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Quantifying 250 years of change to the channel structure of the River Kelvin

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ABSTRACT
The channel systems of the River Kelvin, a major tributary of the River Clyde in the Central Lowlands of Scotland, have been anthropogenically altered and manipulated for more than two centuries. The main stem of the river, which stretches from Kilsyth to Glasgow, and its tributaries have been subject to flood management schemes and changes in catchment land use, which have generally adversely affected river flow regime and biodiversity. Understanding the history of the Kelvin system, and the physical adjustments that have been made to it, is crucial to the success of targeted attempts at restoration of the river. Using a geographical information system (GIS) historical and current maps were analysed to determine the total loss of channel length since the mid-18th century, and to provide insight into the hydrology of the river prior to any changes. A total of 90 km (23%) of river length was lost from the Kelvin catchment between 1752 and 2010, primarily due to the channelisation of sections before 1856. Baseline information provided by this study on the natural course of the river and its tributaries, and subsequent anthropogenic changes, in conjunction with appropriate water chemistry, land use and biological data can help identify high priority areas for future programmes of river restoration.

INTRODUCTION
Anthropogenic alterations to rivers have benefitted human communities for centuries, allowing people to harness the power of water, providing travel routes, and aiding both commercial and agricultural advances (Grabowski et al., 2014; Wohl et al., 2015).

In the United Kingdom, river catchments have been altered extensively for land drainage and flood defence purposes. These sometimes-severe alterations to river channel systems often degrade water quality and ecosystem resources, resulting in unproductive rivers supporting impaired biological communities (Helfield et al., 2012; Grabowski et al., 2014). Environmental problems associated with heavily modified river catchments include biodiversity and habitat loss, increased bank erosion, the spread of invasive species, and pollution (Simpson et al., 2014; Gallardo et al., 2015; Göthe et al., 2015). These factors negatively impact resident aquatic organisms and may also affect riparian communities relying on the river system.

The repercussions of these modifications have been recognised recently and river restoration projects that seek to improve freshwater habitats, biodiversity, and “healthy” water quality have become popular throughout the UK (Newson and Large, 2006; SEPA, 2007; Hall 2010).

The River Kelvin, a tributary of the River Clyde in central Scotland, is a candidate river system for active management in order to restore its productivity and biodiversity. The catchment of the Kelvin (Figs. 1, 2) comprises tributaries such as the Glazert, Luggie, and Allander Waters, as well as a number of smaller streams. Due to the shallow gradient of the river and its location in a low-lying valley, the Kelvin was originally prone to flooding of surrounding farmland and villages during periods of heavy precipitation (Gardiner & Armstrong, 1996; Matheson, 2000). In an attempt to prevent this, the river underwent extensive man-made alterations, beginning in the 1700’s, and as a result, the present-day course of the River Kelvin and many of its tributaries share few similarities with the historically meandering natural course of the river.

Historically, this river system has been vital to the human communities living within its catchment, and changes to the river system were key to the development and economic prosperity of the area from the 18th century onwards (Matheson, 2000). Weirs and dams were built along the length of the river in order to power mills, chemical works, shipbuilders, and paper and flint manufacturing companies relied on the Kelvin as a source of water, as well as for the disposal of their waste waters. Today the Kelvin and its tributaries pass through villages, towns, and the city of Glasgow, as well as agricultural areas that are a source of diffuse pollution into the river (SEPA, 2007).

