Monitoring change in river condition in response to river engineering: developing an index of natural character to maintain river habitat

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Key Points

- River engineering changes river condition and habitat, which is reflected in geomorphic change
- River geomorphology can be quantified simply and rapidly
- Assessing the extent of change in geomorphology generates an index of natural character
- Use of a natural character index (NCI) should be used as a tool to monitor baseline conditions and any subsequent deterioration of habitat in response to human activity in the river channel.

Abstract

This paper sets out an approach to habitat quantification by a simple assessment of stream geomorphology at a reach scale, based primarily on aerial photo interrogation and developed by targeted fieldwork. This provides a rapid, cost-effective means of assessing geomorphic diversity, vis-à-vis habitat quality, which is dependent on the physical structure of a river reach. Aerial photography pre-dating river management schemes in New Zealand provides a means of assessing the pre-intervention 'natural character' of a reach. Reach characteristics can then be compared with more recent imagery to assess the extent to which reach geomorphology has changed following intervention. This can then be used as a baseline from which to measure future reach adjustment. Targeted fieldwork quantifying key parameters likely to change in response to river engineering can be incorporated to refine understanding of reach character. As such a natural character index (NCI) can be used as an ongoing tool to monitor river condition in modified reaches before, during and after river engineering, as well as at sites upstream and downstream of river works to provide context for the impacts of intervention and disentangle human-induced and naturally-driven change.

Keywords

river geomorphology; natural character; NCI; New Zealand

Introduction

The declining quality and quantity of water in many of the world's rivers has rightly received attention from governments and agencies tasked with addressing this decline. In New Zealand, the Land and Water Forum (LWF) has brought together a range of industry groups, environmental and recreational NGOs, iwi (Maori tribal groups), scientists, and other organisations with a stake in freshwater and land management and provides recommendations to the New Zealand government on freshwater management. In its latest report at the end of 2012, it recommends integrated decision-making in catchments, continuous improvement of management practices to improve water quality and clearer rights to take and use water within set limits (Land and Water Forum, 2012). The National Policy Statement (NPS) for Freshwater Management published by New Zealand's Ministry for the Environment (MFE) in 2011 similarly focuses on setting limits for water quality and quantity for regional planning purposes (MFE, 2011). A standard gauge of water quality used by freshwater biologists in New Zealand is the Macroinvertebrate Community Index (MCI) (Stark & Maxted, 2007), but this makes no assessment of stream habitat, being based on taxa abundance.

A healthy stream ecosystem is dependent on more than the quality and abundance of water, since there must also be adequate habitat to support and sustain a viable, healthy ecosystem. However, to date habitat availability has formed little or no part in assessing stream health, and has been notably absent from New Zealand's LWF or NPS. Elsewhere, e.g. Tasmania, the Tasmanian River Condition Index (TRCI) evaluates the condition of four key aspects of waterways: Aquatic Life, Hydrology, Physical Form and the Streamside Zone, each of which is assessed as a sub-index (Tasmanian River Condition Index, 2006). The TRCI thus provides a more holistic assessment of stream health and condition. However, the methodology is detailed and involves discrete field-based assessment of physical form along stream transects to derive an index of condition. This is commendably rigorous, but also very time-consuming and requires considerable effort and man power. A similarly detailed Morphological Quality Index has been published recently in Italy (Rinaldi *et al*., 2013).

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This paper sets out an approach to providing a quantification of habitat by a simple assessment of stream geomorphology at a reach scale, based primarily on aerial photo interrogation, augmented by the use of LiDAR as available. As such, this provides a rapid, cost-effective means of assessing broad scale morphologic character and geomorphic diversity, vis-à-vis habitat quality, which is dependent on the physical structure of the reach (e.g. pools and riffles). We suggest the use of a natural character index (NCI) be incorporated as a tool to monitor baseline conditions and any subsequent deterioration of habitat in response to human activity.

The need for riverine management

The proximity of human activity (settlement, infrastructure, agriculture) to river courses inevitably means intervention is required in the watercourse to prevent loss of life and property. Many rivers require management in some form. In extreme cases all natural features of the channel have been replaced by a concrete slot channel, but in an era of river repair (Brierley & Fryirs, 2008), effective river management ought to be achievable with minimal impact on the natural character of a reach, or at least ongoing management should seek to minimize further habitat losses. The question remains as to how best to measure the impacts of river management or engineering on the natural character of a reach. This assumes natural character can be determined, which may be impossible, if prolonged human activity has modified a catchment and its boundary conditions.

