1995; Ward et al., 2002; Rogers and O'Keeffe, 2003). As noted by Allan (2004), aquatic biodiversity is the product of processes such as hydraulic variability, erosion and deposition, and sediment sorting creating complex and diverse systems. Finding a technique that records changes to the heterogeneity of rivers could be used to infer the condition of the biota.

Human-induced land-use changes have exerted significant effects on stream heterogeneity and biodiversity. More homogeneous channels have fewer habitats and, therefore, lower populations and diversity of biota. Thomson et al. (2001, p. 374) summarized that "a diverse range of high quality habitats will support a biologically diverse, functioning, and balanced ecological community." Beisel et al. (2000) found that heterogeneous river beds supported a higher diversity of macroinvertebrates compared with homogeneous environments that were commonly found to be dominated by only one or two species. Sullivan et al. (2004) found that the percentage of macroinvertebrate community comprising the sensitive Ephemeroptera, Plecoptera, and Trichoptera taxa (%EPT) was significantly correlated with more stable habitats that exhibit better geomorphic condition and better quality habitats. While the notion of heterogeneity and habitat patchiness has become well established, techniques for analyzing it are still not well developed (Blakely et al., 2006).

River Styles Framework

The River Styles Framework created by Brierley and Fryirs (2005) provides a basis to analyze the geomorphic structure and functioning of a river system. Analysis of geomorphic units within any reach provides an insight into the range of form-process relationships, at multiple scales, that shape river character and behavior.

Through further analysis, a simple output of good, moderate, or poor geomorphic condition is provided (Fryirs, 2003). Dollar (2004, p. 420) stated that the River Styles Framework is one of the few procedures that “successfully manages to cross scale boundaries and provide a reasoned integrated and implementable scale-based approach for river management and remediation.” In this study, this flexible and open-ended set of procedures is extended to consider rivers that have been subjected to direct and indirect human manipulation in urban areas.

Geomorphic river condition refers to “the capacity of a river to perform functions that are expected for that river within the valley setting it occupies” (Brierley and Fryirs, 2005, p. 298). This recognizes different types of adjustment and sensitivity will be expected for different river styles. All rivers naturally adjust, and geomorphic condition analysis is based on understanding the natural range of adjustment for each river type. Adjustments can be reversible or irreversible. Irreversible change involves large-scale changes in morphology, as threshold conditions are breached following disturbance, such that a change in river type occurs. The channel now operates under a different set of boundary conditions that reflect the prevailing water and sediment regime, and vegetation associations (Fryirs, 2003; Brierley et al., 2008). In many instances, however, the suite of form-process relationships within any given reach is retained following disturbance, and the reach does not experience a fundamental shift in state. Rather, ongoing adjustments are considered to be part of the behavioral regime for that type of river. State changes can occur naturally (e.g., as a response to a large flood event). Although the reach has changed state, adjustments are reversible and the reach retains the potential to recover to a “good” condition. Understanding the natural range of variability for different river types is a fundamental underpinning of geomorphic based assessments of river condition. In this manuscript, these principles are developed and tested for a small urbanizing catchment in West Auckland, New Zealand.

STUDY AREA

The Twin Streams catchment is located in Waitakere City, Auckland (Fig. 1). Catchments in the Auckland region are small (generally less than 100 ha), resulting in relatively short (either first or second order) and narrow (mostly less than 2 m wide) streams. The climate of the region is temperate, with an average annual rainfall in the headwaters of 2000 mm (Auckland Regional Council, 2002) and a higher proportion falling in the winter months (National Institute of Water and Atmospheric Research, 2006).

Of the more than 10,000 km of streams in the Auckland region, 8% run through urban areas (Maxted, 2005). Other than some intact headwater reaches, streams are severely degraded (Auckland Regional Council, 2004), with levels of metals (e.g., copper), nutrients (e.g., dissolved reactive phosphorous), and contaminants (e.g., fecal coliforms) that are above national guidelines. In the Twin Streams catchment, very low levels of sensitive EPT (macroinvertebrate) taxa have been directly correlated to poor habitat quality in heavily urbanized sites (Diffuse Sources Ltd. et al., 2005; Kingett Mitchell Ltd. et al., 2005). However, to date, these degradational

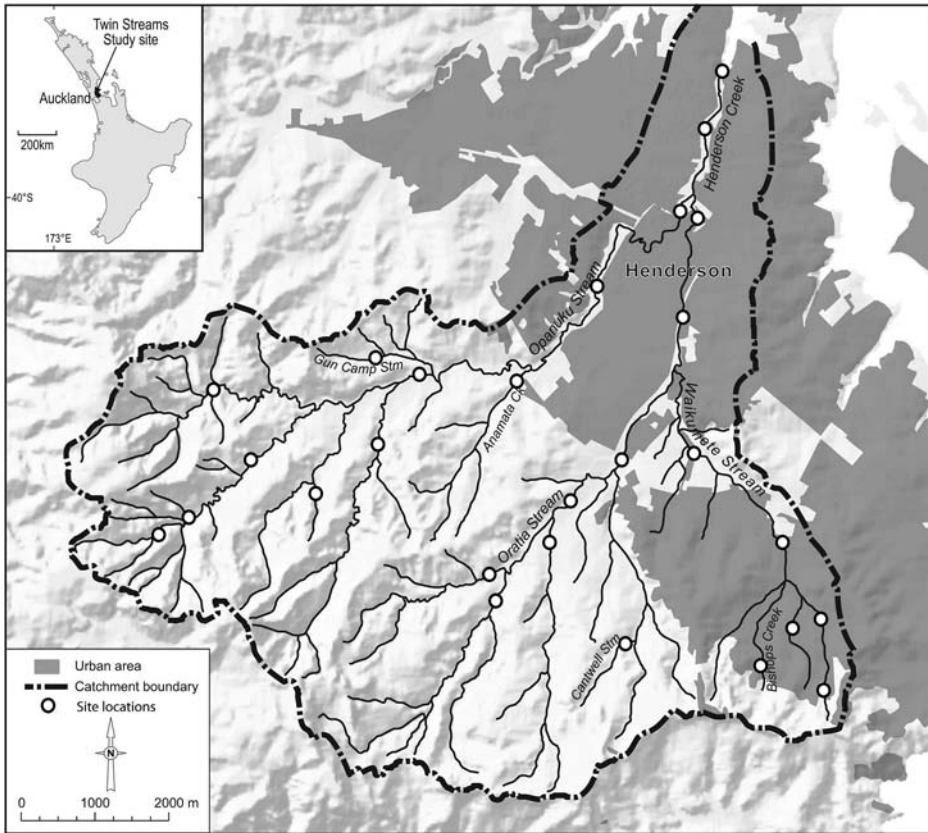


Fig. 1. Location of study area: Twin Streams Catchment, Auckland, New Zealand.

tendencies have not been related to geomorphological analysis of river forms and processes in the region.

Twin Streams Catchment

The Twin Streams catchment comprises four subcatchments: Waikumete Stream, Oratia Stream, and Opanuku Stream, all feeding into Henderson Creek (Fig. 1). Topography varies between subcatchments. The Oratia and Opanuku headwaters are located within steep confined valleys that flatten out into rolling foothills and eventually the lowland plain. The long profile of the Waikumete is gentler with the headwaters being situated in rolling foothills. Henderson Creek lies entirely in the lowland alluvial plain, which becomes tidally influenced as it drains into Waitemata Harbour.

