Chapter 7

Rivers: Environmental Change & Management

1. Introduction

Because rivers are systems that integrate and reflect the complete environment in which they form, as environments change so do the river systems they support. It is the purpose of this final chapter to briefly consider several examples of this disequilibrium behaviour in rivers.

It is very difficult to impossible to tease out the effects of specific components of environmental change on rivers because such changes do not occur in isolation in nature. Such changes and adjustments also play out over a range of timescale. Some changes are almost immediate while others take time to produce accommodations. For example, a shift to regionally warmer temperatures (global warming) has a very complex expression locally. A warmer atmosphere means that more energy is available to drive circulation that can lead to more storminess and
greater precipitation over river basins in the region. This in turn can lead quickly to glacier
retreat and a reduction in the degree to which basins are glacierized. In the longer term, the
climate shift can cause changes in vegetation that can range from modest in temperate areas to
catastrophic in marginal zones such as deserts or cold treeline environments. Each of these
related changes will change the local river hydrology and the supply of sediment to the channel.
Not only is it impossible to isolate these processes, it is rather unrealistic to attempt to consider
them in isolation because that is not the way in which nature works.

Nevertheless, one of the most important aspects of our environment that is subject to change is
climate. Climate is fundamental to river hydrology and as we noted this in turn controls so much
of river behaviour. Climate change occurs over a wide range of time scale although much of it is
poorly understood. We know that climate shifts can occur over decades as a result of global
changes in atmospheric circulation (possibly related in the northern hemisphere to the Pacific
Decadal Oscillation (PDO: http://jisao.washington.edu/pdo/) or in the southern hemisphere to the El
Nino Southern Oscillation (ENSO: http://ww2010.atmos.uiuc.edu/(Gh)/guides/mtr/eln/home.rxml). We are
also aware, of course, of the fundamental shifts in climate brought about by the glacial cycles
operating on a time scale of thousands to tens of thousands of years. A much less-well
understood time scale of climate fluctuation is from centuries to millennia. It is our lack of
understanding here that leads to such vigorous debates about climate change and the role of
humans in contributing to it. But whatever the cause of climate change, we know that it occurs
and that rivers are among the natural systems that record such events.

Some regional vegetation changes can occur without climate change and forest fires represent a
common cause of abrupt but brief increases in the rainfall/runoff ratio and sediment yield in river
basins. But these are short-term transitional states and are probably unimportant in the longer
term (>10 years). Forest destruction by infestations such as the pine-beetle in western Canada
may be a longer-term effect but we are still learning about this impact.

Other long-term changes in the environmental controls on rivers include incision induced by
tectonic and eustatic processes. Tectonic effects (local uplift or tilting of Earth’s crust) on rivers
are evident at time scales of hundreds of years and beyond and eustatic (sea-level) changes are
evident in river estuaries at a time scale of centuries and beyond but only have expression further up the channel after thousands of years or longer.

Human activities also can have a profound influence on rivers and these range from direct effects (such as engineered river diversion and damming) to indirect effects related to landuse changes (such as deforestation and urbanization) and possibly to climate change.

2. River response to environmental change

Channel adjustments to these various kinds of environmental forcing are quite varied. The most important are considered below under the headings of (a) Continuous channel adjustment; (b) Underfit rivers; (c) River cutoffs (as indicators of hydrologic change); and (d) River metamorphosis.

Continuous channel adjustment refers to adjustments in channel width, depth, and slope along with meander wavelength and channel sinuosity that occur in a river without the complete transformation of the channel planform known as river metamorphosis. River metamorphosis (the transformation of a single-channel meandering river to a braided river, for example), as we will see below, is a less common, far more complex, less well-understood and therefore more difficult to predict.

We are a little less uncertain about the likely direction of the continuous change in channel morphology wrought by a change in local hydrology and/or sediment supply because we can draw on the empirical evidence that is the foundation of regional hydraulic geometry. These ideas were formalized by the American geomorphologist Stan Schumm in a seminal paper on channel change (Schumm, 1969) that remains our best guess at what to expect from a shift in climate/hydrology. His approach is based largely on data from sandbed streams in semi-arid and sub-humid regions of the United States and to a lesser extent on data from southeastern Australia. He assumed that $M$ (the percentage silt-clay in the channel perimeter) indicates not only the type of sediment load (bedload channels: $M \leq 5$; mixed-load channels: $5 < M < 20$; suspended-load or wash-load channels: $M \geq 20$) but also the quantity of bedload ($Q_{sb}$). So, if $M \propto \frac{1}{Q_{sb}}$, that
substitution can be made in his equations of channel change. Using a + or – sign to denote an increase or decrease, Schumm suggested the following channel responses (w = channel width, d = channel depth, (w/d) = channel form ratio, \( \lambda \) = meander wavelength, S = sinuosity and s = slope) to changes in discharge (Q) or bedload (Q_{sb}): 

\[
\begin{align*}
Q^+ & \rightarrow w^+, d^+, (w/d)^+, \lambda^+, s^- \\
Q^- & \rightarrow w^-, d^-, (w/d)^-, \lambda^-, s^+ \\
Q_{sb}^+ & \rightarrow w^+, d^-, (w/d)^+, \lambda^-, S^+, s^+ \\
Q_{sb}^- & \rightarrow w^-, d^+, (w/d)^-, \lambda^+, S^-, s^- 
\end{align*}
\]