Defining natural character

All rivers will tend towards attaining a quasi-equilibrium with their catchment boundary conditions (discharge, sediments, vegetation, slope), whether these conditions be pristine, or modified in some form. It is the manifestation of river character in response to these catchment boundary conditions, be they natural or modified, which is key to defining natural character as understood in this paper. A river with a high level of geomorphic or physical integrity (Brierley & Fryirs, 2005) displays equilibrium characteristics / forms that reflect discharge and sediment supplied from its catchment; such a river displays a high level of natural character, which reflects and responds to conditions in the catchment.

Intervention in the river channel through a plethora of channelisation possibilities (Brookes, 1985), usually involves compromising the geomorphic integrity of stream character, which no longer, or to a lesser degree, reflects an equilibrium with the catchment boundary conditions. Direct management, which is required to reduce risk to life and property, usually results in a reduction in geomorphic, and thus habitat, diversity.

Development of an NCI provides at least a means of measuring the loss of geomorphic diversity (aka habitat) and a metric to identify geomorphic trends or trajectories in a reach. This metric is of use in quantifying decline in habitat quality, as well as providing a measure of improvement in response to rehabilitation.

Methodology

Data sources and catchments

Interrogating archive aerial photography that pre-dates river management schemes in New Zealand provides a means of assessing the pre-intervention ‘natural character’ of a reach. Reach characteristics can then be compared with more recent imagery to assess the extent to which reach geomorphology has changed following intervention. This can then be used as a baseline from which to measure future reach adjustment. Airborne laser mapping (Light Detection and Ranging, LiDAR) provides a means of assessing floodplain and channel geomorphology in greater detail. In particular, LiDAR proves useful as a means to precisely define floodplain and channel parameters and identify previous channel courses. Georectified aerial photography and LiDAR data were provided for this study by Greater Wellington Regional Council (GWRC) for three rivers in the GWRC region: Otaki, Waikanae and Hutt (Fig. 1). Analysis was conducted in ArcMap® GIS, version 10.0 using LiDAR imagery dating from 2003, aerial photographs dating from 2010 and historically (Hutt- 1951, Otaki – 1939 and Waikanae – 1952) as well as topographic maps for each river. Each river is managed via a series of sub-reaches, which formed the basis for parameter measurement. The general type of river is best described as wandering, since the reaches assessed here tend to combine the characteristics of both meandering and braided channel patterns, without fully developing either planform (Ferguson & Werritty, 1983; Fuller *et al*., 2003).

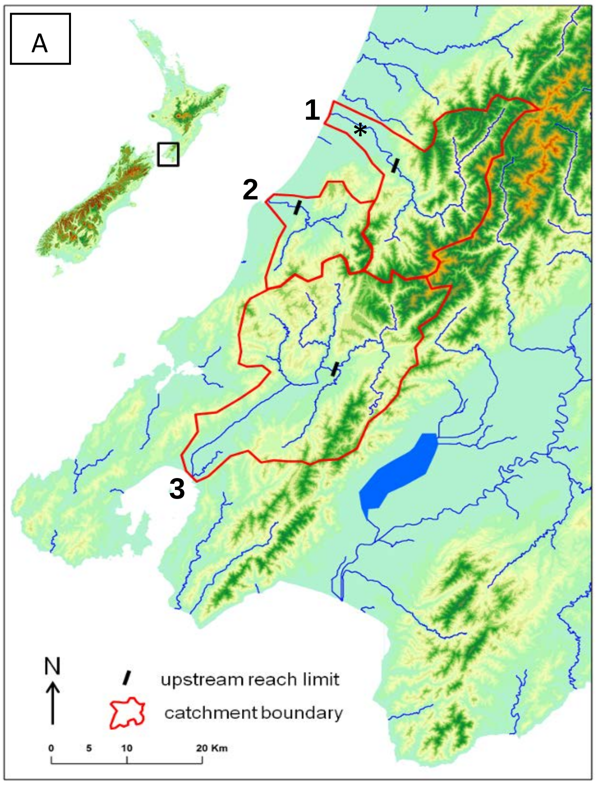

Figure 1. A. Catchment and reach locations: 1. Otaki River and catchment (11.8 km total reach length), 2. Waikanae River and catchment (4.3 km total reach length), 3. Hutt River and catchment (28.3 km total reach length, main stem). B. Otaki River at XS600-490 (cf Table 1 and * in Figure 1A), typical of laterally constrained wandering rivers in this region, photo is looking upstream, bridges are State Highway 1 and railway respectively. Photo: ICF 31 March 2013.