In broad terms, catchment geology can be separated into two regions, with sedimentary volcanoclastic bedrock in the uplands and an alluvial plain in the lower

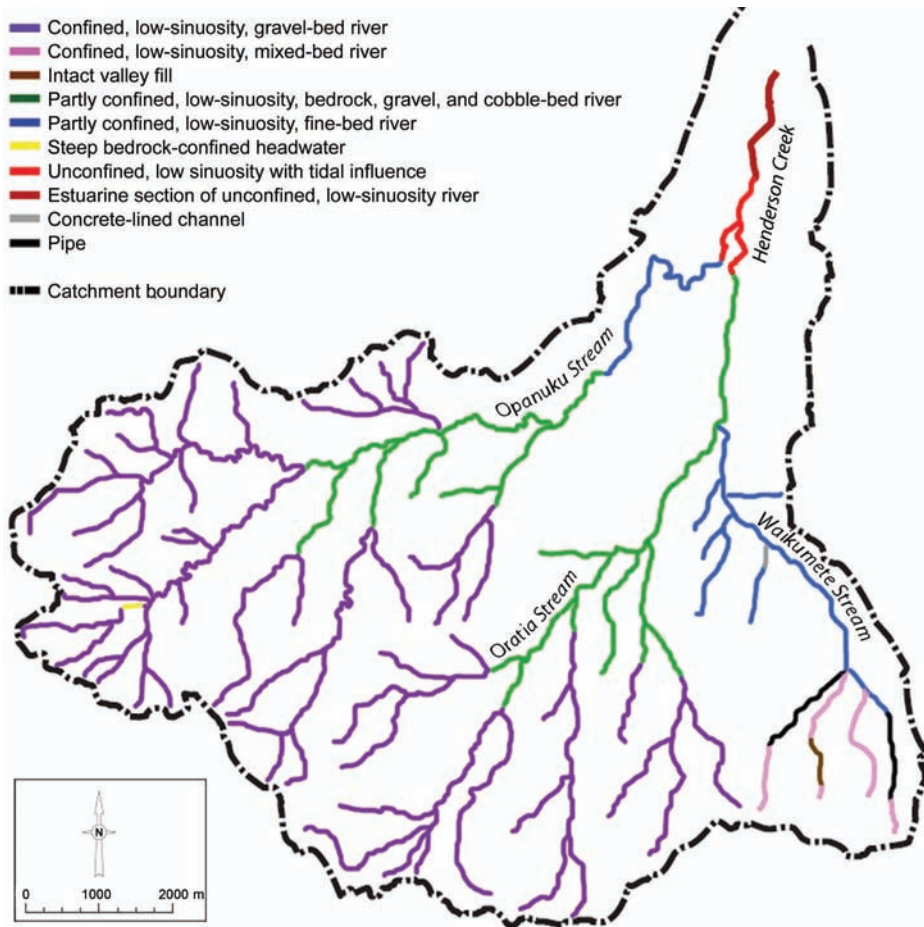


Fig. 2. The distribution of River Styles across Twin Streams Catchment

areas. Geomorphic responses are manifest through two main bed material types—gravel or fine-grained sediments, which are locally referred to as hard bottom and soft bottom streams, respectively. The Waikumete and the lower parts of the catchment consist predominately of soft bottom streams, while the upper-mid areas of the Opanuku and Oratia are gravel-based systems (Fig. 2). Representative photographs of rivers found in confined, partly confined, and laterally unconfined valley settings are presented in Figure 3.

Land-Use History

This catchment has undergone rapid and sustained land-use change from the time of European settlement in the 1840s (Gregory et al., 2008). Maori tribes who originally inhabited the area were displaced by Pakeha settlers around 1849 (Flude,

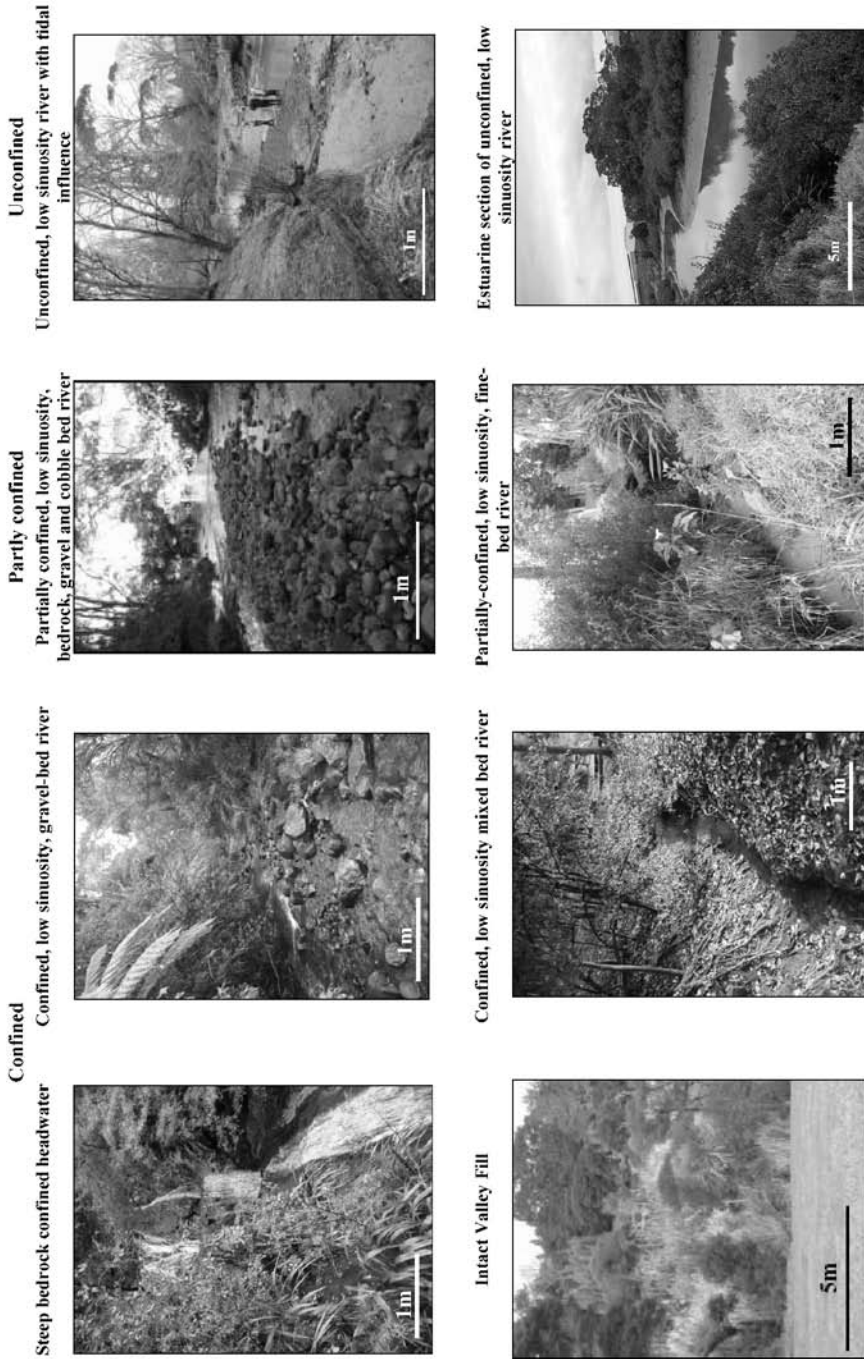


Fig. 3. Photographs of River Styles in confined, partly confined and laterally unconfined valley settings in Twin Streams Catchment.