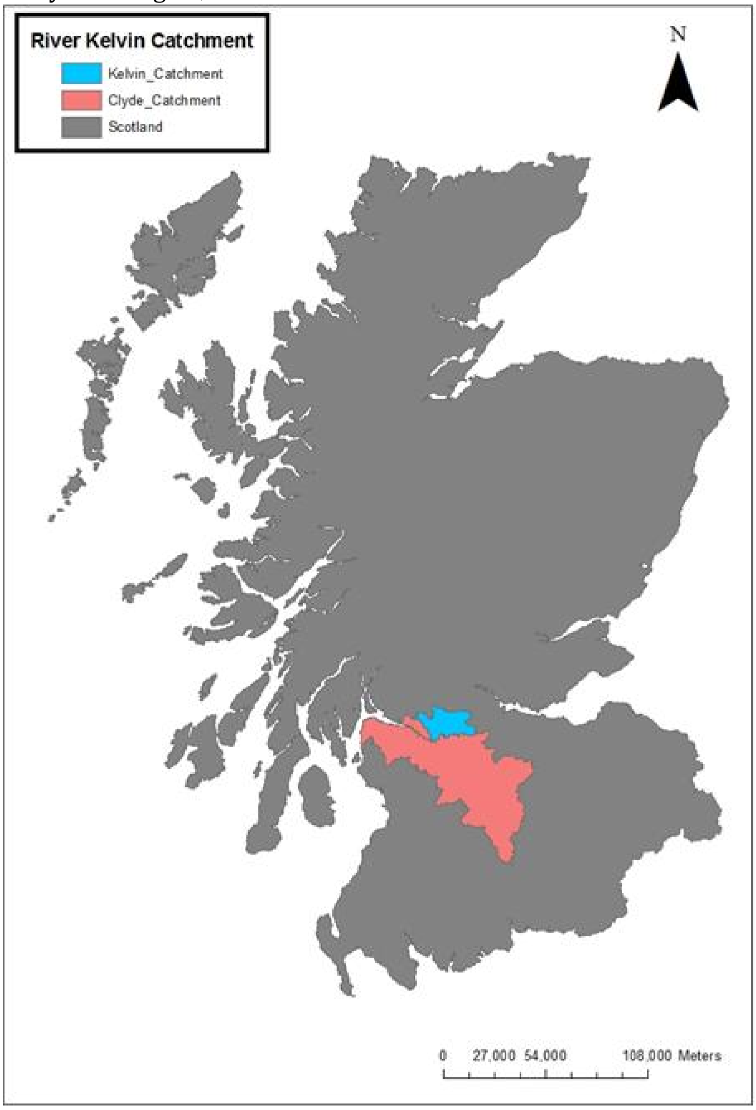

Fig. 1. Map of Scotland with the Clyde catchment (pink) and the Kelvin catchment (blue), (map provided by the Clyde River Foundation, 2013).

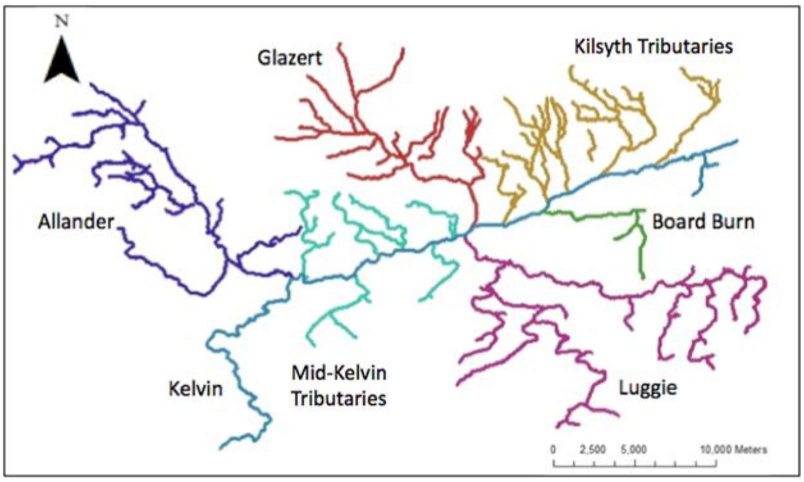

Fig. 2. Seven sections of the Kelvin catchment that were examined individually to determine channel length loss (from 2010 Ordnance Survey map).