(7.1) (7.2) (7.3) (7.4)

Of course, changes in discharge and sediment load rarely occur alone so four other more likely combinations of change are possible:

\[
\begin{align*}
Q^+ Q_{sb}^+ & \rightarrow w^+, d^+, (w/d)^+, \lambda^+, S^-, s^+ \\
Q^- Q_{sb}^- & \rightarrow w^-, d^-, (w/d)^-, \lambda^-, S^+, s^- \\
Q^+ Q_{sb}^- & \rightarrow w^+, d^-, (w/d)^+, \lambda^-, S^+, s^+ \\
Q^- Q_{sb}^+ & \rightarrow w^-, d^+, (w/d)^-, \lambda^+, S^-, s^- 
\end{align*}
\]

(7.5) (7.6) (7.7) (7.8)

Equation (7.5) tells us that the net effect of an increase in both discharge and bed-material load is to produce wider, less sinuous channels with a larger wavelength. The expected change in channel depth and slope are less clear but since the form ratio \((w/d)\) increases depth will remain constant or decrease. When both discharge and sediment load decrease, as might be the case downstream following construction of a new reservoir, the predicted channel responses are reversed.

When the changes in discharge and sediment load are in opposite directions channel responses are more complex. If the climate shifts to more humid conditions that increase discharge but encourages vegetation that might decrease the supply of sediment to the channel, equation (7.7) suggests that channels will become deeper and likely narrower with greater sinuosity and lower gradients. If the climate shifts to more arid conditions so that discharge declines while sediment loads increase, equation (7.8) suggests that channels may steepen by reducing sinuosity and become broader and shallower.
The fact remains, however, that equations (7.1) through (7.8) are simply guidelines to possible channel changes. We should be cautioned by the fact that many case studies of channel change have shown quite varied outcomes, apparently depending on the relative rates of change in $Q$ and $Q_{sb}$ and on the responsiveness of the channel to such imposed environmental changes, factors not accounted for in Schumm’s equations of channel morphodynamics.

One aspect of channel responsiveness that has confounded Canadian engineers and geoscientists in predicting channel change associated with river damming and diversion is the process of river-bed armouring. Bed armouring occurs when the fines are stripped out of the channel bed by competent flows leaving a veneer of imbricated and otherwise well-packed coarse gravel clasts that protect the finer alluvium beneath it from further erosion. There are a number of examples of alluvial spillways downstream of newly constructed dams that have initially been incised by outflows but have quickly been stabilized by this natural process of bed armouring. In other cases, armouring has not developed and post-construction maintenance has been required. The problem is that river scientists have not developed sufficient understanding of this process to predict when it will occur.

**Underfit rivers** are those that appear to be too small for the valley in which they flow. They are the only important class of misfit rivers and they come in two varieties: manifestly underfit streams and Osage-type underfit streams. Underfit rivers are rivers that have adjusted to a significant reduction in channel-forming discharge, and in the case of manifestly underfit rivers, the modern river meanders within a larger meander system representing the channel of a former larger river (meanders within meanders; see Figure 7.1).

The change in the scale of meandering is measured by the underfitness ratio ($\frac{L}{l}$). If we assume that the widely accepted empirical wavelength/discharge relationship for fully equilibrated meandering rivers applies to both the modern channel and to the former larger channel, we can say that:

since $l = 54q_{of}^{0.5}$ and $L = 54Q_{of}^{0.5}$, it follows that: $\frac{L}{l} = \left(\frac{Q_{bf}}{q_{bf}}\right)^{0.5}$ or $\frac{Q_{bf}}{q_{bf}} = \left(\frac{L}{l}\right)^2$. 

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Figure 7.1: Planform of a manifestly underfit stream with a modern channel (with meander wavelength, $l$) forming its sinuous course within a set of large valley meanders (with a large wavelength, $L$) inherited from a former phase of higher discharge. $L/W = 10$ and $l/w=10$ but $L/l >>10$.

That is, the ratio of the bankfull discharge of the former large channel to that of the modern channel ($\frac{Q_{bf}}{q_{bf}}$) is given by the square of the underfitness ratio.

Underfit rivers of the Osage type have an undersized modern channel that simply follows the thalweg of the former larger channel; they are named for the Osage River in central Missouri which exhibits this behaviour Figure 7.2 and 7.3). The present channel does not meander and the former channel might be straight or meander (like the example shown in Figure 7.3). In either case, however, it clearly is not possible to deduce an underfitness ratio based simply on comparative channel wavelengths. If it is possible to measure

Figure 7.2: The Osage River in central Missouri, USA. Google satellite image.
the bankfull width of the former channel (using drill cores or shallow GPR or seismic surveying to establish the former channel boundary) an index of underfitness can be formed by the relative widths of the modern and former channels \( \frac{W}{w} = \frac{L}{l} \). If that is not possible (as is almost always the case) the modern channel bankfull width and the former channel wavelength can be compared on the basis of an underfitness ratio deduced on the assumption that, in a fully equilibrated meandering channel, \( L = 10W \). Thus, \( \frac{L}{l} = \frac{W}{w} = \frac{L}{10w} = \sqrt{\frac{Q_{of}}{q_{bf}}} \).