1977). Kauri (*Agathis australis*) logging became a major industry and much of the catchment was logged prior to 1866. In the upper reaches of the catchment, kauri logs were dragged to the streams, which were dammed and then released to transport logs to the mill, causing large-scale changes and erosive events (Flude, 1977; Jones, 2002; Gregory et al., 2008). A transient population subsequently dug for kauri gum, overturning the earth across large areas of the catchment (Flude, 1977). Agriculture, viticulture, and horticulture began to develop in the middle to lower reaches of the catchment from the 1880s. This was followed by urbanization in the lower reaches around Henderson in the 1910s, slowly at first but faster after WWII. Urban areas now cover almost all of the Waikumete subcatchment and the downstream part of the Opanuku and Oratia catchments and Henderson Creek.

Gregory et al. (2008) demonstrated how different land uses have left their imprint on these river courses. The effects of land clearance and kauri logging are still felt across the catchment. Despite this, river courses have been remarkably resilient to change. Given the high degree of landscape connectivity, disturbance responses have been efficiently conveyed through the system (Brierley et al., 2006). The upper reaches of the Waikumete subcatchment have been modified from an intact valley fill (inferred from historical documentation and sedimentary evidence; Gregory et al., 2008) to a single channel and floodplain, as early settlers sought to utilize the land for agricultural and horticultural purposes. The upper reaches in the Opanuku and Oratia are on the path to recovery as native forest has regenerated. The mid-catchment is also on a pathway of restoration, but continued land-use development in the lower reaches has resulted in ongoing degradation. Disturbance responses are manifest most profoundly in the lower catchment, where the cumulative effects of fine sediment transported from upstream are evident.

METHOD

River Classification

Appraisals of geomorphic river condition must be framed in relation to what is expected for any given type of river (Brierley and Fryirs, 2005). Hence, analysis of the catchmentwide diversity and pattern of river types was a prerequisite for creating protocols to assess river condition. Differentiation of good, moderate, or poor geomorphic condition is based on attributes of character and behavior that are relevant for a given river reach. Selected parameters are related to the potential for adjustment for that type of river (Fryirs, 2003).

In this instance, river reaches were grouped based on valley setting (confined, partly confined, or unconfined) and then further separated based on channel plan-form (number of channels and sinuosity), assemblage of geomorphic units and bed-material texture (Brierley and Fryirs, 2005). Valley setting was established from map analysis. This was followed by rapid field analysis to verify boundaries between reaches (based on assemblages of geomorphic units and bed material texture). Field characterization of geomorphic attributes for each river style was conducted at representative sites (Figs. 2 and 3). For a full overview of the river styles in the Twin

Table 1. Relevant Geoindicators with Which to Assess Geomorphic River Condition for Differing Valley Settings in the Twin Streams Catchment

Geoindicators	Variables	Types of rivers used on
Channel geometry and bank erosion	Channel stability	All
	Bank erosion	Partially confined and unconfined
	Channel Geometry	Partially confined and unconfined
	Grain size and sorting	Confined
Geodiversity	Geomorphic unit diversity	All
	Flow diversity	All
	Floodplain diversity	Partially confined and unconfined
	LWD	All
Riparian vegetation	Natives vs exotic	All
	Continuous distribution	All
	In-stream vegetation	All
Urban index	Land use—Impervious surfaces	All
	Direct urban effects	All
	Rehabilitation efforts	All

Streams catchment including proformas, see Reid et al. (2008) or the River Styles website (www.riverstyles.com).

Condition Assessment Protocol

A protocol was created to assess geomorphic river condition in relation to expected degradational influences of urbanization as identified in the literature. This produced a simple output of good, moderate, or poor conditions. Relevant geoindicators, defined as “parameters used to interpret and explain system structure, function and condition for each degree of freedom” (Brierley and Fryirs, 2005, p. 298), were selected for each river style. These are based on the capacity for adjustment, reflecting geomorphic adjustments that are expected to occur for that river type as a result of anthropogenic disturbance (Table 1; Fryirs, 2003). Criteria used to appraise each geoindicator are framed in terms of series of questions, such that good, moderate, or poor categories can be determined for each geoindicator for each type of river. The flexibility of this approach enables the overall category of condition that is determined for a reach to be broken down into its constituent parts. This allows management applications that use these procedures to target the specific attribute(s) that resulted in the reach being classified as having a degraded condition.

Three geoindicator categories were directly taken from the River Styles Framework—channel geometry, geodiversity, and riparian vegetation. Channel geometry was selected as channel planform can undergo substantial changes following urbanization owing to changes in the sediment and water fluxes, such as bed

incision, aggradation, and channel widening (Paul and Meyer, 2001; Chin, 2006). This allows for analysis of changes to processes in the catchment and their effects on different types of rivers. Geodiversity was used to facilitate links between ecology and geomorphology, highlighting the importance of habitat and flow heterogeneity to biodiversity. Geodiversity also included large woody debris as a habitat aspect, as this is an important input for creating and maintaining heterogeneity in these systems. Floodplain connectivity was analyzed, recognizing the importance of these features in providing diverse habitat in river systems (Ward et al., 2002; Fryirs, 2003). Riparian vegetation was included because of the influence that it exerts on water amenity, affecting the ability of the system to buffer nutrients and maintain low water temperatures. Vegetation provides food for biota and plays an important geomorphological role in increasing bank cohesion and increasing surface roughness (Montgomery and Buffington, 1997; Reeves et al., 2004).

An additional geoinicator represented an Index of Urbanization (Table 1). In this instance, the same set of parameters was used for all river styles, including land use and impervious area, direct urban effects, and rehabilitation efforts. In this way, the intensity of urbanization was analyzed across the catchment.

Inevitably, this framework entails significant qualitative assessment, with an inherent degree of subjectivity. To minimize error, analysis was carried out in a systematic manner by the same operator. A proforma was used to structure and formalize the results for each site, aiding their presentation as a coherent table. Examples of questions used to analyze each geoinicator for representative river styles located in confined, partly confined, and laterally unconfined valley settings are presented in Tables 2–5.

Procedures used to calculate geoinicator condition are shown in Table 6 (Step I). Points were allocated representing geoinicator conditions, with 0 = poor, 1 = moderate, and 2 = good. As there were four categories of geoinicator, the overall condition was presented as a score out of 8 and converted into a percentage value. Scores over 66% gained a good condition, between 33% and 66% were judged as being moderate condition, and below 33% was poor (Table 6; Step II).

Field Methods

Selected sites were evenly spaced across the catchment, in proportion with the frequency of occurrence of each river style. On average, sites were approximately 1.5 km apart. Field analysis consisted of two components. The first component entailed completion of the proforma using the geoinicator question tables for that river style. Second, flow, physical structure, and habitat were mapped to analyze the heterogeneity and linkages at a site, using flow and sediment classification procedures that are outlined in Table 7. Assessment of flow types and functional habitats were based on the interpretation presented in Newson et al. (1998). Habitat and sediment characteristics were superimposed on the map of geomorphic units and flow types using transparent paper. These procedures enabled relationships between geomorphic structure, flow type, and habitat to be analyzed.