The historical and current anthropogenic impacts on the River Kelvin have resulted in a catchment system with numerous environmental problems. These include reduced biodiversity, increased bank erosion and suspended sediment issues, and proliferation of invasive populations of non-native bankside plants (particularly Japanese knotweed, Fallopia japonica; giant hogweed, Heracleum mantegazzianum; and Himalayan balsam, Impatiens glandulifera). Runoff pollution from both urban and agricultural areas within the catchment continues to impact the Kelvin, however, the construction of the Kelvin sewerage system in the 1980's has successfully eliminated major point-source pollution from entering the river (McColl et al., 2009, McColl et al., 2011). The channelisation of the river bed also removed many of the historic fish spawning grounds in the main stem of the river (McColl et al., 2011), although the return of salmonid populations (both trout, Salmo trutta, and salmon, Salmo salar) to the Kelvin in recent years indicates a significant degree of recovery from pollution (Gardiner & Armstrong, 1996).

Understanding the channel structure of the pre-development catchment, as well as subsequent alterations, and current characteristics of the system, will assist river ecosystem restoration (Palmer et al., 2005; Downs et al., 2011; Hammond et al., 2011). A baseline survey of the Kelvin catchment is therefore an important precursor to any potential restoration projects undertaken in the system. Extensive information is available on contemporary water and habitat quality, fish communities, and invasive, non-native species within the Kelvin system (McColl et al., 2009; McColl et al., 2011; Clyde River Foundation, 2013) but historical records are comparatively rare.

The purpose of this study was to reconstruct a historical baseline of channel networks in the Kelvin catchment and to quantify the degree and location of change between the original course of the rivers and their current state, in order to inform future restoration plans for streams within the River Kelvin catchment.

MATERIALS & METHODS

Maps

Two sets of historical and one set of contemporary maps were examined to describe and quantify the original course and length of the river system, and subsequent anthropogenic change.

The earliest detailed map of the study area was produced by the Roy Military Survey of the Scottish Lowlands, undertaken between 1752 and 1755 by a team of cartographers led by Major-General William Roy (Hodson, 2007). This map (produced at a scale of approximately 1:36000) was primarily for military use, and was developed around the accurate measurements of features such as roads and rivers that could provide more exact directions for troops of soldiers moving through the countryside; mountains and towns were sketched or copied less accurately from existing maps (Fleet & Kowal, 2007). Fleet and Kowal (2007) do discuss in their research that the measurements of the Roy Map would not be as precise as measurements taken with present day technology, but given that rivers were important features in the landscape, and were therefore likely to have been surveyed as accurately as possible in the 1750's, the Roy Map probably provides an acceptably-accurate representation of the Kelvin catchment in the latter half of the 18th century. The Kelvin catchment is largely covered by British Library image sheets for the Roy Map of Lowland Scotland coded C.9.b: 5/6a, 5/6b, 5/6c, 5/7c, 5/7b, 5/7d, 5/7f, 15/4f, 15/5a, 15/5d, 15/5e (with smaller stretches of upper catchment streams on other, surrounding image sheets).

The second map series used was the First Edition of the Ordnance Survey (Sheets 30, 31, 38, 39; 1:63360 scale), created between 1856 and 1891. This map provides a view of the Kelvin catchment around a century after the Roy Map had been completed. Both of these historical maps were compared against the 2010 Ordnance Survey map (Sheet 64; 1:50000 scale) of the catchment, to establish the degree of change that had occurred within the river, and how much channel length had been lost since the 18th Century.

The amount of change in the Kelvin channel system was quantified by measuring the river length lost over the past 250 years using ArcGIS 9.2 spatial analysis software (www.esri.com). The digital copy of the Roy Survey map was not geo-referenced, so it was manually adjusted to the British National Grid (BNG) coordinate reference system. This was done by locating a set of readily-identifiable features that could be found on both the historic and modern maps to act as spatial references, and using their current coordinates as geo-reference points for the Roy Map. This ensured that all three maps would accurately line up with one another. Because the Roy Map is divided into small areas over several image sheets, lining up spatial references between historic and modern maps resulted in little to no stretching between points over the historical Kelvin catchment depiction, particularly in the sections depicting the main channel of the river. This would suggest that the original measurements of the Roy Map were accurate and therefore comparable to modern maps today.