![Figure 7.3: Planform of an Osage-type underfit stream with a modern channel (with channel width, w) forming its in-phase sinuous course within a set of large valley meanders (with a large wavelength, L and channel width, W) inherited from a former phase of higher discharge. L/10w>>10](image)

In the case of an underfit stream of the Osage type in which both the former and modern channel are straight, the simplest (but still difficult) way to calculate the reduction in bankfull discharge is to use the underfitness ratio, \( \frac{W}{w} \). A rather more reliable but much more data-intensive means of determining the underfitness ratio is to compare the pool-riffle spacing in the present and former channels. We know that pool-to-pool spacing \( (\lambda_{pp}) \) or riffle-to-riffle spacing \( (\lambda_{rr}) \) is equivalent to a half-wavelength in a meandering channel (see Figures 5.18 and 5.25) so again, we can say that:
\[
\frac{L}{l} = \frac{W}{w} = \frac{L}{10w} = \lambda_{pp} = \lambda_{rr} = \sqrt{\frac{Q_{bf}}{q_{bf}}},
\]
where the upper and lower case on the \( \lambda \) subscripts indicates the former and present channel, respectively.

The hydrologic change implied by regional river underfitness has been attributed directly to climate change in some regions and to waning glacial-meltwater runoff during the late Wisconsinan and early Holocene, in others. It is also recognized that river capture (also termed stream piracy - where expansion of a river system intercepts an adjacent stream network and diverts flow from one to the other basin) can achieve the same end in some local cases of river underfitness. River underfitness and its climatic implications are topics associated with the influential English geomorphologist George H. Dury who wrote extensively on underfit streams in the mid to late 1900s (see Dury, 1958, 1964, 1983, 1985).

**Stream cutoffs** are included in the discussion here, not because they are necessarily a river response to hydrologic change but rather because they can record such change. As meanders laterally migrate, meander loops occasionally meet, short-circuiting the channel to form a meander cutoff. These can be incorporated into a floodplain for long periods of time. We know that the downstream hydraulic geometry norms empirically link channel width to bankfull discharge \( (w = 5.4 Q_{bf}) \) so cutoffs provide a potential opportunity for reconstructing the bankfull discharge of the river at the time the cutoff formed (Figure 7.4). When this information is combined with time control on the cutoff event (established by dated aerial photographs or by carbon dating of the cutoff fill) on floodplains with many such cutoffs formed over a long period of time, there is a good basis for reconstructing a detailed record of the river hydrology. In Figure 7.4 we can see a reach of Mississippi River near Memphis, Tennessee in the United States that has a floodplain with cutoffs of various size and apparent age. This is the kind of environment that appears to be ideal for paleohydrologic reconstruction from cutoff morphology. Aerial photographs (or satellite imagery in this case) yield morphologic information about the former river planform and ground surveys (coring and geophysical surveys) can be used to determine the former cross-sectional area and shape of the river. One of the champions of this method who has contributed greatly to our understanding of the hydrologic and geomorphic history of the Mississippi River using in part the information recorded in meander cutoffs, is
Figure 7.4: The Mississippi River and floodplain near Memphis, Tennessee displaying a number of meander cutoffs of apparently varying age and size (Google satellite image).
River metamorphosis is the term applied to those cases in which river planforms exhibit profound change such as a complete switch from meandering to braiding, or vice versa. This notion of transformation is consistent with the perspective that there are planform stability domains such as those implied by Figure 7.5. For example, if a river is very close to the threshold defined by the line $s = 0.012 Q^{0.44}$ (such as the horizontal arrow in Figure 7.5) a slight increase in bankfull discharge (at slope = 0.001) would shift the channel form the meandering domain to the braided domain and vice versa. Such a change in bankfull discharge might easily be achieved by a slight change in precipitation or in basin vegetation. Similarly, a river with a bankfull discharge of $10\,000\,m^3s^{-1}$ (the vertical arrow in Figure 7.5) occupying a place very close to the threshold line might switch from meandering to braiding if the water-surface slope were to increase slightly, or vice versa. Such a local reduction in slope could be achieved in a meandering channel by the cutoff of one or more meander loops.

The idea of abrupt shifts in planform being related to small environmental shifts is an example of a threshold condition in geomorphology. One of the earliest statements regarding the potential
importance of such threshold condition for rivers was made by Schumm (1979) and the notion has been repeatedly offered as an explanation of certain kinds of abrupt river transformations, one of the most recent restatements being that by Phillips (2006). *Intrinsic thresholds* are those that are reached by the normal incremental evolution of a landform (such as sediment in a delta slowly piling up until it exceeds the angle of rest and abruptly fails) and *extrinsic thresholds* are those that see small environmental change push a landform from stability to instability (such as an small increase in discharge that causes a particle of sediment on the bed of a river to move).