Measured parameters

Channel and floodplain widths

Active channel width, bankfull channel width, natural floodplain and permitted floodplain width were measured within ArcMap®. Active channel width is defined as the width of the wetted channel and the active gravel bars (devoid of vegetation) combined. Bankfull width is defined as the distance from banktop to banktop, encompassing wetted channel, active gravel bars and older semi-vegetated bars. Natural floodplain width is the area of valley floor that would be naturally inundated during a flood, which is usually between the youngest two river terraces at the valley margins in this area of New Zealand, while permitted floodplain width is the floodable valley floor usually confined between two stopbanks (levees / flood walls). Widths were measured at approximately 50 m intervals along the entirety of each reach in each river using the ruler tool in ArcMap®. Values were then averaged for each management reach to simplify subsequent analysis. The interval of measurement was somewhat arbitrary, but approximated typical active channel width in an effort to standardise assessment and account for natural downstream variability in parameters.

Since river management is most likely to result in constraining the river channel (active and bankfull) and its associated floodplain, the extent of this constriction was assessed by deriving a ratio of parameter width in 2010 to width from historic imagery (active and bankfull channel widths, plus permitted floodplain width). In addition, ratios showing the changes in active channel to natural floodplain width, which expresses the proportion of the floodplain occupied by the active channel; bankfull width to natural floodplain width, which expresses the size of the flood channel as a proportion of the natural floodplain; and natural to permitted floodplain width, which highlights any reduction in floodable area; were derived.

Channel planform

River management also tends to straighten channels, the extent to which this occurred can be assessed using sinuosity. The distance between two end points of a reach was measured following the midpoint of the wetted channel, which was then divided by the linear length between the two end points, providing a measure of sinuosity for each reach as per Fuller *et al*. (2013).

Many of New Zealand's rivers are locally braided. Management approaches tend to seek to simplify channel pattern. The extent of braiding was calculated using Brice's index (Brice, 1960), which states that the extent of braiding is 'twice the total length of the bars within the reach divided by the mid-channel reach'. Mid channel bars were identified and the length of each was measured in ArcMap® using the ruler tool. The total was calculated, multiplied by two and then divided by the mid-channel length used in the sinuosity calculation. However, this index was only feasible to generate in the Hutt River, which has clearly defined mid-channel bars. The Waikanae River is, and has been, primarily single thread. The Otaki River also proved difficult to assess in terms of braiding, since properly developed medial bars have not been a consistent characteristic of overall river morphology. However, anabranching channels were evident in 1939. Total thalweg length in each management reach was therefore measured in preference to a braiding index in the Otaki. The number of pools was also counted in each management reach, as a further measure of morphologic character and geomorphic and habitat diversity.

Results

Channel and floodplain widths were averaged for each management reach. The ratio of the mean value in 2010 to the mean historic value was then recorded for each reach (Tables 1 to 3). Channel sinuosity and braiding index (or thalweg length) were calculated for each management reach as a whole. A ratio of 1 indicates no change in parameter. A ratio <1 indicates a reduction in parameter value, indicating a decline in geomorphic diversity and habitat quality, whilst a ratio >1 indicates an improvement in river condition and habitat quality. The overall NCI value for each management reach is derived as a median of the parameter ratios for that reach. The use of the median in preference to the mean avoids skewing of data by single extreme values. Results are summarised in Figs. 2 and 3.

Table 1. NCI parameter ratios and overall median NCI per management reach defined by cross-section distance upstream from the river mouth (km), Otaki River.