Shapefiles were created by tracing the course of the Kelvin and its tributaries on all three maps. Some spatial issues arose with the individual images of the Roy map sheets covering the catchment, where smaller streams often did not match up precisely between the individual sheets. To compensate for these "missing" sections of river, the ArcGIS editing tool was used to connect the features together using a straight line, allowing one large shapefile to be created to represent the catchment. Unfortunately, by filling in the "missing" sections of the river using straight lines, an underestimation of the total length of burns in that area would have occurred due of the lack representation of the natural meanders. However, it was thought that this was the most efficient, albeit conservative, way to demonstrate the change in channel length over time.

Another problem found using the 2010 Ordnance Survey map, which was by far the most detailed map, was that it showed smaller streams and tributaries that were not present on the older maps. These smaller streams were probably overlooked by previous cartographers because they considered them insignificant, or because they lacked the methods to map them. To avoid problems with this issue, several small streams found on the 2010 map that were not present on the earlier maps were deleted from the shapefile.

It was also noted that several small streams in the 2010 map were longer than previously reported in the historical maps, most likely because of similar decisions made by cartographers to exclude sections of small burns that they considered irrelevant. In order to correct this oversight, the identified streams on the 2010 map were clipped using the editing tool at the upstream section where the historical map's streams ended to ensure that the lengths were compatible.

Once the channel system present on each map had been digitised and converted into shapefiles, total channel length was measured, within each of seven sub-sections making up the total catchment: Kelvin (main channel); Allander; Mid-Kelvin Tributaries; Glazert; Luggie; Board Burn; and Kilsyth Tributaries (Fig. 2).

Change in channel length

Channel length of the entire catchment, and within each of the seven individual sub-sections, was compared between maps of:

(a) the Roy Lowland Scotland Survey (1752-1755) and the 1st Edition Ordnance Survey (1856-1891);

(b) the 1st Edition Ordnance Survey (1856-1891) and the 2010 Ordnance Survey; and

(c) the Roy Survey (1752-1755) and the 2010 Ordnance Survey.

The difference in channel length (km), and percentage of channel length change was recorded between each pair of maps, as well as the rate of loss (km/year) between the successive publication dates.

RESULTS

Channel length

Because of the spatial inconsistencies present in the Roy Survey (1752-1755), two different values were calculated for the channel lengths to account for the "missing" sections of the Kelvin catchment. The total channel length unaccounted for in the map was 4.6 km or 1% of the total. The area affected most by spatial inconsistencies was the Kilsyth Tributaries section, where 2.7 km, or an estimated 4% of the total channel length of 71.2 km in that section was "missing". The total 18th Century channel length including the "missing" sections was 397.5 km (total channel length without the "missing" sections was 392.9 km), compared with a 19th Century length of 327.6 km, and a length in 2010 of 307.4 km (Table 1).

	Roy (1752) (km)	OS (1856) (km)	OS Modern (2010) (km)	Total length lost (km)	% lost	Rate of loss (1752-2010) (km/ year)
Whole Catchment	397.47	327.56	307.38	90.09	22.67	0.35
Allander	67.97	56.50	55.96	12.01	17.67	0.05
Mid-Kelvin Tributaries	41.30	34.39	33.96	7.34	17.78	0.03
Glazert	57.70	51.75	45.35	12.36	21.42	0.05
Kilsyth Tributaries	71.22	66.41	58.08	13.14	18.44	0.05
Luggie	82.71	71.82	66.69	16.02	19.37	0.06
Kelvin	58.75	38.84	38.39	20.36	34.65	0.08
Board Burn	13.48	7.76	8.58	4.91	36.38	0.02

Table 1. Comparison of the Kelvin catchment (whole-channel network and subsections: see Fig. 2) channel lengths (km), between Roy Military Survey (1752-1755), 1st edition Ordnance Survey (1856-1891), and modern Ordnance Survey (2010) maps. Channel lengths recorded for the Roy Survey include the "missing" sections of the Kelvin catchment that were drawn in during the creation of shapefiles.