The problem of applying these ideas on thresholds and planform domains as a predictive model, as we noted earlier, is that we do not know precisely the universal threshold conditions for the shift in channel pattern although it may be possible to build regional models.

There are numerous documented cases of river metamorphosis but one of the best known examples is the regional response to increased runoff of rivers in the American Midwest, particularly the case of the Cimmaron River. Schumm (1969) describes how the Cimarron River channel in southwest Kansas was transformed between 1914 and 1939 by a major flood in 1914 from a narrow (15 m) single-channel sinuous meandering river to a very wide (366 m) and straight bedload-dominated river channel.

Recently some river scientists have cautioned that river metamorphosis can occur without a change in regional controls such as climate and that river metamorphosis by itself should not be interpreted as a necessary indicator of general environmental change. For example, Brizga and Finlayson (2006) describe a shift in channel morphology (to a steeper, more incised, more sinuous and longer wavelength channel) on Thompson River in Victoria, Australia, that was caused simply by a channel avulsion. This view, that avulsion as a common cause of river metamorphosis, also has been recently restated by Schumm (2008).

There is some evidence to suggest that the lower Mississippi River may have been poised near a threshold for channel change (meandering to braided) before European settlement and that human activity may have moved the river into a new planform stability domain to which it is now trying to adjust (Biedenharn *et al*, 2000). Although there clearly have been landuse changes related to the replacement of natural forests by agriculture in the Mississippi Basin over the last
three centuries, by far the most significant impact on the river during the last century has been the engineered shortening of the lower Mississippi River by construction of artificial cutoffs.

After the catastrophic flood of 1927 on Mississippi River the American government launched the Mississippi River and Tributaries (MR&T) project designed to reduce flooding (in part by making the channel more efficient) and to improve navigation and commerce (in part by shortening the river). It was a massive engineering project orchestrated by the US Army Corps of Engineers and between 1933 and 1942 involved a series of major meander cutoffs between Memphis TN and Red River Landing, LA (Winkley, 1977, 1994). The river distance between these two locations was shortened by 30% from 885 km (in 1929) to 611 km (in 1942)! Since the period of cutoff construction the Mississippi River has experienced here an increase of 27-36% in stream slope and a related 20-38% increase in stream power (Biedenharn et al, 2000). As a result, locally increased bed-load transport and downstream-migrating sediment slugs have destabilized the channel (shoaling, bar deposition and bank erosion) at various locations that now require further engineering remediation. These morphologic responses have been interpreted by some to be the signs of crossing the threshold for river metamorphosis (a switch from a meandering channel to a braided channel) that can only be prevented by continued engineering intervention.

3. River terraces
Another very obvious geomorphic expression of disequilibrium in a river system is terracing. An alluvial river terrace is a former floodplain of a river that has for some reason been abandoned through river incision (or by avulsion and subsequent incision) so that it now sits above the contemporary floodplain (Figure 7.6 and 7.7).

Figure 7.6: A flight of river terraces at a channel confluence in Kazakhstan-Kyrgyzstan. Photo by Dr Michael Richter.
Figure 7.7: River terraces along lower Nicola River near Spences Bridge, British Columbia. Surface (A) is a remnant of a perched alluvial fan deposited by a tributary when the present Nicola River was less incised than at present. Surfaces (B), (C) and (D) are the tops of small terraces above the present floodplain (F). Google satellite image.

**Types of river terraces** include unpaired terraces, paired terraces, flights of terraces, or they may be nested (Figure 7.8). Within a valley a single phase of incision followed by vertical

**Figure 7.8**: Types of river terraces (T: terrace; R: river; F: floodplain) depicted as cross-sections within an alluvial valley fill: (A) a single unpaired terrace (T); (B) two remnants of the same former floodplain constitutes a paired terrace (T); (C): A flight of terraces (T1, T2, T3) formed by the river as it migrates to the right and experiences phases of incision; (D): A set of nested terraces (T1, T2...T5) implying a complex history of incision/aggradation cycles.
stability but continued lateral erosion by the river can leave a single unpaired terrace as shown in Figure 7.8A. The same scenario but with less active lateral erosion can leave former floodplain remnants on both sides of the valley, producing the paired terrace shown in Figure 7.8B. If the incision occurs in episodes while the river migrates across the valley floor, a flight of descending terraces such as those depicted in Figure 7.8C may form. This terrace-formation scenario is very common in the valley systems of British Columbia (see Figure 7.7). Figure 7.8D shows a set of nested terraces (terraces within terraces) implying repeated cycles of incision/aggradation. Of course the only way to distinguish the terrace flight from the nested terraces in Figure 7.8 would be to examine in the field the detailed stratigraphy of the deposits; morphologically, they may be identical.

**Causes of river terracing** include river incision by (a) negative sediment-budget; (b) tectonism; (c) base-level change; and (d) complex response effects.