Table 2. Questions Used to Analyze Each Geoinicator for River Styles in Confined Valley Settings

Geoinicator	Variable	Steep bedrock confined river	Confined, low sinuosity, gravel-bed river	Confined, low sinuosity, Mixed-bed river	Condition scores
Channel geometry and Bank erosion	Bed level stability	Is the channel acting as a source reach that is competence limited? (Channel is expected to be stable for relatively long time periods as the stream's competence limited; Church, 2002). Is vertical downcutting the process taking place with little accumulation except in pools?			
	Largest clast size	Is there a range of clasts including fines and organics accumulating in plunge pools and behind LWD and larger sediments creating structure and smaller clasts occupying the lag area? (Note this RS would be expected to have far fewer clasts than in the confined low sinuosity gravel bed river)	Is there a range of clasts including larger clasts creating structure and smaller clasts occupying the lag area with fines accumulating in pools and behind LWD with no infilled pools or sand-sheets?	Is there a range of clasts including larger clasts creating structure and smaller clasts occupying the lag areas with fines accumulating but not infilling in pools and behind LWD?	Good = 2/2 Med = 1/2 Poor = 0/2
Geodiversity	Diversity of geomorphic units	Is there a high diversity of geomorphic units as would be expected in this river type?	Is there a high diversity of geomorphic units as would be expected in this river type with steps and pools common?	Does a diversity of geomorphic units exist relative to what would be expected in this river type?	Good = 3/3 Med = 2/3 Poor = 1/3
	Diversity of flow	Is there a good diversity of flow between the units as would be expected in this river type, such as steps and pool morphologies?		Does a diversity of flow exist relative to what is expected for this river style?	
	LWD	Is LWD present in the stream at locations where it can add to habitat and help increase the diversity in the system?			
Riparian vegetation	Natives vs. exotics	Is most of the vegetation adjacent to the stream bed native and does it have a secondary structure? (Willows and grass are signs of a degraded riparian strip)			Good = 3/3 Med = 2/3 Poor = 1/3
	Continuous strip	Does this form a continuous strip alongside the river with a secondary structure?			
	In-stream vegetation	Is any in-stream vegetation present in the channel and is it exotic?			
Urban modification ^a	Land-use-impervious surfaces	What is the intensity of urbanization present in the predominant land use in the area visible surrounding the stream? G = native forest with a few residents present, M = Pastoral or scattered housing, low impervious, P = dense urban residential or commercial, ^a high impervious.			
	Direct urban effects	What is the intensity of effects of the direct urban impacts in the area on stream geomorphology (such as stormwater outlets (creates scour holes and indicates increased flow), or direct channel or bank modifications? G, M, or P ^a)			>66% = Good 33–66% = Mod <33% = Poor
	Rehabilitation efforts	Is there any indication of rehabilitation efforts within the reach? This indicator will only be used in rivers with a disturbed riparian stretch) Y or N			

^aEvery G is allocated 2 points, M gets 1 point and P gets 0 points. For rehabilitation Yes gets 1 points and No, 0. This means that every site has an urbanization index out of 6 points or if rehabilitation is included then out of 8 points.

Table 3. Questions Used to Analyze Each Geoinicator for the Intact Valley Fill River Style (Along with the Urban Modification Index Presented in Table 2)

Variables	Intact valley fill	Condition scores
Species diversity	Does the site display a high diversity of plants with plants at different heights and of different kinds?	
Riparian vegetation	Is good riparian vegetation present at the site and is it mostly native and in a fairly continuous covering around the site?	
Sedimentation/erosion	Is there evidence of sedimentation or erosion? This includes the appearance of aspects such as suspended sediments, headcuts, sediment burying plants and changes in soil color.	0–1/5 = Poor 2–3/5 = Mod 4–5/5 = Good
Dryland plant invasion	Is there evidence of dryland plants beginning to encroach on the wetland area such as broom or manuka?	
Hydrological integrity	Are there any features that indicate changes in the hydrological integrity of the wetland. This includes structures such as drains, stopbanks and things that will affect the hydrology? What is the intensity of these features based on their contribution in size, coverage, depth and effectiveness?	

Source: Based on criteria indicated by Clarkson et al. (2004).

RESULTS

The distribution of geomorphic river condition in Twin Streams catchment is presented in Figure 4. Schematic representations of good, moderate, and poor variants of the physical structure/flow/habitat diagrams for bedrock/gravel and mixed-bed/fine-grained rivers in confined, partly confined, and laterally unconfined valley settings are presented in Figures 5 and 6. Completed proformas for all river styles are available in Reid et al. (2008).

Variability in Geomorphic Condition Within Individual River Styles

Bed-material size exerts a key control on physical heterogeneity of rivers in Twin Streams catchment, with stark contrasts between bedrock/gravel-bed and mixed/fine-grained rivers.

Bedrock/gravel-bed rivers. Three river styles within the catchment have bedrock or gravel beds (Fig. 2).

(1) The *steep bedrock headwaters* river style occurs within a localized area of the upper catchment. The good condition of this reach can be attributed to limited human disturbance and the resilience of this type of river, owing to its very steep slope, high stream power, and prominence of bedrock on the bed.

(2) The *confined, low-sinuosity, gravel-bed river style* exhibited exceptional levels of heterogeneity in the good-condition reaches. This included a large range of clast sizes, with specific sediment characteristics for different flow features including riffles, runs, steps, and slower flow features such as bars, pools, and deadwater

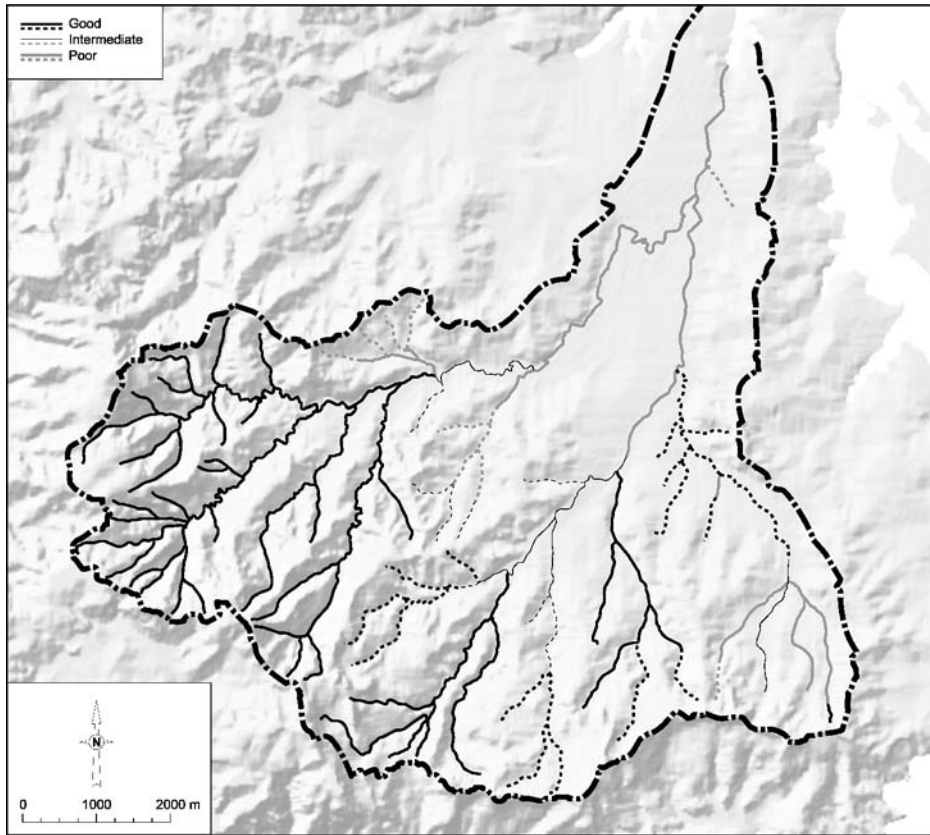


Fig. 4. The distribution of geomorphic river condition in Twin Streams Catchment. Dotted lines indicate a lower certainty of condition assessment.