Channel losses

When comparing channel lengths between the Roy Survey and the 1st edition Ordnance Survey, the values used from the Roy Survey included the "missing" segments. During the 120 years between the median dates of publication of the two maps, 69.9 km, or 18%, of the Kelvin catchment channel length was lost (Table 1). Most of that loss occurred in the main stem of the River Kelvin, with the channel length declining from 58.8 km to 38.8 km, equal to a loss of 34% of its total length. The Board Burn also saw a large decline, losing 43% of its channel length.

The results of the comparison of the two Ordnance Surveys maps (with median publication dates separated by 127 years), demonstrated that while channel alterations were still occurring within the Kelvin catchment between the 19th and 21st Centuries, the overall loss of channel length was much smaller than it was between the 18th and 19th Centuries. Over the more recent period, the total catchment lost 20.2 km, or 6% of its channel length, and the majority of this loss occurred within the Kilsyth Tributaries section, with a loss of 8.3 km, or 13% of their length (Table 1).

By comparing the Roy Survey and the 2010 Ordnance survey, the total channel length lost in the entire Kelvin catchment was calculated to be 90.1 km, or 23%, since the 1750s (. 3; Table 1). Most of this loss occurred in the main stem of the River Kelvin, with its channel length (in 1752 – 1755) of 58.8 km shrinking to 20.4 km, a loss of 35%, by 2010. The Board Burn also suffered substantial changes, losing 36% of its total length and decreasing from 13.5 km to 8.6 km, over this period.

Rate of loss

The rate of channel loss was examined between median map publication dates. When the Roy Military Survey (1752-1755) was compared to the 1st edition Ordnance Survey (1856-1891), the average loss rate was 0.6 km/year throughout the catchment (Table I). When the 1st edition Ordnance Survey (1856-1891) was compared with the current Ordnance Survey (2010), the rate of channel loss had declined to 0.1 km/year. Finally, the overall rate of channel loss in the Kelvin catchment was determined by comparing the Roy Survey (1752-1755) to the current Ordnance Survey (2010). This showed that over the full period of the study, the channels of the Kelvin system decreased in length by an average of 0.35 km/year.

DISCUSSION

By examining the earliest existing detailed map of the Kelvin catchment, a general outline of the natural course of the river can be broadly determined, prior to the major changes made to its course from the latter part of the 18th century onwards. Although there are some mapping inconsistencies within the Roy Survey map, it does appear to provide a reasonably accurate representation of the course of the Kelvin and its tributaries before major channelisation began in the catchment (Gardiner & Armstrong, 1996; Fleet & Kowal, 2007).

Comparison of the Roy Survey with the 1st edition Ordnance Survey highlighted the straightening of the main stem of the River Kelvin prior to the mid-1800s. These adjustments were made to manage flooding, create more available farmland, and provide water supply to the new Forth and Clyde Canal, for example from the Bothlin Burn (Matheson, 2000; Ross et al., 1986). In future research, a closer investigation could focus on the driving forces behind specific changes in different sections of the Kelvin catchment, providing more insight into the overall alterations that occurred.

With the majority of the main stem of the river straightened, modifications were subsequently made to the tributaries, such as the Luggie and the Glazert, though these had less impact on total channel loss. Overall however, the present course of the Kelvin is very different to that in the 18th and 19th centuries, with loss of natural meanders being the main observed channel feature reduction. The detailed results of the study show where these changes occurred, and can be used to identify reaches of the river system and its tributaries where appropriate re-wilding or other restoration measures might best be implemented.