*River incision by negative sediment budget* occurs wherever a channel is in disequilibrium in the sense that the sediment being removed from a reach by erosion is greater than the supply of sediment to the reach from upstream. In the long-term, sediment removal and supply are balanced in a river in equilibrium with its environment. But if a river competent to transport bed material is unable to derive an appropriate amount of bed-material from the upstream supply, it will mine the reach for it locally and in so doing will erosively lower the bed. We say that the river is incising. At various times during a year a river may *cut* or *fill* its bed but over the course of a year the cut and fill will balance out so that the average bed elevation does not vary much from year to year. If the cut and fill are in sustained imbalance we say that the bed is *aggrading* (fill > cut) or *degrading* (or incising: cut > fill).

Reasons for the disequilibrium state of the sediment budget are varied. In the long term we see the effects of the dramatic environmental impact of the glacial cycles. Because almost all river valleys in British Columbia experienced a very high rate of sediment supply from retreating glaciers at the end of the last glacial cycle (ending some 10 000 years ago), rivers aggraded and deposited thick alluvial valley fills. But eventually, several thousand years into the Holocene this once abundant sediment supply began to diminish as readily available sediment along the valleys was removed by erosion. Consequently rivers began to incise the valley fill as the local
sediment budgets became negative. Incision appears to have occurred in phases as the rivers worked across their valleys because the remnants of the old alluvial fill are terraced in the most spectacular fashion in most valleys in British Columbia.

In the shorter term (centuries to thousands of years) there are many factors that can lead to disequilibrium induced river incision. Short-term changes in climate have an immediate impact on rivers, particularly on the magnitude of formative discharge and on local sediment budgets. For example, recently completed research in the Department of Geography at SFU (Greg Bauch, MSc) has shown that the intensity of fall (September-December) storms moving across Squamish River basin north of Vancouver has quite dramatically increased over the last 50 years. As a result, annual peak floods have increased so that the rate of erosion (and deposition) in Squamish River has measurably accelerated over the same period. Along several long reaches this river is now eroding more material from its channel boundary than it is depositing; that is, the local sediment budget clearly is negative. If this state of water/sediment imbalance is sustained we can expect to see incision and new terrace formation in Squamish valley. We cannot be certain of the cause in the climate shift that has caused this increase in storminess but a likely candidate explanation is jet-stream oscillation over Hawaii that gives rise to the so-called pineapple-express weather events (http://en.wikipedia.org/wiki/Pineapple_Express) here in the Pacific Northwest.

Climate fluctuates on a range of time scale and longer-term events such as the Little Ice Age also had a marked influence on local glacier mass balance and therefore on runoff to rivers. The Little Ice Age is a cooler period marked locally by several valley-glacier advances in the 16th to 19th centuries following an earlier warm phase (the Medieval Warm Period). The most recent (in the mid 1800s) in the Coast Mountains of British Columbia is clearly in evidence in most river valleys. The maximum advance of valley glaciers is marked by terminal moraines on the valley floors and by lateral moraines, kame deposits and trim lines along the valley walls. Runoff fluctuations and varying sediment supply almost certainly impacted the sediment budgets of rivers and may have resulted in terracing in some valleys.
Sediment budgets in rivers can also be changed more directly by impacts at the basin level that affect the hydrology of the river. As noted in the *Introduction* to this chapter, these impacts include natural changes such as those related to forest fires and to other natural disturbances to forest cover (pine-beetle attacks). Human-induced changes to drainage-basin properties include landuse changes (deforestation, overgrazing, and urbanization). More direct impacts still by human activity include the damming of rivers, interbasin diversion of river flow, and withdrawal of river flow for irrigation and other water-supply purposes.

It has long been recognized that the conversion of natural basins to various landuses such as agriculture and livestock grazing can cause increased runoff and river incision and gullying (Happ et al, 1940; Leopold, 1956; Strahler, 1956). Indeed, in the United States there is a long history of government agency remedial programs to deal with soil loss through gullyling and downcutting of rural streams. Considerable controversy continues to accompany the debate, however, about whether such regional changes in river systems in the U.S. (and elsewhere) are the result of European settlement or of accompanying climatic change (Knox, 2006).

The effects of deforestation on runoff of water and sediment to rivers are also well studied. In general, forest removal allows water from precipitation to reach rivers sooner and discharge peaks are increased. These effects are particularly evident if more than a third of the natural forest cover is removed. Sediment supply to rivers can also be increased by logging although this seems to be more related to the construction of logging roads than it does to the actual stripping of the forest.

Urbanisation also has obvious hydrologic effects because the natural hydrology is so fundamentally disrupted. In short, the construction of impervious surfaces (such as roads and parking lots and the roofs of buildings) together with the introduction of storm sewers, lead to water running off the land to rivers far faster than it would do so naturally. Flood hydrograph peaks are exaggerated and lag times are reduced.

Enough is now known about the operation of the hydrologic cycle in river basins that increases in runoff under various landuse scenarios is routinely modeled numerically as a planning tool to obtain forecasts of the related change in river discharge (for example, see Li *et al*, 2007).
Dams on rivers constitute the most direct human interference with rivers and they certainly have a profound impact on the rivers concerned (Collier et al., 1998). A number of British Columbia’s rivers were dammed in the 1950s as part of a major hydro-power development scheme orchestrated by BC Hydro. The Peace and Columbia Rivers were especially impacted. Interestingly, Fraser River escaped with just one major dam: the Kenney dam on the Nechako River, a tributary that joins the Fraser near Prince George.