areas (Fig. 5A). Deterioration of geomorphic condition reflected simplification of complexity at differing sites of this river style. Heterogeneity of bed features in the moderate-condition river is not as pronounced, though it does still exist. The reach shown in Figure 5B comprises glides, runs, and riffles, but has no pools or deadwater areas for refugia. High volumes of sand and silt cover the bed in some sections of channel. The poor-condition stream shows dramatic changes from the good or medium-condition variant (Fig. 5C). The entire stream bed has been covered in silt, and any structure that may have existed has been lost. In-stream vegetation growth is high, choking the channel. This can likely be linked to excess nutrients from the surrounding agricultural land use. This overgrowth results in some diversity of flow, which would be positive for biota, but overall this is a very degraded system.

(3) *The partly confined, low-sinuosity, bedrock, gravel, and cobble-bed river style* shows a very similar trend to the confined gravel-bed river style. The good-condition reach does not have the same degree of heterogeneity of features compared with the confined variant, owing to lower stream power and slope (Fig. 5D). Steps are not observed, but runs, riffles, and pools have different characteristic

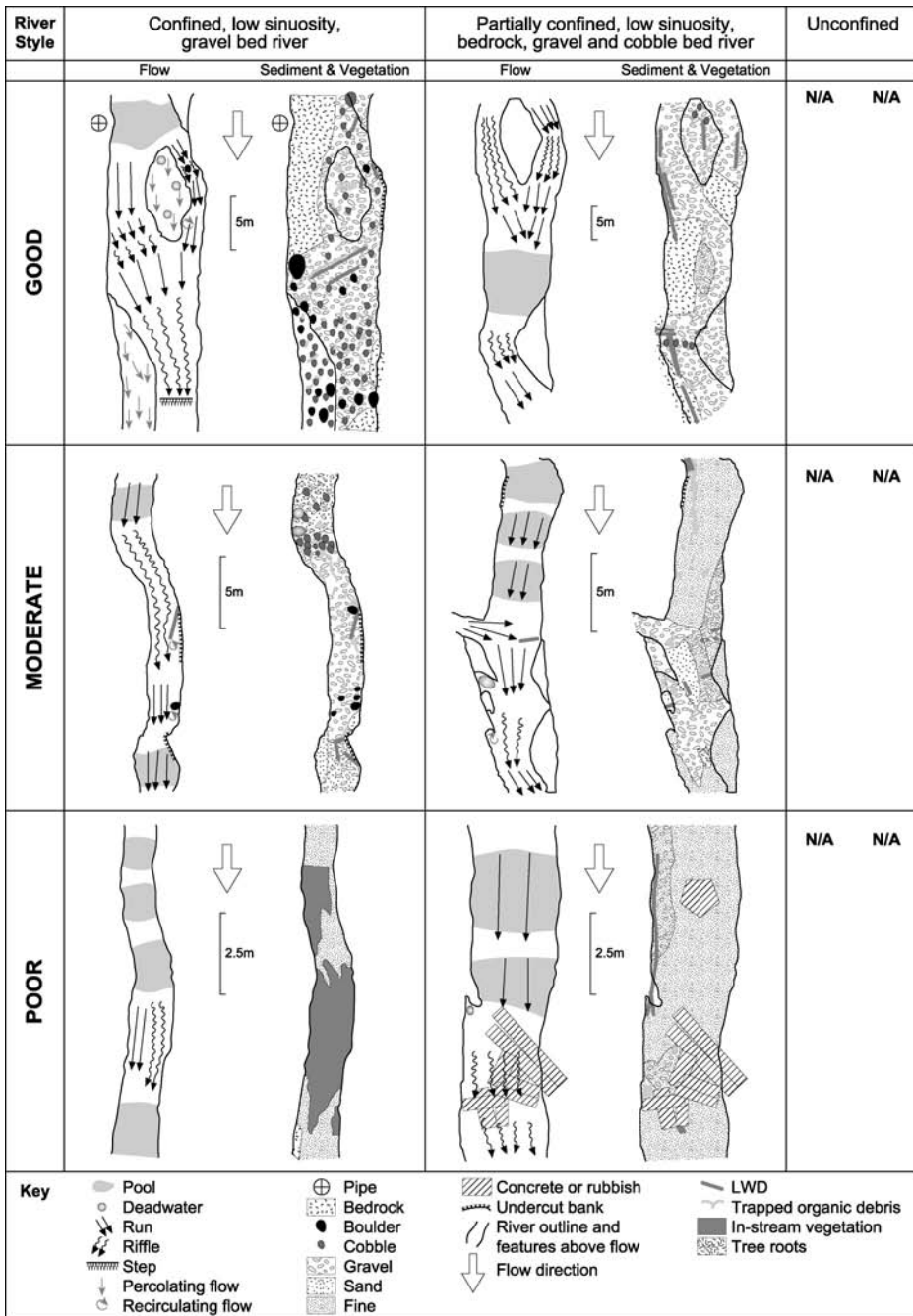


Fig. 5. Schematic representations of good, moderate and poor-condition variants of physical structure/habitat and flow for bedrock/gravel-bed rivers in confined and partly confined valley settings in Twin Streams Catchment.