It is not possible to restore the Kelvin catchment channel system to its original length and course because of the extent of urban and other infrastructure development along the banks. It is, however, possible to use the results of this study to inform restoration programmes by indicating reaches which were formerly (for example) more meandering, and where appropriate restoration of the previous physical habitat might be undertaken. Examples of such locations identified by the study data (each comprising a 1 – 2 km stretch of channel, with at least "Fair" water quality as defined by SEPA (2007), and with a small amount of suitably sized gravel substrate needed for productive salmonid spawning habitats: McColl et al., 2011), include two sites located in the main stem of the Kelvin, between Kilsyth and Kirkintilloch, and three others at the mouths of the Allander and the Glazert Waters, and the Bothlin Burn (Fig. 4). Restoration projects targeting such sections may optimise the benefits from investment to improve the ecological health of the channelised river ecosystems present within the Kelvin catchment

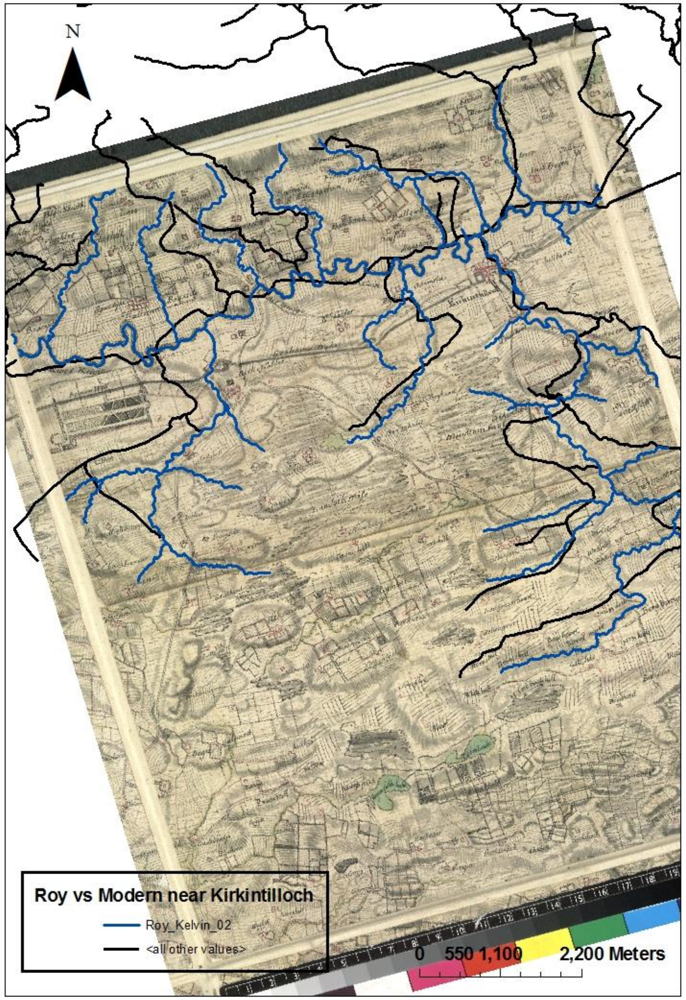

Fig. 3. Comparison of the River Kelvin system near Kirkintilloch as portrayed by the Roy Map (1752-1755) and the 2010 Ordnance Survey reported as "<all other values>"(map provided by the British Library. 2013).