Peace River below Bennett Dam has significantly contracted and the former high annual peak channel-forming flows no longer occur. As a result, since the dam was completed in 1967 much of the former river channel has infilled with sand bars, now becoming vegetated. Many tributaries are incising near their confluences with Peace River because their local base-level has dropped. Large fans at tributary confluences are no longer eroded away each year during the spring freshet and instead are becoming vegetated and represent a local mechanism for contracting the channel boundary to better reflect the current reduced flow regime (Figure 7.9).

Figure 7.9: The large alluvial fan formed where Beatton River meets Peace River is slowly becoming a vegetated permanent feature of the channel Google satellite image.
Dams obviously reduce flows downstream and trap virtually all the sediment being transported by the river. Downstream of dams rivers contract but also being deprived of sediment they will often incise leaving the former pre-dam floodplain as a terrace (Petts, 1979, Church, 2006). River dam schemes often include river diversions that see some basins deprived of flow and others enhanced. The geomorphic consequences of such projects are complex and difficult to predict but river incision and terrace formation have been documented in a number of cases (Kellerhals, et al, 1979).

Irrigation schemes with or without dams are notorious for contracting rivers and altering the natural water-sediment balance. Former floodplains are left stranded well above the present river and as such become terraces. An area that has been greatly impacted by the withdrawal of water from rivers for irrigating crops is the central Great Plains in Nebraska that is drained by the Platte River (Figure 7.10). The once almost mile-wide (1-2 km) channel has been reduced to 50-100 metres or so today because of the demands of irrigation (Nadler and Schumm, 1981).

Figure 7.10: South Platte River today is a very small stream flowing within the far broader and now vegetated swath of fluvial sediments once active in the former pre-irrigation channel. Google satellite image.
A similar but perhaps less spectacular example is the Thompson River in British Columbia that is the source of irrigation water for agricultural crops along that valley and has seen flows significantly reduced in recent decades.

*River incision by tectonism* is something that most of us are familiar with as a process occurring on a broad regional scale and operating over long periods of geologic time. Perhaps the most spectacular example is this type of fluvial response is the incision of the Colorado River into the Colorado Plateau to form the Grand Canyon (Figure 7.11). But tectonism can also be an

![Figure 7.11: Colorado River at the base of the Grand Canyon, Arizona: six million years of river incision.](image)

an important control of channel incision at much smaller space and time scales. Tectonism in the style of local folding or doming can cause terracing where uplift cuts across the longitudinal profile of a river (Burnett and Schumm, 1983; Ouchi, 1985). If the river is able to maintain its
slope by incising it becomes *antecedent* and slowly abandons slowly abandons its former channel as a terrace (Figure 7.12). Examples of rivers being influenced in this way by active tectonics in the U.S. include the Middle Rio Grande in New Mexico, and the Guadalupe and San Antonio Rivers in the Texas Coast region (Ouchi, 1985). Many rivers in Canada are influenced by regional tectonism related to the isostatic rebound of the land as the glaciers retreated at the end of the last glacial cycle. Some rivers may have experienced channel pattern changes because of isostatically-induced changes in the regional slope. For example, the lower Attawapiskat River in northeastern Ontario has developed an anastomosing channel pattern where it traverses the low gradient Hudson Bay Lowland, a region still rising at about 7 mm/year (King and Martini, 1984). In British Columbia many of the terraces in the major valleys of the Fraser River system likely are the result of river incision following isostatic rebound.

*River incision by base-level change* is another common mechanism of terrace formation although it tends to be most important near coastlines where the processes of channel adjustment are most intense. A fully adjusted equilibrium river profile takes the form of a concave-upward semi-logarithmic profile that is asymptotic (graded) to base level (see Figure 5.10). Base level may be the main channel for tributaries or it may be a lake or the sea for rivers flowing to a water body. Base-level change most commonly expresses itself through a lowering of relative sea level because coastlines are continually adjusting to environmental change. By *relative change in sea level* I mean the level of the sea with respect to the land. In this context a river responds the same way whether the land goes up (because of tectonics, especially isostatic adjustments) or the sea level falls (because of eustatic causes such as the coming and going of
continental ice caps). Whatever the cause, the resulting increase in the overall slope of the river leads to channel incision, leaving the former floodplain as a terrace (Figure 7.13). If channel adjustment takes the form of vertical incision along the entire longitudinal profile the former floodplain is left as a terrace along the entire valley (Figure 7.13A). But longitudinal profile adjustments commonly are more complex than this simple response. Channel slope adjustments to a lowered sea level may require steepening in the downstream reaches but less slope in the headwaters if, for example, accompanying climate change results in a smaller calibre of bed material being supplied to the river. In Figure 7.13B the former floodplain actually crosses the new river profile now graded to the lower sea level. The headwaters experience aggradation that buries the old floodplain beneath the aggrading alluvial fill and the downstream reaches experience incision, leaving the former floodplain as a terrace.