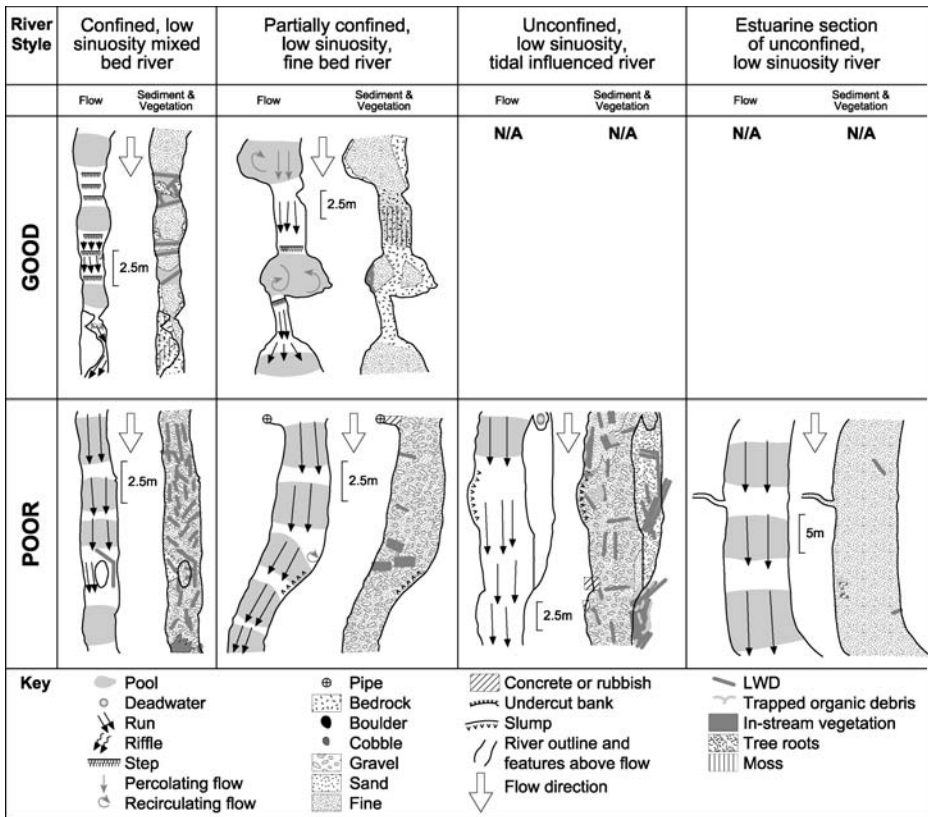


Fig. 6. Schematic representations of good and poor-condition variants of physical structure/habitat and flow diagrams for good and poor variants of mixed-bed/fine-grained rivers in confined and partly confined valley settings in Twin Streams Catchment. Moderate-condition variants were not observed in this analysis.

grain sizes. The moderate-condition reach has a lower diversity with greater volumes of fine-grained sediment and more homogeneous flows (Fig. 5E). The poor-condition section is completely degraded, as fine-grained sediments have swamped the bed, deteriorating its structure (Fig. 5F). Flow is homogeneous, with instream litter creating the only diversity.

Fine-grained or mixed-bed rivers. Four river styles fall into the category of fine-grained and mixed-bed rivers where the bed largely consists of sands, silts and clays (Fig. 2).

(1) In the headwaters of the Waikumete, there is one section of swamp or *intact valley fill*. This was judged to be in a moderate condition primarily because of indications of changes to its hydrology (e.g., dryland plant encroachment).

(2) Other headwater areas in the Waikumete consist of the *confined, low-sinuosity, mixed-bed river style*. This is dominated by fine-grained sediment and has a simpler structure with less diversity relative to gravel-bed systems. The good-condition site shows quite a high diversity of character, induced primarily by large

Table 4. Questions Used to Analyze Each Geoinicator for River Styles in Partly Confined Valley Settings^a

Geoinicator	Variable	Partially confined, low sinuosity, bedrock, gravel and cobble bed river	Partially confined, low sinuosity, fine bed river	Condition scores
Channel geometry and bank erosion	Channel stability	Is the channel acting as a transfer zone which is relatively stable with some lateral cutting and some sediment storage in the form of floodplains?		
	Bank erosion	Is erosion minimal and mainly in the areas below the plant roots creating undercut banks or directly adjacent to the bars where the flow may be pushed against the side? (Church, 2002)		
	Channel geometry	Do the rivers appear to have the width/depth ratio and pool and riffle diversity associated with the amount of flow expected in the catchment? (done through comparison with more intact reaches in the area). Does it have a geometry associated with a less disturbed reach? (Not overwidened; Chin, 2006)	Do the rivers appear to have the width/depth ratio associated with the amount of flow expected in the catchment? (done through comparison with more intact reaches in the area). Does it have a geometry associated with a less disturbed reach? (i.e., narrower and deeper rather than overwidened; Church, 2002; Chin, 2006)	Good = 3/3 Mod = 2/3 Poor = 1/3
Geodiversity	Diversity of geomorphic units	Is there a high diversity of geomorphic units including not infilling of pools and a diversity in grain size and sorting across the channel?	Is there a diversity of geomorphic units present in the system, including a diversity in grain size distribution and channel geometry?	
	Diversity of flow	Is there a good diversity of flow between the units with different flow units present such as runs, riffles and pools?	Does a diversity of flow exist would be expected for this river type this includes variations in flow created by LWD and variations in the bed?	Good = 4/4 Mod = 2-3/4 Poor = 1/4
	Floodplain diversity	Is the floodplain still functionally active and attached to the channel? Does it display diversity and fluvially created features such as back channels?		
	LWD	Is LWD present in the stream at locations where it can add to habitat and help increase the diversity in the system?		

^aQuestions for the riparian vegetation and urban modification geoindicators are presented in Table 3 (these geoinicator questions are the same for all river styles).

woody debris, organic debris, and bedrock-forced features (Fig. 6A). In the poor-condition variant, fine-grained sediment completely covered all structure (Fig. 6B). Bed material and flow types were uniform (i.e., lacked heterogeneity).

(3) The *partly confined, fine-bed river* only existed in good or poor condition. The good-condition reach had significant bedrock control, which created diversity in flow and structure (Fig. 6C). Fine sediment was only present in pools. The poor-condition site showed no diversity in geomorphic units (Fig. 6D). The uniform channel exhibited little diversity in flow type.

(4) The *Unconfined, low-sinuosity, tidal-influenced river style* is only found at the downstream end of the catchment. Given its location, this reach is subjected to

Table 5. Questions Used to Analyze Each Geoinicator for River Styles in Laterally Unconfined Valley Settings^a

Geoinicator	Variable	Unconfined, low sinuosity, tidal influenced river	Estuarine section of the unconfined, low sinuosity, tidal influenced river	Condition scores
Channel geometry and bank erosion	Channel stability	Is the channel acting as a accumulation zone which is relatively stable with some lateral movement and areas of floodplain storage?	–	
	Bank erosion	Is erosion minimal and mainly in the areas below the plant roots creating undercut banks or directly adjacent to the bars where the flow may be pushed against the side? (Church, 2002)	–	Good = 3/3 Mod = 2/3 Poor = 1/3
	Channel geometry	Relative to more intact reaches in the area, does the channel have an appropriate width/depth ratio and geometry given the amount of flow (i.e., narrower and deeper rather than overwidened; Church, 2002; Chin, 2006)?	–	
Water quality	Bed material	–	Does the bed material display a range of sediment depositional forms other than mud? This includes shoals that consist of clean fluvial sands and gravels that are visible at low water.	Good = 2/2 Mod = 1/2 Poor = 0/2
	Excess algae growth	–	Is there any indication of excess algal or phytoplankton growth such as accumulations of wrack or algae in the water column?	
Geodiversity	Diversity of geomorphic units	Is there appropriate diversity of geomorphic units, grain size and channel geometry?	Is there appropriate diversity of geomorphic units in the system (a poor system would be smooth and channelized, and able to flush sediments)?	
	Diversity of flow	Does a diversity of flow exist that would be expected for this river type, including variations in flow created by woody debris and variations in the bed?	Does little diversity in flow exist?	Good = 4/4 Mod = 2–3/4 Poor = 1/4
	Floodplain diversity	Is the floodplain still functionally active and attached to the channel? Does it display diversity and fluvially created features such as back channels?	Is the floodplain still functionally active and attached to the channel? Does it display diversity and fluvially created features such as back channels or wetlands?	
	LWD	Is LWD present in the stream at locations where it can add to habitat and help increase the diversity in the system?		

^aQuestions for the riparian vegetation and urban modification geoindicators are presented in Table 3 (these geoinicator questions are the same for all river styles).

Table 6. Method Used to Convert Parameter Scores into Geindicator Health and Condition Outcomes

Number of variables within a geindicator category	Number of good-condition variables needed for each condition outcome								
	Good		Moderate		Poor				
Step I: Variables converted into geindicator health									
1 ^a	1		N/A		0				
2	2		1		0				
3	3		2		1				
4	4		2-3		1				
Step II: Geindicators assigned a score based on their condition. Good condition = 2, Moderate = 1, and Poor = 0, to create a score out of 8 (due to 4 geindicators). The scores of the geindicators converted into a percentage to work out the condition score for the site									
Geindicator score out of 8	0	1	2	3	4	5	6	7	8
Converted to %	0%	12.5%	25%	37.5%	50%	62.5%	75%	87.5%	100%
Final condition outcome	Poor		Moderate		Good				

^aOnly used for the intact valley fill.

cumulative impacts from upstream (Gregory et al., 2008). Coupled with its location in a heavily developed area, this has resulted in the poor condition of this reach, with a homogeneous structure and flow, and the bed predominantly consisting of mud with localized gravel accumulations (Fig. 6E). The channel is overwidened, and floodplains are no longer connected to the contemporary channel.

The Distribution in Geomorphic River Condition Across the Catchment

Distinct downstream patterns of geomorphic river condition are evident for different subcatchments of Twin Streams catchment, as shown in Figure 4.

Waikumete Stream. Other than a small section of the eastern-most channel, the geomorphic condition of headwater tributaries to the Waikumete is poor to moderate. This reflects the obvious degradation in morphology associated with the piped river style. Most streams have disturbed riparian vegetation, with a fragmented distribution of plants, many of which are exotic. Channel geometry is characterized as poor and there are low levels of geomorphic diversity. The exception is Bishops Creek tributary, an intact valley fill that was sampled using a different set of criteria (as this is a different river style). The moderate condition of this reach reflects invasion by exotic plants and altered hydraulic integrity in response to stormwater pipes.

Surprisingly, given the poor-condition streams of upstream (tributary) reaches, the trunk stream itself was found to be in good condition. Channel geometry and geodiversity was healthy, while riparian vegetation was either in a good or moderate condition. However, geomorphic condition rapidly declines at the confluence of the Waikumete and the Oratia.

Oratia Stream. The Oratia also shows a decline in geomorphic condition at a point fairly high up in the catchment. Some tributaries remain in a good condition, such as Cantwell Stream and Oratia Stream (located on Fig. 1), while others are

Table 7. Bed Texture and Flow Unit Attributes Used to Prepare Habitat/Biotope Diagrams

Flow types	Description	Functional habitats	Sediment categories
Pool ^a	Slow moving water that occurs over the full channel width	LWD	Bedrock
Scour pool	Area with a pool geomorphology but formed below water falls as a result of the power of the water	Trapped organic debris	Boulder
Deadwater ^a	Slow moving water that does not occur over the full channel width	Instream vegetation	Cobble
Run ^a	Surface turbulence does not produce waves	Tree roots	Gravel
Riffle ^a	Undulating standing waves in which the crest faces upstream without breaking	Moss	Sand
Step ^a (or Chute)	Fast, smooth boundary turbulent flow over boulders or bedrock. Flow is in contact with the substrate, and exhibits upstream convergence and downstream divergence		Fine
Waterfall ^a	Water falls vertically and without obstruction from a distinct feature, generally more than 1 m high and often across the full channel width		Concrete or trash
Cascade ^a (or broken standing waves)	White-water "tumbling" waves with the crest facing in an upstream direction. Associated with "surging" flow		
Percolating flow	Water that percolates shallowly through a bar		
Recirculating flow	Areas of eddy where a part of the flow circles in a direction that is different to the flow in the rest of the channel		

^aFlow descriptions were gained from Newson and Newson (2000).

degraded and have a poor condition. One of the main causes of degradation is excess fine-grained sediment that smothers the bed. Areas of bank erosion were also observed, but their location and extent were not anomalous to what is expected in natural conditions. Despite high volumes of fine-grained sediment, high diversity of physical structure and flow remains, with variations in channel width and flow caused by local variations in slope. In addition, the floodplain has been retained and high loadings of large woody debris are evident, resulting in good scores for the geodiversity geoinicator. The riparian margin was disturbed at half of the sites and had a patchy distribution.

The Oratia trunk stream downstream of these tributaries was found to be in poor condition. Excess fine-grained material has covered the bed, creating homogenous structure and flow with very little variation in channel geometry. Aggradation and bank erosion was apparent along most reaches. Relatively high (artificial) levees disconnect the channel from its floodplain. The riparian margin is very disturbed, with a mix of native and exotic species and a patchy distribution. Large amounts of

litter were present, locally choking the stream. Stormwater pipes have altered the flow regime, locally inducing scour.

Opanuku Stream. The Opanuku shows a fairly linear downstream pattern of degradation. The headwater streams mostly retain intact native vegetation and are in a good condition. They flow into an area of pasture where excess sediment is delivered to the stream and condition deteriorates. Two tributaries that join the Opanuku in midcatchment, Gun Camp Stream, and Anamata Stream (located on Fig. 1) have both been smothered with fine-grained sediment resulting in a homogenous bed and channel geometry and little diversity of flow type. Riparian margins were non-existent around sample sites and very little vegetation is evident along neighboring streams.

Downstream of these tributaries, all sites are in a poor geomorphic condition. This reflects upstream impacts along with the heavily urbanized, industrial, and commercial land use. Geodiversity is low throughout this area. Channels have been smothered by fine-grained sediment and there are no characteristic sediment accumulations or changes in flow type. Floodplains have little or no connection to the channel. Large woody debris is still relatively common and provides some habitat and local changes in flow type. Channel geometry is degraded with overwidened channels, bank erosion, and aggradation of fine-grained material on the channel bed. Riparian vegetation cover is sparse, reducing the amount of nutrient and sediment buffering that could occur.

DISCUSSION

Retention of native vegetation in the headwaters of the Opanuku and Oratia trunk streams has resulted in streams with good geomorphic condition. Their steep V-shaped valleys limit prospects for human developments. Other than initial responses to forest clearance over 100 years ago, these areas remain relatively isolated from human disturbance (Gregory et al., 2008). As noted by Kasai (2006) and Kasai et al. (2005), once vegetation cover returns, sediment yield is likely to rapidly diminish. The resilience of these reaches is aided by their high slope and stream power, enabling flow to flush sediment downstream (Gregory et al., 2008).

The Waikumete trunk stream and some of the lower headwater reaches of the Oratia and the Opanuku have a degraded condition as excess fine-grained material smothers all features on the bed. The Waikumete drains a smaller catchment area than the other gravel based systems, resulting in lower total stream power. Similarly, sedimentation in the Opanuku and the Oratia occurs mainly in tributaries that have a small drainage area and, therefore, lower stream power, restricting their capacity to flush fine-grained material. The lower gradient of the Waikumete also makes it more suitable for human land use. Heavy development has removed most vegetation along the riparian margin, reducing the ability of these zones to buffer sediment inputs. Typically, headwater areas are conceptualized as "source" zones that evacuate fine-grained sediment (e.g., Schumm, 1977; Church, 2002), but upper areas of Waikumete subcatchment act as storage zones. The intact valley fill in the upper Waikumete acts as a buffer (*sensu* Fryirs et al., 2007), trapping sediment on the valley floor. In the past, the upper reaches of the Waikumete had many intact

valley fills, most of which were drained for development (Vela, 1989; Gregory et al., 2008). Previously, these fills restricted sediment delivery to lower sections of the Waikumete. Removal of these features has increased longitudinal connectivity and the efficiency of sediment transfer.

Land use in the transfer zone of the Twin Streams catchment is urbanized along the Waikumete trunk stream, while the slopes of the Oratia and the Opanuku are characterized by pasture and orchards in the top half and urban areas in the lower section. Intensity of development is much greater in the accumulation zone, with dense urban and commercial land use and less riparian margin remaining.

Streams in the transfer zone display local variability in condition. As noted by Grable and Harden (2006), local-scale patterns of erosion and deposition are evident in this urban part of the catchment. However, sampled sites along the Waikumete are in good condition, despite the presence of poor-condition variants upstream and the dense urban character of the surrounding land use. Seemingly, the channel has adjusted its cross-section in more alluvial areas in a way that has increased slope, such that fine-grained materials have been flushed through this reach (i.e., channel capacity has increased and the channel has straightened; Petts, 1984). Bedrock reaches of the partly confined river in the Waikumete are less sensitive to change. Their steeper slope facilitates flushing of sediment.

The lowland part of catchments act as the receiving basin for upstream impacts of differing land uses, most notably increased sediment loads and the intensity of degradation. Though local variability is evident, most lowland reaches in the Twin Streams catchment are in poor geomorphic condition. This is marked by limited physical heterogeneity and extensive accumulation of fine-grained sediment. Low slope and lower stream power conditions, along with the laterally extensive floodplains that dissipate flood energy, restrict the capacity of these lowland reaches to flush all of these fine-grained sediments through to the estuary. However, accentuated deposition along the lowland channel has been complemented by enhanced rates of sediment accumulation in the estuary in the period since European settlement (Hayward et al., 2006).

The poor geomorphic condition of streams in lower parts of Twin Streams catchment is not only induced by upstream factors. This was the first part of the catchment to be settled by Europeans, and contemporary urban impacts are of greater intensity in these areas than elsewhere. Channel homogeneity has also been increased by artificial straightening of channels in downstream areas (Waitakere City Council, 2006). Construction of artificial levees in lower reaches has disconnected the channel from its floodplain. As a result, accumulation is limited to in-channel deposition, enhancing the sediment load within the channel.

In addition, dense networks of stormwater channels in the mid-lower catchment rapidly convey water and sediment to the trunk stream increasing connectivity of biophysical processes in these urban areas. Stormwater pipes in the Twin Streams catchment have a relatively dense distribution across Waikumete subcatchment and in the middle and lower sections of the Opanuku and the Oratia. Although urbanization processes are commonly associated with a decrease in sediment flux (Chin, 2006; Gregory, 2006), stormwater pipes in this system act as conduits for sediment conveyance from across the floodplain, linking peripheral areas that were

previously separated (disconnected) from the channel, thereby increasing sediment inputs. In addition, these stormwater pipes have increased drainage density. Pipes also increase flow and reduce lag times for water to reach the channel, causing larger flood events that induce overwidened channels (Paul and Meyer, 2001; Chin, 2006). This enhanced flow connectivity, coupled with the high proportion of impervious surfaces, results in lower groundwater recharge, creating lower discharge at low water stages (Allan, 2004). However, streams at "normal" flow stages have a lower ability to move the excess sediment that has entered the system (Paul and Meyer, 2001). Increased loadings of fine-grained sediment degrades habitats, creating more homogenous channels (Figs. 5 and 6). Reduced areas of pools restrict the presence and viability of refugia at low-flow stages. Fine-grained materials also limit habitat availability/viability in interstitial areas, leading to the absence of drift susceptible species (Paul and Meyer, 2001; Allan, 2004). The Twin Streams catchment displays a significant decrease in heterogeneity in the lower areas of the catchment associated with higher densities of urban development. Reduced diversity of structure and habitat has implications for lower biodiversity and degraded ecosystems (Beisel et al., 2000), as does lower geomorphic condition (Sullivan et al., 2004; Chessman et al., 2006).

CONCLUSION

Three key considerations for analysis of the geomorphic condition of river systems emerge from this study. First, as noted by Fryirs (2003), procedures to assess river condition must refer specifically to river type, measuring geoindicators that are relevant to the reach under investigation. Second, spatial variation in geomorphic river condition cannot be explained unless reaches are viewed in their catchment context. In the Twin Streams catchment, differing patterns of condition have been shown for Waikumete subcatchment relative to Oratia and Opanuku subcatchments. Third, the contemporary geomorphic condition of river courses in the Twin Streams catchment is largely a product of the legacy of past disturbance events. Hence, studies of river evolution provide critical insights with which to explain variation in geomorphic river condition for any given system. In this instance, it was geomorphic responses to previous land-use changes (especially the initial phase of logging, operation of kauri dams, and gumdigging) that induced the flushing of fine-grained sediments that modified the geomorphic behavior of rivers (Gregory et al., 2008), rather than more-recent responses to land-use intensification by urbanization. Perhaps the most remarkable finding here, however, is the remarkably healthy condition of many of the river courses in this urbanizing catchment, with significant diversity of instream river structure still evident across much of the middle and upper catchment.

Linking heterogeneity of river structure to variability in flow type provides a powerful basis to assess geomorphic river condition for different types of stream. Critically, these relationships must be framed in relation to what is "expected" for any given type of river. Putting aside inherent limitations of the "field of dreams" approach to rehabilitation (Hilderbrand et al., 2005), geomorphic considerations provide the critical foundations for more holistic approaches to river rehabilitation.

While “getting the river structure right” provides no guarantee whatsoever that aquatic species will return to the system, the viability of aquatic ecosystems will not be improved or sustained unless efforts are made to improve the diversity of geomorphic river structure, and retain this level of diversity in light of prevailing flow/sediment fluxes.

Procedures documented in this study provide a rapid assessment technique with which to analyze the geomorphic condition of differing river types, framed in relation to the physical heterogeneity of the stream, linkage to flow variability, and inferred habitat availability. While impacts of urbanization have been the focus here, equivalent procedures could be developed to assess other human impacts on river systems, such as mining, dams, or agriculture. Future management strategies that strive to improve the ecological integrity of urban streams, in efforts to create and maintain more naturally functioning waterways (Walsh et al., 2005), must build on endeavors to reinstate natural diversity in physical structure across a catchment.

Acknowledgments: Financial support for this research was provided by the Institute of Earth Sciences and Engineering (IESE) at the University of Auckland. Particular thanks are extended to Anil Karan and Ian Boothroyd, who facilitated provision of background data at Waitakere City Council and Kingitt-Mitchell (now Golder), respectively. Susan Owen helped to coordinate this research. Tim Nolan is thanked for drafting the figures. Field assistants who helped make this work possible include Iain McGillvary, Angel Soja, and Florian Welter.

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