	XS220–XS120	XS370–XS220	XS490-XS370	XS600-XS490	XS720–XS600	XS860–XS720	XS1020–XS860	XS1180–XS1020	**Median**
Sinuosity	0.92	0.91	0.99	0.83	0.86	1.21	0.97	0.97	**0.95**
Active channel	0.47	1.13	1.01	0.75	0.68	0.94	0.62	0.84	**0.79**
Bankfull channel	0.24	0.26	0.34	0.62	0.25	0.57	0.71	0.92	**0.45**
Permitted Floodplain	0.10	0.11	0.23	0.34	0.84	0.36	0.82	0.97	**0.35**
Thalweg length	0.41	0.59	0.79	0.47	0.94	1.53	1.06	1.01	**0.87**
Pools	0	0.32	0.64	0	0	0.75	1.26	0	**0.16**
OVERALL NCI	**0.41**	**0.32**	**0.64**	**0.62**	**0.68**	**0.75**	**0.82**	**0.92**	**0.71**

Table 2. NCI parameter ratios and overall median NCI per management reach defined by cross-section distance upstream from the river mouth (km), Waikanae River

	XS210–XS100	XS360–XS210	XS510-XS360	XS850-XS510	XS1090-XS850	XS1350–XS1090	XS1630-XS1350	XS1920-XS1630	XS2270-XS1920	XS2550-XS2270	XS2780-XS2550	XS2830-XS2780	Median
Sinuosity	1.0	1.0	0.87	0.98	1.00	0.99	0.98	0.98	0.89	0.99	1.00	0.95	**0.99**
Active channel	0.98	1.13	0.78	0.64	0.65	0.79	0.89	0.72	0.95	1.21	0.95	0.70	**0.84**
Bankfull channel	0.73	1.03	0.50	0.47	0.56	0.72	0.59	0.81	0.57	1.06	0.91	0.90	**0.73**
Permitted Floodplain	0.22	1.00	0.98	0.28	0.59	0.54	0.28	0.09	0.17	0.44	0.98	0.98	**0.49**
Braiding Index	0.00	0.00	0.00	0.26	0.00	0.11	0.44	0.14	0.49	0.00	0.16	0.00	**0.06**
Pools	0.00	0.00	1.00	0.31	0.76	0.40	0.00	0.78	1.00	2.00	1.00	2.10	**0.77**
OVERALL NCI	**0.73**	**1.0**	**0.78**	**0.47**	**0.59**	**0.72**	**0.59**	**0.72**	**0.57**	**1.06**	**0.95**	**0.90**	**0.73**

Table 3. NCI parameter ratios and overall median NCI per management reach defined by cross-section distance upstream from the river mouth (km), Hutt River

	XS80 – XS20	XS175 – XS80	XS240 – XS175	XS310 – XS240	XS350 – XS310	XS430 – XS350	Median
Sinuosity	0.96	0.97	0.79	0.98	0.98	0.74	**0.97**
Active channel	1.10	0.94	1.27	0.79	0.76	1.03	**0.99**
Bankfull channel	1.00	1.00	0.99	1.00	0.99	1.00	**1.00**
Permitted Floodplain	1.02	0.99	0.73	0.41	0.52	0.82	**0.78**
Pools	1.00	0.80	1.50	0.00	0.26	0.83	**0.82**
OVERALL NCI	**1.00**	**0.97**	**0.99**	**0.79**	**0.76**	**0.83**	**0.97**

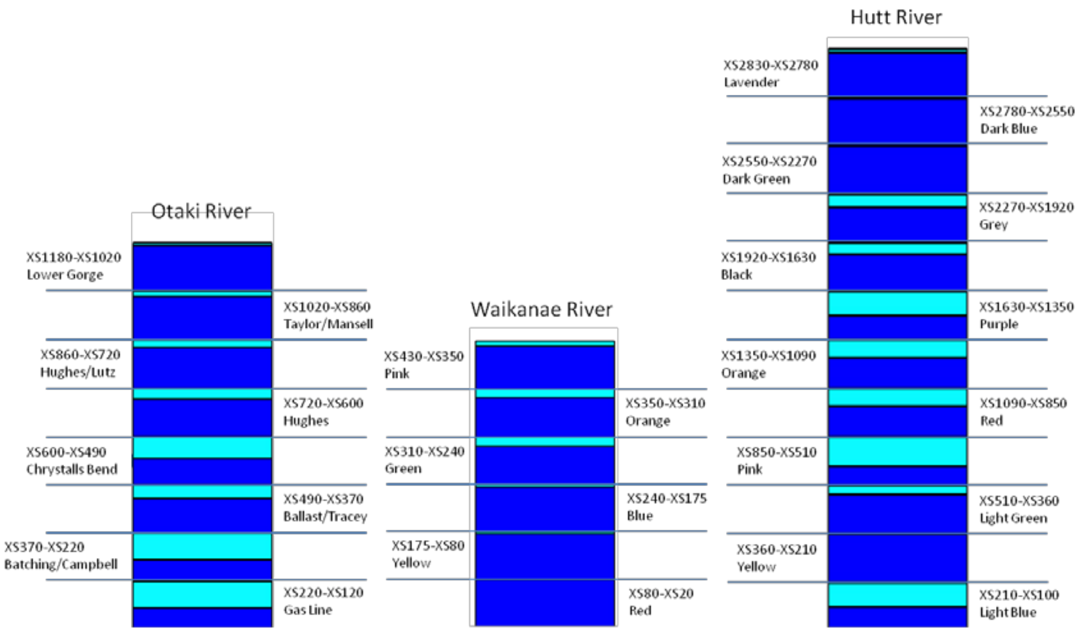

Figure 2. Summary of reach NCI scores in the Otaki, Waikanae, and Hutt Rivers, per management reach defined by cross-section distance upstream from the river mouth (km) and named according to river management scheme definitions. The colour scheme visualises extent of modification: greater proportions of light blue represent greater change from the reference condition and lower NCI.

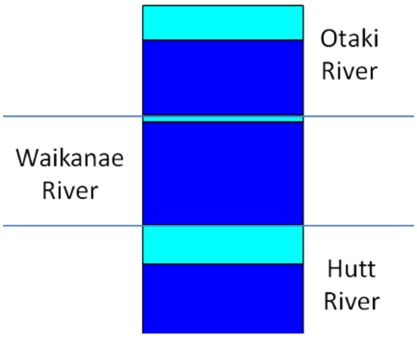

Figure 3. Summary of overall NCI scores for each river. The colour scheme visualises extent of modification: greater proportions of light blue represent greater change from the reference condition and lower NCI.

Discussion

Extent of modification

The extent of modification between reaches and between rivers is highly variable. Overall, the least modified, most natural character is evident in the Waikanae River, while the most modified, least natural is the Otaki River (Fig. 3). It should be noted however, that modification of the lower reaches in the Hutt River and much of the Waikanae River preceded the earliest aerial photos available of the reach. The starting conditions for these reaches, are thus not strictly entirely natural and the full extent of modification may be greater than quantified by the NCI. This may explain the higher than expected NCI score in Yellow reach in the Hutt River (Fig. 2). In each river, the most modified reaches are generally towards the lower extents of the river (i.e. towards the river mouth), which is where population density is highest in each catchment. The upper reaches of the Otaki, for example, are situated at the outlet of a natural gorge and as such, although the river as a whole has the lowest NCI score, the uppermost reaches have been relatively untouched. In the Waikanae River, the lowermost reach is located beyond the urban area and has not been engineered, thus retaining its natural character (cf. Fig. 2).

Parameter sensitivity to quantifying habitat

Consistently, the least changed parameter in these rivers over the assessment period is sinuosity (cf. Tables 1-3). This may reflect the fact that these wandering rivers are not classic meandering systems. Arguably therefore, this is not an appropriate measure of natural character in these river types. However, whilst this could also suggest that modification in these reaches has done little to affect natural planform, thalweg length in the Otaki and braiding index in the Hutt have been impacted, the latter severely (cf. Table 3). In the Hutt River, the dramatic decline in braiding is a product of the simplification of channel form that has been attempted by river engineering as part of flood protection in these reaches, through both direct channel planform modification and gravel extraction. In multi-threaded systems, these parameters appear to be sensitive measures of habitat quality and geomorphic diversity.

Active channel and bankfull channel widths, indicate variable degrees of channel modification, from very little in the Waikanae River to more substantial in the Hutt and Otaki Rivers. However, the extent of modification of these parameters in these rivers ranges from 0.45 (Otaki bankfull) to 0.85 (Hutt active), indicating that both river channels have been narrowed, the Otaki to a more considerable degree. This has a significant impact on habitat diversity, because the channel form has necessarily become simplified and high flows have become more confined, producing a greater hydraulic uniformity in the channel, relative to a more natural diversity in a wider channel. This is consistent with the observed reduction in pools in these rivers, most marked in the Otaki River (median NCI score 0.16). In more hydraulically uniform, narrowed channels, sediment transport tends to be more efficient (a goal of river management to mitigate flood risk by maintaining channel capacity) and as such pool-riffle sequences may become less distinct as the river bed becomes more uniform and less diverse.

The extent of floodable area is less significant for aquatic habitat diversity, but nevertheless all three rivers in this study demonstrate a marked reduction in permitted floodplain width, suggesting this is a sensitive indicator of natural character. This reduction is inevitable with the occupation and development of floodplains by housing, industry and infrastructure. This confinement of floodwaters may also contribute to reduction within in-channel habitat diversity, since flood flows that once dissipated across broad floodplains are now confined within the channel. This, together with channel narrowing itself exacerbates increased flow energy and raises sediment transport potential, potentially contributing to change in morphologic character and habitat reduction. However, this could be mitigated by using excess flow energy to deepen pools in rock-armoured reaches by facilitating bed scour. This mitigation has been proposed in the Hutt River Global Consents process (Berghan, pers. comm.).

Use, limitations and refinement of NCI to evaluate habitat quality

Evaluation of river natural character via a score based on geomorphic variables is inevitably highly generalized, since river morphology continuously varies downstream, in response to changing boundary conditions of discharge, gradient and sediment. It is nevertheless important that river character be classified using relatively homogenous reaches, so that variability in geomorphology and habitat within a reach does exceed that variability between reaches. This study has attempted to ensure this is the case by using reaches defined by current river managers in each river, as coherent management reaches, although hard and fast boundaries may be difficult to discern. It is important to make an assessment at this homogenous reach scale because the NCI of extended reaches (such as the c.12, 4 and 28 km reaches of the Otaki, Waikanae and Hutt Rivers) masks substantial deterioration of river condition at the sub-reach scale at which the river is managed. If NCI is to be used as a management tool, it must be applied at the appropriate scale. Furthermore, appropriate parameters must also be measured: there is little to be gained in quantifying a braiding index if the river is only locally divided or lacks proper medial bar development, or assessing sinuosity if the river lacks a meandering planform.

With these limitations in mind it is our intention to refine the NCI approach using targeted field-based analysis of key habitat-forming parameters. Research is currently underway in the Hutt River to assess both the sensitivity of the NCI approach and its relevance for informing current practice. To do this, parameters including surface grain size and bed compaction based on field measurements are quantified upstream of river works, as well as at the modified site and downstream of the works site. Aerial photographs of these reaches before and after engineering will also be interrogated to derive the proportion of active channel that is riffle, pool, run and bar at these locations. This will enable the pre-engineering baseline ("natural" condition) to be compared with the effects of river works on these parameters, generating an NCI value which assesses the impacts of specific activity in the river channel. Assessment of reaches upstream and downstream of the works site will permit identification of any natural change trajectories in the channel, e.g. due to downstream progression of coherent bedload sheets, or the impact of a particular flow event. The rate of geomorphic adjustment towards some form of equilibrium following engineering is dependent upon the frequency of geomorphically effective flows. Reassessment of NCI at engineered sites over an appropriate time period (up to e.g. 10 years) would enable tracking of change in river condition as the channel reaches a new equilibrium.

Conclusions

NCI is not a detailed descriptor of river condition, unlike the TRCI. However, its value lies in the relative ease and rapidity afforded by such a desk-based and potentially targeted field assessment. It should not be understood as an absolute measure of habitat diversity and quality, but as a means of quantifying relative changes in geomorphic characteristics and parameters associated with habitat quality between successive phases of human intervention in river channels. Its usefulness lies in providing a simple score, which can be re-measured as part of ongoing river monitoring before and after river works. Deterioration of the score should be avoided by deploying appropriate river management strategies, and rehabilitation schemes may seek to establish improvements in NCIs of degraded reaches. As such, NCI provides a useful, simple approach to quantifying habitat quality, which has hitherto been overlooked, particularly in New Zealand, and as such we suggest the use of a natural character index (NCI) be incorporated as a tool to monitor baseline conditions and any subsequent deterioration of habitat in response to human activity in the river channel.

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