![Figure 7.13: Schematic illustration of channel responses to a drop in sea level](image)

*Figure 7.13: Schematic illustration of channel responses to a drop in sea level (A) a river vertically incises leaving the former floodplain above a new longitudinal profile graded to a lower sea level. (B) A river vertically incises in the lower reaches but aggrades in the headwaters; the former floodplain in the headwaters is buried beneath the aggrading fill and downstream it is left as a terrace. (C) A transient state of (B) in which the channel profile adjustment is by headward erosion of a knick point.*

The new longitudinal profiles in Figures 17A and B represent the ideal end-point of the adjustment process that occurs by vertical incision. But we know that in many cases, the profile adjustment process occurs first in the oversteepened reach of channel closest to the fallen base level and works its way upstream by backwearing. We see this for example, on Peace River, where tributaries have initially steepened the slope of their channels near to the confluence. This
oversteepened reach lengthens by backwearing of a knick-point along the river profile to reestablish the equilibrium slope regime. The knick point may take the form of a steep reach, or in the extreme, a waterfall may mark the abrupt transition between the new longitudinal profile and the former surface upstream (Figure 7.13C).

Although geomorphologists have attempted to use the extrapolation of the longitudinal profiles of rivers to reconstruct former levels of the sea, the task is a daunting one because sea level tends to fluctuate more rapidly than even a small river system is able to fully respond to the changes. In consequence river profiles often contain transient and incomplete responses to particular sea-level changes.

*River incision by complex response* refers to the non-linear river responses we see induced by environmental change. In particular, we here focus on the “waves” of knick point backwearing that occur within a drainage network in response to a single change in base-level. Because each stream channel acts as the base level for its tributaries, a single drop in base level may cause a knick point to migrate upstream and as it passes each tributary confluence it initiates a new wave of incision (and terrace formation) that in turn migrates upslope along the tributary valleys and in turn initiates further incision in their lower order tributaries, and so on. This adjustment process is further complicated by the fact that vigorous incision in a tributary immediately above a confluence can generate such large amounts of bed-material transport that aggradation may occur in the lower-slope main channel downstream of the confluence! Thus, incision may be followed by aggradation which may be followed by incision as local sediment budgets switch back and forth between negative and positive states; it is indeed, a *complex response*!

Complex response means that, after a single base-level drop simultaneously affecting two adjacent basins, a wave of backwearing initiated at the same point in time can commonly move through two such basins with quite different consequences for the location, timing and type of terrace formation because the drainage networks are not identical. For this reason, among some others, interpreting environmental change from terraces is difficult at best and seeking morphologically-based correlations among terraces within valleys is a challenge and among
Terraces between valleys is almost impossible without additional evidence such as independent chronological control.

**Interpreting river terrace history**

The study of terraces in geomorphology has a long history and it is not our purpose here to review the huge literature on this subject although Knighton (1998: 270-274; 281-2 and 324) is a good place to start if that is what turns your crank. Instead we will concern ourselves with the principles and problems of interpreting river terrace history.

*Terrace correlation* within a single valley can often be achieved on the basis of terrace-surface continuity. Even if much of the former floodplain sediments have been eroded away, the discontinuous flat tops of valley-fill remnants in the valley may be provide a basis for reconstructing the longitudinal profile. In the simplest case of a single incision event and one terrace, it may be possible to reconstruct the former floodplain surface throughout the drainage network.

But nature is rarely so co-operative and the more common situation is the presence of several river terraces in a valley. If the terraces are well separated in elevation and parallel throughout the valley the problem of reconstructing the longitudinal profiles of terraces on the basis of morphological continuity may be straightforward. If the terrace elevations are close together and both are not always present in the valley the problem of recognizing terrace surfaces becomes more challenging and even more challenging if the surfaces are convergent along the valley and eventually cross (see Figure 7.13C). In these cases where morphological separation of terraces becomes ambiguous other evidence must be employed to distinguish one terrace level from another.

In some cases a terrace surface along a valley can be distinguished from others on the basis of some signature property such as (a) sediment calibre; (b) sediment provenance; (c) soil formation; (d) marker beds; and even (e) vegetation.

*Sediment calibre* may significantly vary between terraces if the competence of rivers forming the respective former floodplains differed. For example, some terraces may contain abundant gravel while others are formed of sands. *Sediment provenance* refers to the source from which
sediment was derived. For example, if much of the sediment found in a particular terrace was
derived from a tributary basin formed in basic volcanic rocks (such as a basaltic lava flow) it
may be distinguished from other terraces that were derived mainly from sediments sourced
elsewhere in a different lithology. Soil formation can be an indicator of relative age. For
example, if terrace sediments display well-formed soils (pronounced leaching with well-defined
soil horizons) while others do not, soil properties become a basis for identification of the terrace
surface along the valley. Marker beds are simply some distinctive property of the terrace
sediments that distinguish it from others. These might include unusually elevated levels of
charcoal related to a forest fire or to a thin bed of volcanic glass caused by a dusting from a
volcanic eruption or the collapse of a nearby volcanic cone. Recent incision (over the last
century) has been recognized because of the strontium-90 that settled out of the atmosphere
during the era of atomic weapons testing in the atmosphere in the 1950s. Vegetation can be a
very sensitive indicator of small differences in nutrient supply or drainage and as such may
preferentially grow on a particular terrace surface.