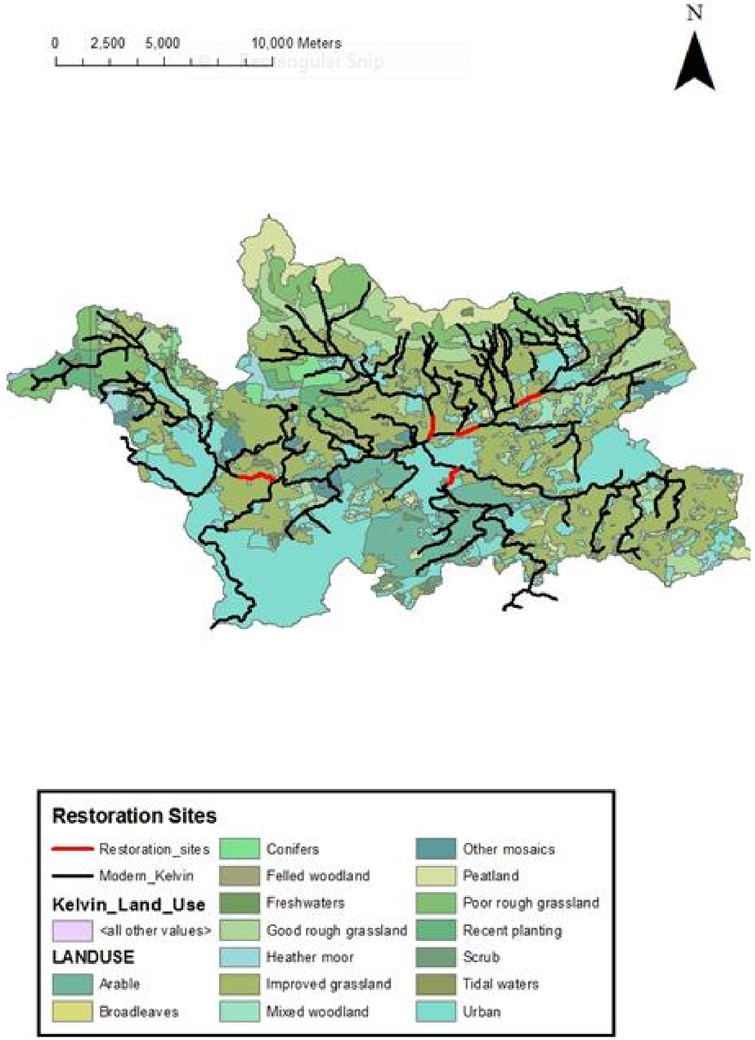

Fig. 4. The Kelvin catchment with potential restoration sites highlighted in red over a land use map of the area (reproduced with kind permission of the Clyde River Foundation 2013).

This paper uses a historic dataset to provide an initial insight to the natural state of a well-known Scottish river. However, future research could investigate numerous other questions that arose from this particular project, including how stream gradient and flow rate might have influenced the manipulation of certain segments of the river, the driving forces behind alterations in different parts of the catchment, and the impacts of river restoration on the communities around it (i.e. flood risks, aesthetic value, etc.)

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REFERENCES

Brown, A., Harper, D. & Peterken, G. (1997). European floodplain forests: structure functioning and management. Global Ecology and Biogeography Letters 6, 169-178.

Clyde River Foundation (2013). The River Clyde Fisheries Management Plan Review 2013). www.clyderiverfoundation.org.

Downs, P., Singer, M., Orr, B., Diggory, Z. & Church, T. (2011). Restoring ecological integrity in highly regulated rivers: The role of baseline data and analytical references. Environmental Management 48, 847-864.

Fleet, C. & Kowal, K. (2007). Roy Military Survey map of Scotland (1747-1755): mosaicing, geo-referencing, and web delivery. e-Perimetron 2,194-208.

Gallardo, B., Clavero, M., Sánchez, M. & Vilà, M. (2015). Global ecological impacts of invasive species in aquatic ecosystems. Global Change Biology. doi:10.1111/gcb.13004.

Gardiner, R. & Armstrong, J. (1996). Migratory salmonids in the River Kelvin. Fisheries Research Services Report 4/96. Freshwater Fisheries Laboratory, Pitlochry:

Göthe, E., Wiberg-Larson, P., Kristensen, E., Baattrup-Pedersen, A., Sadin, L. & Friberg, N. (2015). Impacts of habitat degradation and stream spatial location on biodiversity in a disturbed riverine landscape. Biodiversity and Conservation 24, 1423-1441.

Grabowski, R., Surian, N. & Gurnell, A.M. (2014). Characterizing geomorphological change to support sustainable river restoration and management. Wiley Interdisciplinary Reviews: Water 1, 483-512. doi: 10.1002/wat2.1037

Hall, M. (2010). Introduction: Tempo and Mode in Restoration. In Hall, M. (editor), Restoration and History: The Search for A Useable Environmental Past (eds pp 1-13. Routledge, New York:

Hammond, D., Mant, J., Holloway, J., Ellbourne, N. & James, M. (2011). Practical River Restoration Appraisal Guidance for Monitoring Options: Guidance document on suitable monitoring for river and floodplain restoration projects (PRAGMO). The River Restoration Centre, Cranfield, ,Bedfordshire.

Helfield, J., Engstrom, J., Michel, J., Nilsson, C. & Jansson, R. (2012). Effects of river restoration on riparian biodiversity in secondary channels of the Pite River, Sweden. Environmental Management 49, 130-141.

Hodson. Y. (2007). The Great Map: the military survey of Scotland, 1747-55; with introductory essays by Yolande Hodson, Chris Tabraham, and Charles Withers.. pp 7-24.National Library of Scotland, Edinburgh.

Matheson, A. (2000). Glasgow's Other River: Exploring the Kelvin. Fort Publishing Ltd., Ayr.

McColl, D., Yeomans, W., McGillivray, C. & Olszewska, J. (2009). The River Clyde Fishery Management Plan 2009-2015. Clyde River Foundation, Report 2009/09, Glasgow.

McColl, D., Yeomans, W., McGillivary, C., Sinclair, H. & Olszewska, J. (2011). River Kelvin Habitat Survey. Clyde River Foundation. Report CRF 2011/01, Glasgow.

Newson, M. & Large, A. (2006). "Natural" rivers, "hydromorphological quality" and river restoration: A challenging new agenda for applied fluvial geomorphology. Earth Surface Processes and Landforms 31, 1606-1624.

Palmer, M., Bernhardt, E., Allan, J., Lake, P., Alexander, G., Brooks, S., Carr, J., Clayton, S., Dahrn, C., Shah, J., Galat, D., Loss, S., Goodwin, P., Hart, D., Hasset, B., Jenkinson, R., Kondolf, G., Lave, R., Meyer, J., O'Donnell, T., Pagano, L. & Sudduth, E. (2005). Standards for ecological successful river restoration. Journal of Applied Ecology 42, 208-217.

Ross, S.L., Doughty, C.R. & Murphy, K.J. (1986). Cause, effects, and environmental management of a Lemna problem in a Scottish canal. Proceedings European Weed Research Society/Association of Applied Biologists 7th International Symposium on Aquatic Weeds 1986, 277 - 283. EWRS, Wageningen, The Netherlands

Rotherham, I. (2011). Implications of Landscape History and Cultural Severance for Restoration in England. In: Egan, D., Hjerpe, E. & Abrams, J. (editors), Human Dimensions of Ecological Restoration pp 277-287. Island Press, Washington, DC.

SEPA (Scottish Environmental Protection Agency) (2007). Scotland's Water Environment Review 2000-2006. SEPA, Stirling.

Simpson, A., Turner, I., Brantely, E. & Helms, B. (2014). Bank erosion hazard index as an indicator of near-bank aquatic habitat and community structure in a southeastern Piedmont stream. Ecological Indicators 43, 19-28.

Wohl, E., S. N. Lane & A. C. Wilcox (2015). The science and practice of river restoration, Water Resources Research 51, 5974–5997, doi:10.1002/2014WR016874.