Chronological control of some sort is essential for making terrace correlations between
valleys. These dating methods include carbon dating, optical dating and cosmogenic dating.
Carbon dating measures the amount of carbon-14 left in carbonaceous material from once living
organisms (commonly plants and shells). When a plant dies the carbon-14 content matches that
of the atmosphere but after plants die or are consumed by other organisms (for example, by
humans or other animals) the \(^{14}\text{C}\) fraction of this organic material declines at a fixed exponential
rate due to the radioactive decay of \(^{14}\text{C}\). Comparing the remaining \(^{14}\text{C}\) fraction of a sample to that
expected from atmospheric \(^{14}\text{C}\) allows the age of the sample to be estimated. Carbon dating is
commonly used to date material in the 100-40 000 years range although it can be pushed back to
60 000 years in ideal circumstances.

Optical dating (or optically stimulated luminescence - OSL – dating) is a method for
determining how long ago minerals (usually quartz) were last exposed to sunlight. All alluvial
sediments contain trace amounts of radioactive isotopes such as uranium, thorium, rubidium and
potassium and these slowly decay over time yielding ionizing radiation that is absorbed by quartz
and feldspar. The resulting radiation damage within these minerals remains as structurally
unstable electron traps within the mineral grains. Stimulating samples of quartz using infrared light causes a luminescence signal to be emitted as the stored unstable electron energy is released, the intensity of which varies depending on the amount of radiation absorbed during burial. The radiation damage accumulates at a rate over time determined by the amount of radioactive elements in the sample. Exposure to sunlight resets the luminescence signal and so the time period since the sediment was buried can be calculated.

Cosmogenic dating is based on cosmogenic isotopes created when elements in the atmosphere or earth are bombarded by cosmic rays that penetrate into the atmosphere from outer space. Some cosmic ray particles reach the surface of the earth and contribute to the natural background radiation. Cosmic rays interact with silica and oxygen in quartz to produce measurable amounts of the isotopes Beryllium-10 and Aluminium-26. The accumulation of these isotopes within a rock surface can be used to establish how long that surface has been exposed to the atmosphere. Assuming a constant rate of production, the number of atoms of Be-10 and Al-26 that accumulate in a rock surface will be proportional to the length of time the rocks were exposed to cosmic ray bombardment and the respective rates of radioactive decay for each isotope. An age determined by measurement of the amount of each nuclide is an estimate of the minimum time that the particular surface had been exposed. Exposures of surfaces a few thousand to about 10 million years old can be dated by the measurement of the Be-10 and Al-26 isotopes.

There are other ways to obtain absolute dates on terrace sediments (for example, archaeological artifacts and pollen content matched to known vegetation history) but these three methods of dating outlined above are by far the most important at present.

4. River management and restoration

As we noted in Chapter 1, rivers are among the world’s great biophysical treasures and they literally sustain life on our planet. Humans have made use of rivers for as long as they have walked the Earth and that history is too well in evidence in many places. We now realize that much of that river use is actually river abuse and this new environmental awareness of the importance of rivers has spawned an industry devoted to their maintenance and rehabilitation. Indeed, Vancouver is a centre for consulting companies specializing in remediating the
environmental impacts on rivers, especially in the mountain environments of our coastal streams where logging is practiced.

River restoration as a subdiscipline now supports a number of professional journals (for example, *Aquatic Conservation, Journal of Applied Ecology, Ecology, Environmental Management, Freshwater Biology, Regulated Rivers: Research and Management, Restoration Ecology, River Research and Applications*) and a number of influential books specifically addressing issues relating to river restoration such as Rosgen and Silvey (1996) and Brierley and Fryirs (2005).

One of the interesting issues facing those who are attempting to restore rivers is the question: restoration to what? Rivers change over time and what represents a natural state is often not entirely clear. Furthermore, the natural state is not necessarily a desirable state for all things. For example, in Australia many of the inland rivers (in the Murray-Murrumbidgee river system) were clogged with large woody debris in their natural state and these were cleared for navigation and flood-control purposes during the early phase of European settlement. For over 200 years these rivers have existed in their present state supporting an ecology fully adapted to the rivers as they are today. Should they be restored to their former natural woody-debris choked state? Some argue that they should because that state represents a valuable lost natural riverine and riparian ecology that should be restored. Others argue that such a restoration represents change but not necessarily improvement.

But there are many more straightforward cases where restoration of a river to a natural state does represent an unequivocal improvement over the existing conditions. In all these exercises of stewardship it is our understanding of the way the natural fluvial system works that must be the foundation any management program.

**5. Some further reading**

If you feel that you would like to read further in the area of channel change you might try the following section in Knighton (1998):

Other sources cited in this chapter are:


