DEMYSTIFYING DAM REMOVAL

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> The Report of the World Commission on Dams (WCD 2000) specifies that negative influences of water dams on the environment exceed the positive results. In many cases, dams have led to a significant and irreversible loss of species and ecosystems, and efforts to mitigate these impacts have often been unsuccessful.
>
> Pg. 142, Kornijów, 2009

Review of the impact of dam decommissioning on riverine ecology

To better understand the impact of a dam to the riverine ecology, an understanding of the mechanics of a free flowing river is required. At its simplest, a stream transports both water and sediment and it is the relationship between these two variables that determines the equilibrium (or graded) channel characteristic.

> *The graded stream is one in which, over a period of years, slope is delicately adjusted to provide, with available discharge and with prevailing channel characteristics, just the velocity required for the transportation of the load supplied from the drainage basin. The graded stream is a system in equilibrium; its diagnostic characteristic is that any change in any of the controlling factors will cause a displacement of the equilibrium in a direction that will tend to absorb the effect of the change.*
>
> (Mackin, 1948)

A change to either of these two factors (variation in flow rates or natural phenomena such as landslides or slumping), causes the stream to adjust as it re-establishes this balance. This is achieved through either degradation (erosion) or aggradation (deposition). A dam impacts both the water's flow rate and the sediments transported within the stream. With dam removal, the stream undergoes the process of re-establishing itself as the sedimentation in the reservoir has likely increased the height of the streambed compared to the original elevation of the river maintained downstream from the dam. From a watershed perspective, a stream's equilibrium can also be influenced by any landuse change from forest to cropland or urban development or vice versa. Landuse changes can introduce variations in intensity of stream flow and impact the quantity and quality of sediment present in a stream transported by overland flow.

Rivers are a complex combination of ecological factors and physical components. The movement of materials downstream from the head waters of the river to its mouth is characterised by the grade of the stream and the surrounding materials. These characteristics can be used to predict the impact a dam has on a river and what factors need to be considered should that dam be decommissioned. This review explores the ecological impact of dams on river networks and the literature on dam decommissioning is summarised so that the various concerns associated with dam removal can be examined.

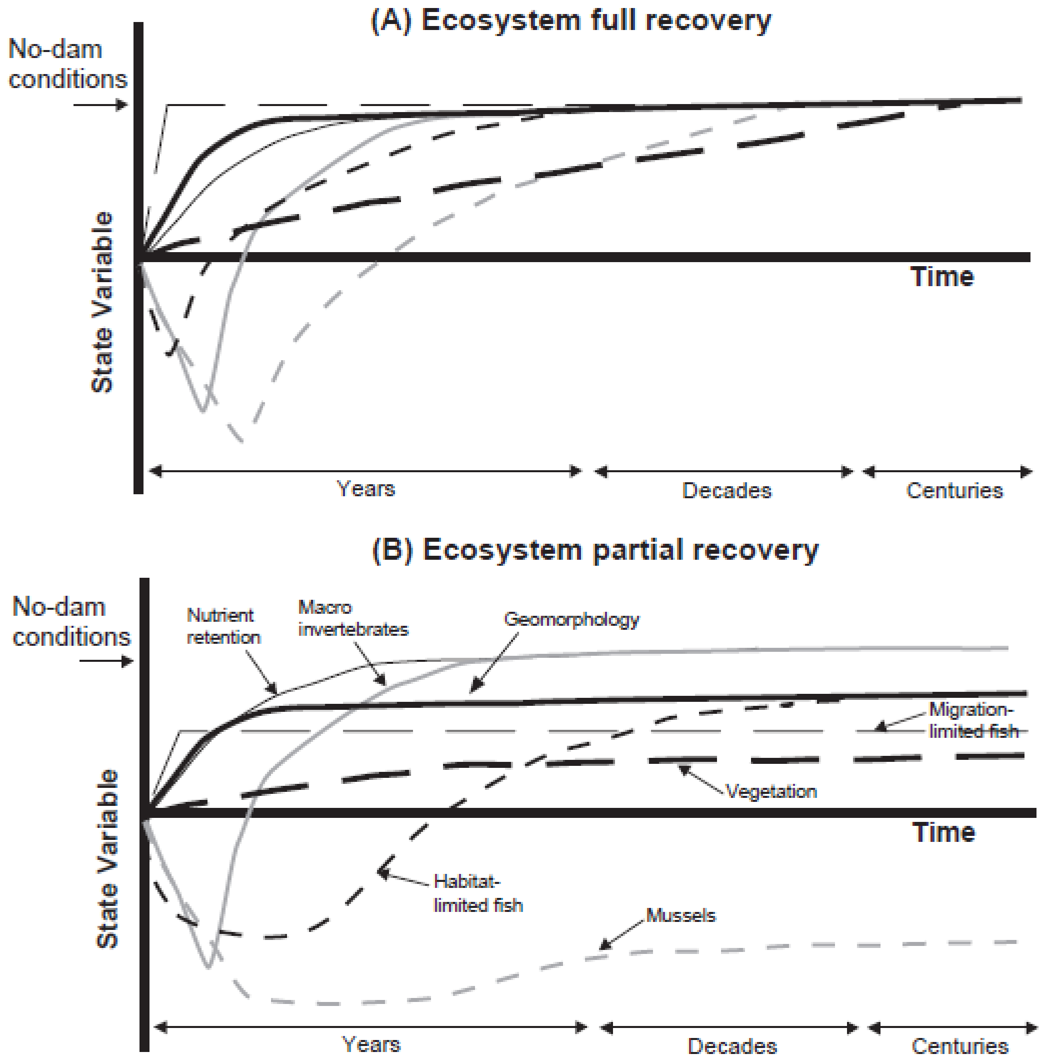
Ecological Factors

There are a number of ecological factors impacted when the movement of water within a river is restricted (Poff and Hart, 2002). The severity of the impacts is often associated with the size of the dam, however even small dams can have adverse effects as small changes impact the ecology of the river (Poff and Hart, 2002). The alteration to the flow of water and sediment changes the availability of nutrients to various organisms within the river downstream and impacts aquatic and riparian habitat (Graf, 2005, and Poff and Hart, 2002). The change in the sediment budget can result in the stream bed downstream of the bed becoming incised and isolated from the riparian habitat as well as the armouring of the bed material as fine sediment is removed (Graf, 2005, and Poff and Hart, 2002).

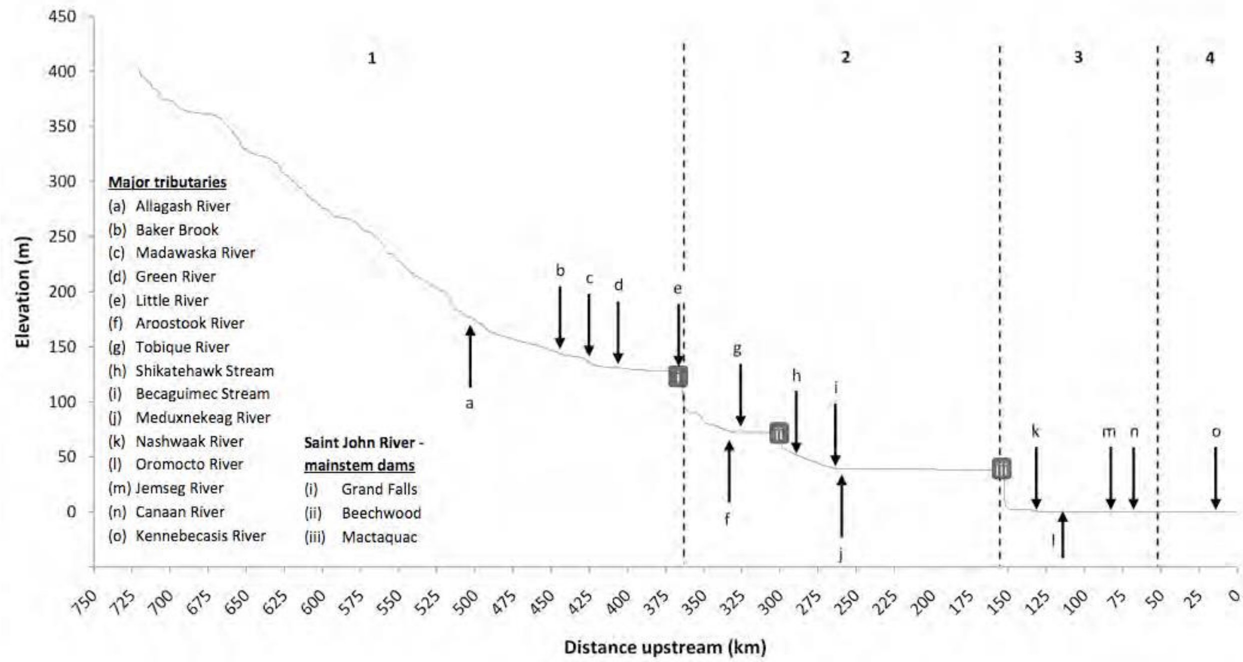
The barrier created by the dam also restricts the flow of organisms and nutrients limiting their spatial range and influencing the type of organisms present (Poff and Hart, 2002, and Kidd, Curry, and Munkittrick, 2011). Nutrients move downstream passively in the current of the river and actively upstream as organisms and fish migrate up the stream channel and contribute to the nutrient load (video by SG About lamprey). Riverine ecosystems are also sensitive to water temperature fluctuations. The temperature difference between the water stored in reservoirs compared to the water downstream from the dam can impact the organisms and their vitality rates (Poff and Hart, 2002). Changes in the flow regime impact the fish present as river species prefer cooler, fast flowing (lotic) water as opposed to species which prefer still (lentic) water such as reservoirs and lakes. Dam removal has demonstrated that fish species in the reservoir area quickly shift back to lotic from lentic species (Hart et al., 2002) in some instances this shift happened within a day of the barrier being removed though, more commonly, fish return to the upper reaches of the river during the following migration season (that year or the following one).

> (a) [Dams] alter the downstream flux of water and sediment, which modifies biogeochemical cycles as well as the structure and dynamics of aquatic and riparian habitats.(b) They change water temperatures, which influences organismal bioenergetics and vital rates. (c) And they create barriers to upstream–downstream movement of organisms and nutrients, which hinders biotic exchange. These fundamental alterations have significant ecological ramifications at a range of spatial and temporal scales.
>
> pg. 660, Poff and Hart, 2002

> Another oxygen issue in the Saint John River is related to water temperature. When river temperatures rise, oxygen levels drop. River water becomes warmer when reservoirs are created by dams. In the Saint John River downstream of the Beechwood Dam, river levels in summer can vary by 1-2 m and water temperatures can vary as much as 7^{o}C in a day compared to 1^{o}C upstream of all the main stem dams. Cold- and cool-water fish in the river are most likely stressed by the warmer, low oxygen waters, conditions which also promote survival and expansion of non-native fish, and this temperature-oxygen problem will increase as our climate continues to warm.
>
> pg. 84, Kidd, Curry, and Munkittrick, 2011



Conceptual framework for ecosystem recovery following removal of a small dam. Full ecosystem recover assumes that all components of the stream ecosystem return to pre-dam conditions, but at variable rates of recovery. Partial ecosystem recover assumes that some components recover to pre-dam conditions, but that others only partially recover while still others are actually damaged by dam removal and not able to recover at all. Pg 239, Doyle et al., 2005.



Elevational profile of the Saint John River from the headwaters to the river mouth. Arrows indicate location of major tributaries; squares represent location of main stem hydroelectric dams. Vertical dashed lines show divisions between the four study reaches. Pg. 64, Kidd, Curry, and Munkittrick, 2011.

Flow rates

The benefits of dams are usually derived from their control of the volume of the water passing over or through the dam. Power generation is among the principle benefits but dams are also built for drinking water supply, irrigation and flood control, all of which limit the fluctuations in a river's natural flow regime. For example, storage dams often draw down their reservoirs before rainy seasons beginning, effectively changing the downstream flow regimes by increasing the flow before the rainy season begins and limiting the volume of water released during the period which characterised by high water levels (Poff and Hart, 2002). Numerous species have adapted to the variation in flow regimes such as seed dispersal of riparian vegetation and triggers for fish migration (Kidd, Curry, and Munkittrick, 2011, and Poff and Hart, 2002). These changes in flow regime can result in species being unable to take advantage of these events. For example, the migration of juvenile anadromous fish is aided by spring floods which help the fish drift downs stream within the short period of time it takes for them to transition from freshwater fish to fish that can survive in saline ocean water. The presence of reservoirs and the lack of sufficient flow slows this process which are fatal to smolts that are trapped upstream (http://www.internationalrivers.org/dams-and-migratory-fish, and Kidd, Curry, and Munkittrick, 2011).

> The downstream migration of the juvenile salmon, or smolts, can be fatally delayed by the time needed to drift and swim through multiple reservoirs — if the smolts do not reach the sea within around 15 days after spawning they may lose their downstream swimming behaviour and their ability to switch from a freshwater to saltwater environment. During years of relatively low flow, smolts from the upper Snake River, the

Columbia's main tributary, can now take up to 39 days to swim to the sea, compared with less than three days before the dams were built.

http://www.internationalrivers.org/dams-and-migratory-fish

As flow is reduced and disappears in the reservoirs, salmon smolts appear to lose their orientation and downstream movements stop. In the Mactaquac Dam’s reservoir, up to 100% of tagged migrating smolts that entered the reservoir failed to find the downstream exit. Delays of lesser magnitude were also detected in the other reservoirs upriver.

p.64, Kidd, Curry, and Munkittrick, 2011

Flow rates determine the volume of water in the river which, in turn, influences the temperature of the water. Low flow rates result in lower water levels and a reduction in the transport of sediment and nutrients, as well as an increase in water temperature which reduces the available oxygen in the water (Kidd, Curry, and Munkittrick, 2011). Furthermore, low water levels reduce the width of the main channel, isolating the river from the floodplain, and restrict the access of fish to riparian habitat. (Poff and Hart, 2002)

Tributaries and islands also impact the characteristics of the riverine ecology. Along the Saint John River, there are four tributaries which contribute cold water plumes that provide refuge for fish during periods of low flow during the summer months. Additionally, groundwater discharge within the Saint John River has been located is some areas, such as between islands within the main channel. Islands also contribute to the variety of fish habitat available within the river through additional variation in shoreline and river bed composition. While the islands submerged in the headpond may contribute to fish habitat in some capacity, it is unlikely that they could provide the same richness of fish habitat as the shorelines and present before inundation.

Islands are common in the river. They provide unique and significant habitat complexity in terms of flow refuge zones, increased littoral (shoreline) habitats, and ultimately, increase the habitat complexity along the river. River islands are also important as stepping-stone habitats for the movement and colonization of river corridors. Thus, any alteration or reduction of these riverscape features may affect their contribution as [fish] habitat.

Pg. 65, Kidd, Curry, and Munkittrick, 2011

Reach	**Tributaries**
1	Big Black (L), Little Black (L), Allagash (R), Francis (L), Fish (R), Madawaska*(L), Baker (L), Green*(L), Quisbis (L), Grande (L)
2	Little (L), Salmon (L), Aroostook*(R), Tobique*(L), Monquart*(L), Shikatehawk (L), Big Presquile (R), Little Presquile (R), Eel (R), Meduxnekeag (R), Becaquimec (L)
3	Keswick (L), Nashwaak (L), Oromocto (R), Jemseg (L), Canaan (L)
4	Nerepis (R), Kennebecasis (L)

Tributaries ≥ order 3 located in the four reaches of the Saint John River. Bracketed letters refer to the river-side of entry of the tributary. Asterisks refer to tributaries with man-made barriers in their lower reaches. Shading indicates cool water sources. From Kidd, Curry, and Munkittrick, 2011

Sediment

Streams transports both water and solids in the form of sediment and dissolved minerals. When a dam is constructed, the flow of water is restricted, reducing the river's velocity and causing deposition of sediment to occur within the reservoir area. This has two impacts on the quantity of sediment transported; sedimentation of the reservoir and a reduction of sediment flowing to the river downstream of the dam resulting in the armouring of the stream bed (Graf, 2005). Sediment which would typically satisfy the stream's capacity is deposited upstream of the dam in the reservoir when the velocity slows. Once the stream passes through the dam, its velocity increases along with its carrying capacity and the stream bed is therefore vulnerable to degradation.

The build-up sediment in the reservoir can be difficult to quantify and to anticipate how it will move downstream once the dam is removed. The type of river and the characteristics of the sediment transported can affect how quickly sediment deposited within the reservoir is transported from the area (Burroughs et al., 2009). Sediment within the stream channel is transported more quickly than the sediment deposited along the stream bank and therefore the sediment within the stream path will be transported first (Burroughs et al., 2009).

For smaller dams, the volume of sediment transported following its removal, may be approximate to the stream's annual budget resulting in fewer ecological impacts. Flood waters transport smaller sediment from the riparian areas, and for small gravel-bed rivers, the volume of sediment may be rather minimal (Burroughs et al., 2009). However, larger dams, due to their greater height and larger reservoirs, have additional concerns regarding the volume of water and sediment to be released. The sudden removal of a dam results in a large volume of water to move quickly downstream. The velocity of the water increases dramatically, increasing the stream's capacity to transport sediment and the turbidity of the water. This can have devastating consequences on the downstream fish populations and ecology and result in flooding and damage property downstream. Therefore it is more common that the reservoirs of large dams are drawn down slowly overtime. This is achieved by increasing the volume of water to flow through the gates or by partially removing the top of the dam to allow it to be breached in a controlled manner. This technique also reduces the amount of sediment transported since the volume of water released is increased slightly over a prolonged period. As well, the draw down occurs by creating notches along the top of the dam, so the water at the top of the reservoir would be released leaving the bottom of the reservoir and the sediment deposited there largely undisturbed until later in the dam removal process. The slow draw down of the reservoir can also allow for the banks to re-vegetate slowly, stabilizing them as they become exposed.

Initial analysis of the Mactaquac dam headpond indicates that not much sediment has accumulated – approximately half a metre in most areas, with upwards of 6m in a few places – and the main river channel and islands appear to be in place and relatively unchanged (correspondence with Simon Mitchell August 26th 2014). While it is difficult to predict the stream's path post removal (Graf, 2005), the apparent lack of significant sedimentation upstream form the Mactaquac dam would likely result in the river returning to its previous path, especially in areas that had steep stream banks pre dam, as documented in images obtained from the Provincial Archive of the pre-dam assessments. Additional considerations is that the Beechwood Dam, 150km upstream, has greater control on the flow of the Saint John River (Kidd, Curry, and Munkittrick, 2011), and therefore, it may take some time for riparian zones to be fully re-established if persistent low flows occur.

> Another important consideration is the spatial scale of geomorphic adjustments, i.e., how far upstream and downstream the impacts of dam removal are evident. Based on previous studies of geomorphic response to analogous disturbances (e.g., Simon, 1992), geomorphic response to disturbance should be most evident directly adjacent to the dam removal, and then decrease exponentially with both distance and time.

Pg.229, Doyle et al., 2005

> The majority of sediments stored in the former reservoir remained in place, with only 12% of the estimated reservoir sediment fill being eroded. Approximately 14% of the net erosion was deposited within the stream channel 1 km downstream of the dam location, with the remainder being transported further downstream or deposited in the floodplain

Pg.92, Burroughs et al., 2009

> In general, greater amounts of erosion occurred closer to the [Stronach] dam site with the magnitude of erosion attenuating upstream. During the first several years of the removal [in 1997], erosion progressed upstream only through the easily recognizable former reservoir (1.21 km), and it was not until 2001–2002 that net erosion was documented at the farthest upstream extent of the original impoundment, 3.89 km from the dam.

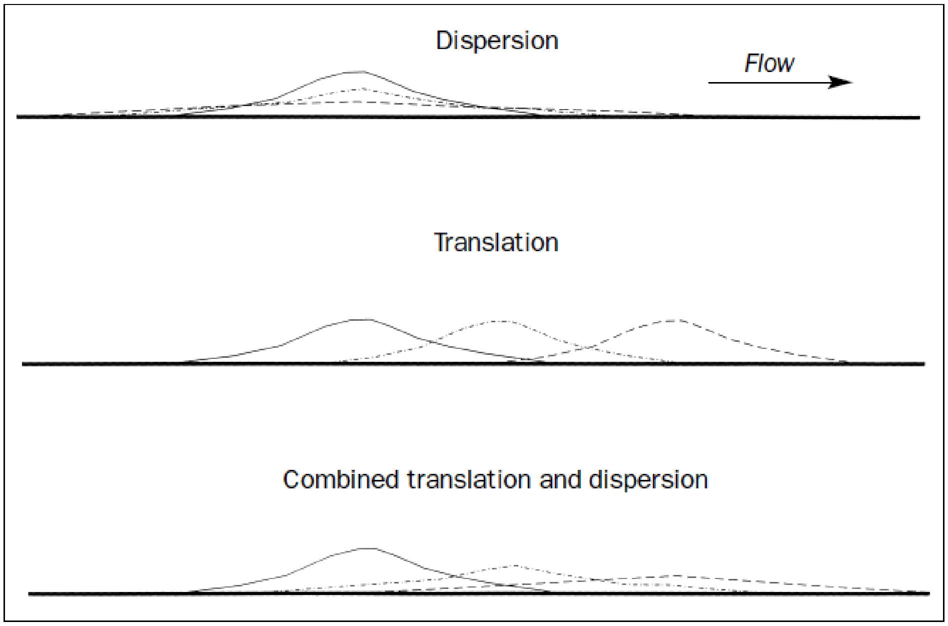
p101, Burroughs et al., 2009

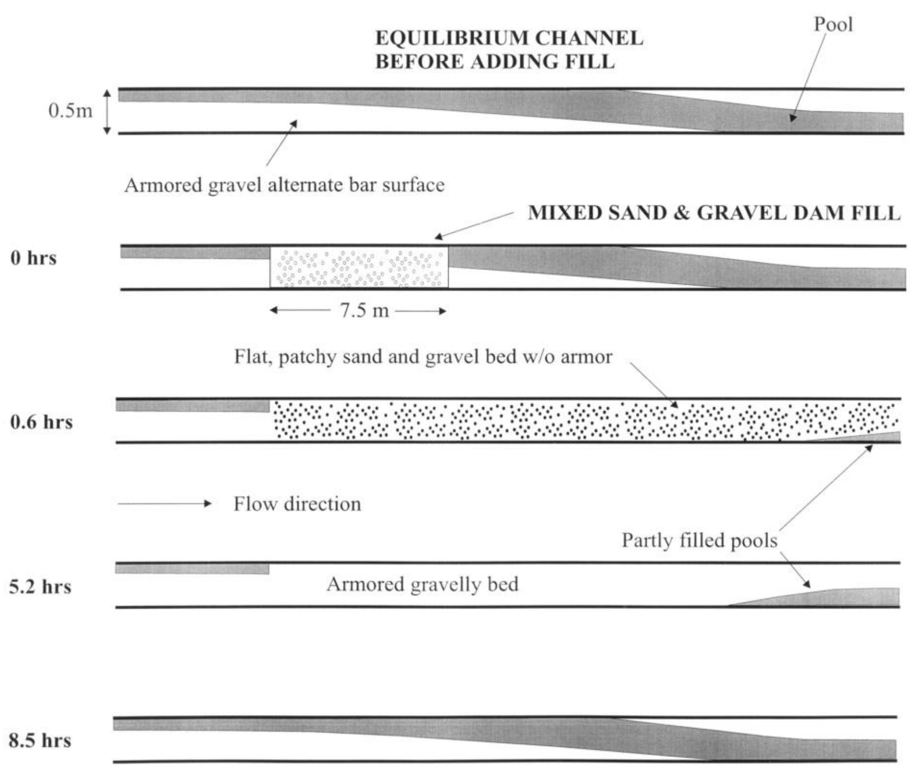
How sediment is transported

In addition to the volume of sediment that will be transported when a dam decommission, is how this sediment will be transported. The method can have different implications for downstream riverine and coastal ecologies as this an affect the rate and volume of sediment deposition.

Although many geomorphologists have suggested that sediment inputs translate as waves (Gilbert 1917,Madej and Ozaki 1996), recent experimental (Lisle et al. 1997, 2001), theoretical (Cui and Parker 1997), and field studies (Ball et al. forthcoming) suggest that dispersion should predominate.[…] Determining the relative importance of dispersion and translation is significant because the two models have different implications for downstream sediment impacts following dam removal. If a bed material wave translates without decreasing in amplitude, then serious sediment impacts could propagate downstream. Dispersive bed material waves, on the other hand, create sediment impacts that decrease in severity both with time and distance downstream.

Pg. 686, Pizutto 2002

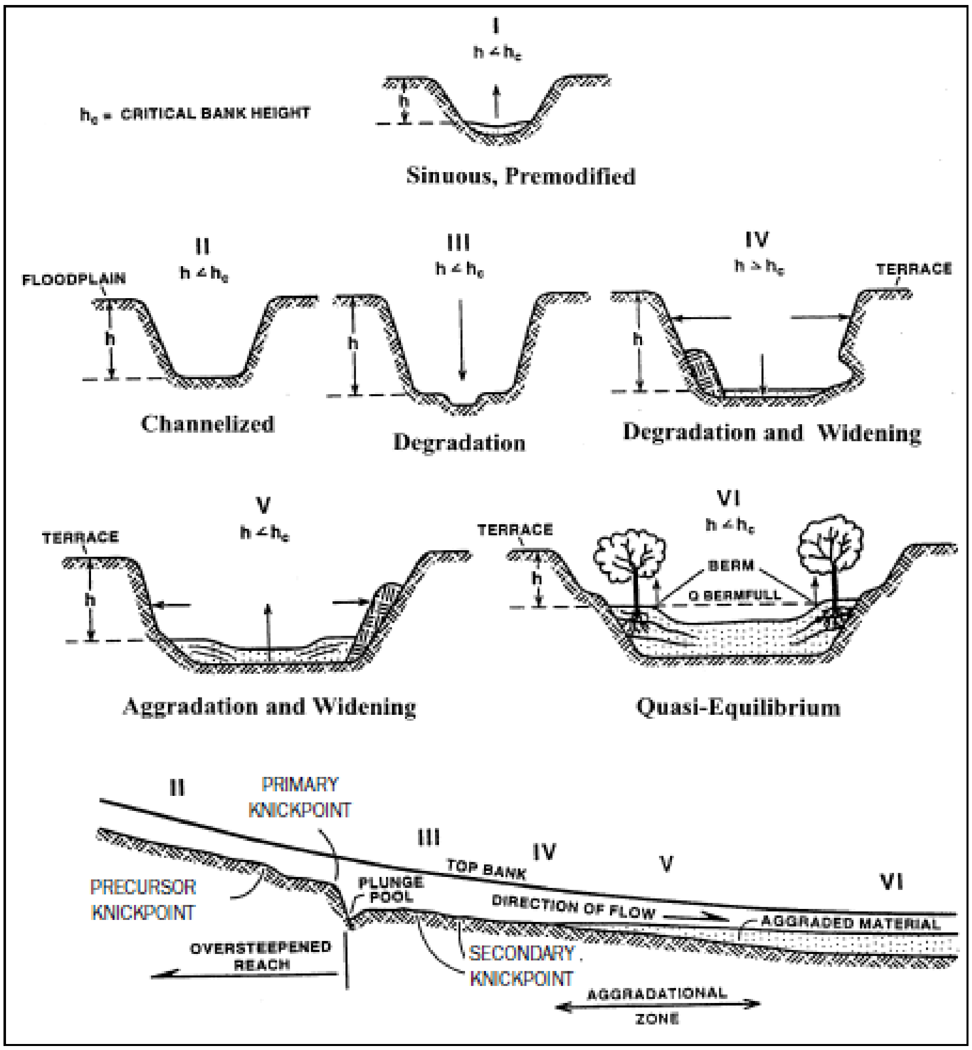




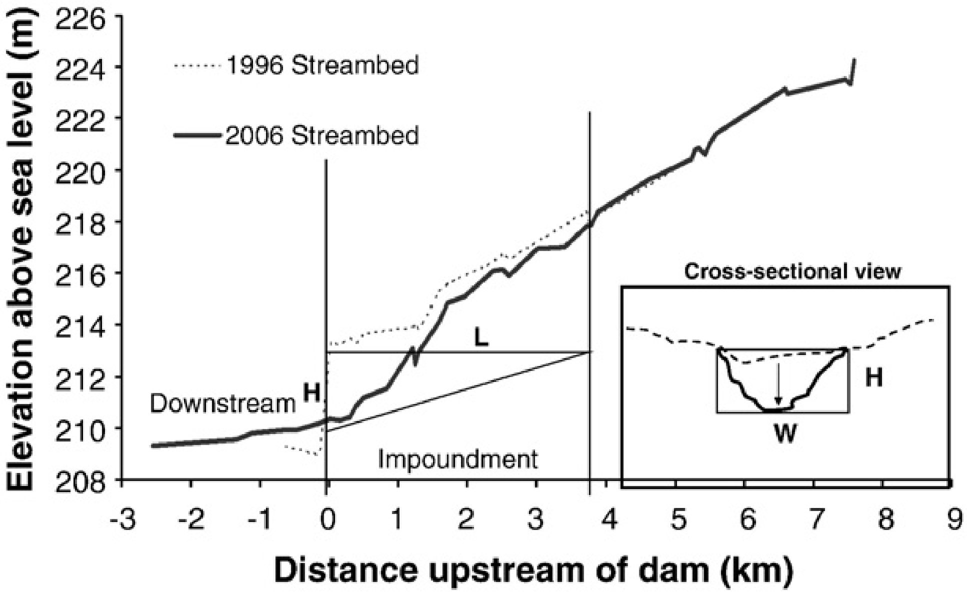
Top: Dispersion, translation, and combined translation and dispersion of bed material waves illustrated in profile. Bottom: Evolution of a sediment wave in an experimental channel. At 0 hours (hrs), an equilibrium channel is illustrated. After 0.75 hrs, a pulse of sediment 3 cm high and 20 meters long was introduced into the channel. This pulse essentially decayed in place. Pg. 687, Pizzuto, 2002.

Incision of the stream path

The removal of the dam's barrier has been compared to uplift in geomorphology by Pizutto, 2002 and Doyle et al., 2005. Uplift is a type of disturbance where a section of the land is raised suddenly, through tectonic activity, and disrupts the equilibrium of the river by increasing the grade of the streambed at an isolated point called the 'knickpoint'. A dam's removal can create a similar change in grade as the river drops from the elevated height created by sedimentation of the reservoir to the pre-existing stream bed left intact downstream. The effect of this change in grade is that the increase in the stream's velocity will cause the streambed to be incised, decreasing its cross section, as the stream's capacity increases and the volume of bed material it transports also increases (Pizzuto, 2002; and Doyle et al., 2005). The knickpoint moves upstream as bed material is degraded by the high velocity at this location. The migration of the knickpoint upstream begins the process of the river re-establishing a grade reflective of the topography and bed material.



Six-stage sequence of incised channel evolution. Pg 686, Pizutto, 2002.



Longitudinal profile of the Pine River streambed before and after dam removal. The triangle approximates the area of the sediment fill and, along with average stream width upstream of the impoundment, can be used to estimate the volume of sediment that can be mobilized at a dam removal. (Pg. 104, Burroughs et al., 2009)

The volume of sediment exported from a reservoir area varies with the magnitude of stream's velocity and the type of sediment impounded and this can strong influence the remediation of the reservoir area (Doyle et al., 2005). If the bed material is composed of fine sediment, the initial incision will be steep and narrow (Doyle et al., 2005). Larger sediment will take longer to be transported as an increase in velocity may not increase the stream's capacity sufficiently. Overtime the banks of the river will be undercut resulting in slumping and a widening of the river channel. The channel width will become more stable as both the grade of the river bed stabilizes and vegetation long the banks of the river are established. The frequency of flood events can hasten the establishment of the floodplain.

> [Channel Evolution Models] models were developed from incising channels and predict that, following dam removal, bank slopes in former impoundments should increase along with vertical incision (and so should be steeper, initially, closest to the dam). Banks should continue to steepen with further incision until a point is reached where the slope is too great for the cohesive forces of the sediment or vegetation to continue holding it together, causing slumping and a reduction in bank slope and allowing for the development of equilibrium channel dimensions.
>
> P. 104, Burroughs et al., 2009

One of the challenges with the removal of the sediment from the reservoir, is that it is only the sediment within the channel is actively being transported (Doyle et al., 2005). Once the dam is removed, most of the sediment will be located on the banks surrounding the stream. Depending on the makeup of the sedimentation within the reservoir the material can vary and may be transported during wetting events, when water travels over the ground, through overland flow, or during floods and high water events. Fine sediment is easily transported, while coarser sediment will take longer to be removed from a reservoir area. The removal of sediment will be further reduced as vegetation is established in the area formerly impounded.

Reservoirs with shallow sedimentation may not experience the high levels of sediment transport typically associated with dam decommissioning. Instead, the sediment exposed after the reservoir is drained may establish a floodplain within the stream channel (Pizzuto, 2002). As already discussed, the sedimentation present in the headpond at Mactaquac Dam is relatively low with a predominant depth of approximately half a metre, and up to 6m in a few locations.

> Determining the relative importance of dispersion and translation is significant because the two models have different implications for downstream sediment impacts following dam removal. If a bed material wave translates without decreasing in amplitude, then serious sediment impacts could propagate downstream. Dispersive bed material waves, on the other hand, create sediment impacts that decrease in severity both with time and distance downstream.
>
> P686, Pizzuto, 2002.

> Upstream from the dam, geomorphic processes should follow a coherent sequence (figure 1). First, the channel will incise through the sediment fill. Bank failures will occur if the channel depth increases above a critical value that depends on the strength of the soil and the detailed geometry of the stream. The additional sediment supplied by bank failures could be used to build floodplains and, ultimately, a new equilibrium channel. The complete sequence will probably require at least a decade and will depend greatly on the mass and grain size of the sediment stored behind the dam.
>
> Pg 684, Pizzuto, 2002.

> Sandy fills could be subject to sapping as groundwater emerges at the base of a headcut. Other mass wasting processes related to liquefaction of sandy sediment could also occur, particularly when the reservoir fill is thick. Otherwise, a knickpoint (an abrupt increase in slope) could migrate upstream through a sandy fill. Fills composed of sand or cohesive silt and clay are likely to erode even during low flows, but fills composed of gravel may be incised only during high-flow events that are competent to move coarse sediment (Egan 2001, Doyle et al. forthcoming). For this reason, gravel fills are labeled as “event-driven” in figure 2.
>
> Pg 684, Pizzuto, 2002

Riparian

Stakeholders often express concern about what the area will look like post dam decommissioning. A common assumption is that the reservoir area will become a large mud flat for an extended period of time. While riparian areas require a longer time frame to be fully re-established (Doyle et al., 2005), there is little evidence that the surrounding area while remain a barren, muddy landscape for an extended period of time (Wyrick et al., 2009). Rather, the area adjusts as it would to other disturbances:

vegetation typically reappears quickly as grasses appear and subsequently transition to shrubs and trees. These newly exposed areas are vulnerable to invasive species and replanting these areas can help mitigate the effects of reservoir removal by reducing the time required for an area to become re-established, stabilize the banks and reduce the presence of invasive species (Doyle et al., 2005). The time frame required for remediation of riparian zones is unpredictable and can vary from a few years to decades (Doyle et al., 2005). The longer time frame may reflect the type of vegetation typical of riparian zones in that area. Trees and shrubs require a much longer period to become established than grasses. Of note is that these extended time periods do not intend to suggest that the riparian areas will remain bare earth, rather that the complete establishment of species may take longer with slower growing trees and shrubs compared to grasses.

Re-emerging vegetation within the riparian zone – one year after dam removal, Sterling Lake. (Wyrick et al., 2009)

Re-vegetated lakebed one year after the removal of Wrights Mill Dam. (Wyrick et al., 2009)

Exposed lakebed of Wadsworth Dam following gate valve opening. This reservoir was annually drained during the dry season, resulting in a dry lake bed for up to two months a year. Illustrated what a newly drained reservoir may resemble (Wyrick et al., 2009).

Nutrients

Nutrients are transported to streams through overland flow and in point and non-point source pollution. Depending on the rate and quality of these sources of nutrients, an increase in their concentration can occur and surpass what is desirable for a stream and a reservoir. An additional consideration is that nutrients undergo biochemical cycling differently in a reservoir or lake compared to a stream and an increase in concentrations can impact the water quality of the reservoir (Poff and Hart, 2002). Nutrients trapped in the reservoirs can result in depleted areas downstream as these areas are no longer replenished by the upstream activities (Doyle et al., 2005, and Poff and Hart, 2002). Nutrient loading is most significant in the area immediately upstream from the impoundment due to the sediment being trapped there and when a reservoir is drained nutrients are removed as sediment is transported downstream (Doyle et al., 2005, Stanley and Doyle, 2002). Since sediment is transported over time, the depletion of nutrients from the impounded area is tied to the time it takes for an area to reach a state of equilibrium (Doyle et al., 2005).

Nitrogen (N) and phosphorous (P) are two prominent nutrients that influence the rates of biological processes in aquatic environments. Excessive concentrations of these nutrients result in additional, undesirable productivity (Stanley and Doyle, 2002). Like sediment, these nutrients can also become stored in a reservoir and have adverse effects on the downstream ecosystems during the dam decommissioning process.

Nitrogen

Nitrate (NO3-) is the dominant form of nitrogen in enriched systems and is easily soluble, moving from surface water to groundwater to streams with relative ease. It is also easily consumed by algae and bacteria and can result in the excessive growth of these organisms. In anaerobic environments, bacteria converts nitrate to the gaseous form of nitrogen (N_2), rendering it largely inert. This can also occur as nitrate passes through the stream bed if the bed material is composed of fine sediment as opposed to porous coarse sediment, or in deep, stratified reservoirs that have anaerobic conditions. Typically, NH_4^+ is present in reservoir in high quantities.

Phosphorous

The dominant form of P is phosphate, (PO_4^{3-}) which attaches easily to mineral surfaces, such as those found in soil and sediment. Phosphate is therefore introduced to streams through the erosion of agricultural and urban land. Its movement is limited to that of the soil or sediment it is attached to and therefor reservoirs with agricultural and urban development upstream may contain large amounts of phosphorous within the sediment. Similar to nitrogen, above normal concentrations can also lead to algal blooms that cover the water's surface like a mat. The algae have unpleasant odour and when the mats dies, they sink to the bottom to decay reducing the oxygen available to levels fatal to fish and other organisms (http://www.ec.gc.ca/grandslacs-greatlakes/default.asp?lang=En&n=6201FD24-1#a3).

Both nutrients trapped in the sediment within a reservoir can be transported downstream during decommissioning. They share similar downstream transportation and an increase in their concentrations can impact the ecology of the river and coastal regions.

> Because the availability of nitrogen (N) or phosphorus (P) (or both) often limits rates of biological processes in aquatic systems, recent increases in delivery of N and P to lakes, streams, and rivers have acted to fertilize not only the receiving freshwater ecosystem but also coastal areas, resulting in undesirable increases in productivity in both freshwater and marine systems (Carpenter et al.1998, NRC 2000).

P. 693, Stanley and Doyle, 2002.

> The greatest retention occurred in the final 500 m of the impoundment, where flow was the most stagnant and thus conducive to nutrient retention. Removal of the dam and formation of a narrow channel in the lower impoundment worked to greatly increase flow velocity, reducing the potential for nutrient retention. However, upstream of the headcut, the reservoir remained mostly unaffected by the dam removal, and so the nutrient retention trends are similar to when the dam was still in place. Final equilibrium conditions showed decreased, although still persistent nutrient retention. These simulation results suggest that changes in channel morphology following dam removal can cause large changes in nutrient retention patterns within a stream.

Pg 237, Doyle et al., 2005.

Contaminants

Similar to excessive nutrients, contaminants can be present in streams through point and non-point pollution as well as overland flow (Bohlen and Lewis). The concern for contaminants in dam removal is whether the sediment trapped in the dam's reservoir contains toxic contaminants, contaminants such as PCBs and pesticides, which could be harmful to the riverine ecosystem downstream.

Containment of the contaminants is often of a higher priority when persistent toxins are found within the reservoirs sediment. If the sediment is contaminated with various pollutants (PCBs, for example), then releasing the sediment can have long term affects downstream as the sediment is continually transported and deposited with changing flow rates. With heavily contaminated sites, containing the sediment in its present location may be the best option to reduce further contamination.

However, contaminants may also be located within the dam itself or on the dam site as regulations regarding oil storage, lead paint, and asbestos have changed over the years. (Elwha River video- http://ehp.niehs.nih.gov/120-a430/) Mitigation of the dam site and disposal of the construction material is an additional manner to reduce the amount of contaminants that move downstream during the decommissioning process.

While dam decommissioning is often cited as the most effect tool to mitigate the degradation of a river, there are other steps which can be taken to improve pollution and sedimentation. Reducing non-point pollution and limiting run off into rivers in developed and developing areas, regulating point source pollution (Hart et al., 2002).

Fish

One of the most significant impacts of dam construction is the barrier that is imposed on fish migration and the change from lentic to lotic conditions. Many older dams did not include fish ladders in their design. The strategy to mitigate the impact of the Mactaquac dam on fish populations was to capture and truck fish upstream. The full process is described below:

> At Mactaquac, all upstream migrating fish are trapped and transported by tank truck to various destinations in the river system. The fish passage facilities include a collection gallery, cantilevered from the powerhouse wall and supplied with a constant flow of

> water so as to provide an attraction to upstream migrating species. Entrance to the gallery is by way of six submerged gates spaced along its length (Figure 6). Salmon and other upstream migrating species move against the current in the collection gallery to a holding pool where a mechanical crowder forces them into a primary sorting facility. The sorting facility, comprised of two interconnected brail pools, is designed to exploit the jumping behaviour of Atlantic salmon to isolate them from the large numbers of other migrating species. From the brail pools, fish are lifted by hoppers and released into tank trucks for further distribution.
>
> Ruggles, 1975

Removal of the Mactaquac dam would allow for fish to migrate further upstream and increase their habitat tremendously. However, Mactaquac is one of four dams which have been built along the Saint John River and its tributaries that affect anadromous fish populations. If Mactaquac were to be decommissioned, this would still result in a significant increase in these species habitat as the next dam, Beechwood, is located approximately 150km upstream. Fish recovery quickly post-dam removal, returning to upstream reaches that same season or within the following migration season while lentic species tend to migrate to areas of still water, such as lakes found upstream (Hart et al., 2002). The return of anadromous fish has been documented in various videos which follow the ecological recovery of fish species post dam removal and is modelled in the ecosystems recovery chart above (Page 4 of this reort). The return of native anadromous species is becomes a major consideration of dam decommissioning as many of these fish populations are in decline.

> Juvenile Atlantic salmon habitat upstream from the Mactaquac Dam was restricted to those river reaches with a gradient between 0.1% and <15.0% based on previous work by Amiro (1993). Before the construction of hydroelectric dams on the Aroostook River (1922) and Tobique River (1955), and at Beechwood (1957) and Mactaquac (1968), 2,379 ha of such habitat was available for salmon production upstream of Mactaquac Dam (Washburn & Gillis Associates Limited 1996). After the dams there was 1,347 ha of habitat, of which 58% was located in the Tobique River basin. This represents an overall loss of 44% of juvenile salmon rearing habitat in the Saint John River in Reaches 1 and 2 (upstream of Mactaquac Dam) as a consequence of the dams and associated habitat changes (from river to headpond reservoir).
>
> Pg 64, Kidd, Curry, and Munkittrick, 2011

Additional considerations:

Wetlands

Once a reservoir is established, it can alter the vegetation of the area surrounding it resulting in the establishment of riparian and wetland habitats. With dam decommissioning and the draining of the reservoirs, the wetland areas may also be drained and decrease the presence of wetland habitat (Hart et al., 2002, and Newman et al. n.d.). However, little discussion has been given to how wetlands may be re-established within the stream channel once a reservoir is drained.

Seismic activity

The flooding of an area adds weight to the area and, for areas that are seismically active, larger reservoirs can increase seismic activity (Kornijów, 2009)

> The third aspect of influence of dams on the environment, rarely considered, concerns changes of mutual hydrodynamic regime between aquifer horizons (Rashad, Ismail 2000). Such changes can result in even a few meter drop of the ground water level, and disappearance of water in wells (Adel 2001).
>
> Kornijów, 2009

Ground Water

A large reservoir increases the area where surface water can infiltrate increasing groundwater recharge. If this is a significant area, the water table may become higher. Inversely, the removal of the reservoir may result in lowering of the ground table as the volume of ground water recharge is reduced. In area where development has occurred, household well can be affected as the water table levels lower with the removal of the reservoir through and reduce the ground water recharge (Hart et al., 2002, and Newman et al., n.d). The changes to the water table occurred due to the presence of the reservoir, so changes to the volume of ground water reflects the pre-dam conditions for the area.

A study of the aquifer in the location of the Mactaquac dam look the impact this dam may have had and there was some indication that the change in sediment immediately upstream of the dam has reduced the rate of ground water recharge in this area (Tawil and Harriman, 2001). The study area is the dam site and not the entire head pond and so further research would need to be conducted to establish the impact of the reservoir on the water table.

Public opinion

> One obstacle is sheer velocity. What once appeared impossible suddenly seems inevitable. Five years ago, people asked of dam removal, Why? or whether. Society now asks: Which ones, when, and how? … But moving from one project to the next does not mean we cannot revisit those removals to assess and determine whether expectations were met.
>
> Another obstacle is overcoming our instincts. Removal feels so right and makes so much sense to so many: Surely, consensus-based dam removal would heal the hidden wounds that dams inflicted, restore river functions, bring back the anadromous fisheries from coast to coast. … But even though we have anecdotal evidence of improvements, there is little hard evidence to confirm it.
>
> A third obstacle is economic limits—that is, cost. Not one removal I took part in came top-down from Washington, DC. Each opportunity was driven upward, by local necessity—safety, cost, health, imminent extinction, budgets, and litigation. Local forces were the mothers of invention; we adapted our approach, funding, constituency, answers, funding, tools, and management to the unique needs of the watershed in which the dam belonged. That is politically sound but economically difficult. It often

> proved hard enough to scrape together funds to ensure safe, low-impact removal, let alone to set aside money for post-removal studies.
>
> Babbit, 2002

Public consultation

A number of points have been raised in the literature reviewed regarding the public consultation process. People feel that they have a democratic right to participate in the decision making process (Tilt, Braunm and He, 2009), however, the decision for dam removal is often made quickly when concerns about safety are discovered and the time required to consult with the public is neither a priority or available (Johnstone and Graber, 2002). Dams and their associated reservoir become culturally significant and their removal can be of great concern to local communities (Graf, 2005). This can result in local people feeling alienated and create an environment where emotions run high, making future consultations challenging. Similar results can occur when the option of dam removal is introduced unexpectedly, or when outsiders appear to be involved in the decision making process. In addition, Wyrick (2009) noted that homeowners concerns are generally not considered as government tends to favour removal. While this finding may be more common with smaller dams which can be quickly removed if they pose a safety risk, the removal of larger dams require additional preparation and consideration and significantly altering the landscape. However, dams are typically more expensive to repair than remove and if the dam is not meeting its original purpose (irrigation, drinking water, power generation) then decommission is often viewed as a reasonable option by the organisation that manage them. Additional consideration is the change in regulations for fish ladders, as many larger dams were not built with fish ladders. The cost associated with adding this infrastructure cost can be prohibitive for some projects.

> By far, the most discussed issue was that the removal of the dams would cause a significant loss in wildlife and vegetation, which matches the concerns reported by Doyle et al. (2000). They are worried that their backyards will transform from a scenic lake into a mud hole in the future. This may be predicated on the fact that during the current dam conditions with the gate valve completely opened on Wadsworth Dam, there is no storage during the dry summer months. During this time, the lake level decreases and a typical stream forms through the sediments, leaving most of the lakebed exposed. This situation only occurs for a couple months of the year, which does not give the riparian vegetation enough time to repopulate the area.
>
> pS274, Wyrick et al., 2009

One of the concerns around the public consultation process is that the communities do not have the information necessary to make informed decisions. Nor do they have the ability or the desire to analyse the various options and it can be difficult to weigh ecology considerations with conflicting social costs (Bohlen and Lewis). Increasing the scientific knowledge within a community is one mechanism to help improve the consultation process as it permits citizens to be in a better position to make informed decisions (Johnstone and Graber (2002); and Wyrick et al., 2009). The strategy of increasing the knowledge-base of the community or targeted community members can be used to reduce or influence people's reliance on psychological short cuts. As people will unwitting reflect the social norms of their community, Johnstone and Graber (2002) discuss how to target key community representatives and increase their understanding of the benefits of natural rivers. By informing these key representatives and altering their perspective to differ from the social norms, this may increase public support as other members of the community diver to community leaders. This strategy can be a key component of a successful public information program. Other examples provided by Johnstone and Graber (2002) include targeting early adopters, social marketing, and identified real and perceived barriers. When uncertainty is high, as it would be in a large dam removal project, an additional barrier to overcome is the hopelessness or lack of control community members may experience.

While Johnstone and Graber (2002) explore how to influence psychological shortcuts so that the social norms are supportive of dam removal and natural rivers, Wyrick (2009) explored methods to increase the scientific knowledge base of the community and suggest that modeling and education can help address local concerns on dam removal and increase the understanding of ecological benefits. This might reduce the likelihood of the 'It's here now and we like it' sentiment common in dam removal opposition (Wyrick et al., 2009). Similarly, Tilt, Braun, and He suggest identifying impacts in advance of the consultation process can help facilitate decision making. Working with impacted with affected communities can be challenging and the above strategies can be further explored for a better understanding of how to consult on topics that may be emotionally charged.

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Appendix 1: Dam classifications

The type and size of a dam has different ecological impacts on affected river network and understanding the various types of dams can assist in evaluating their associated impacts. However, how dams are classified can vary depending on an association's criteria. While classification by facility (type of dam) is consistent, the application of these classifications are not. An example is the use of run of river dams to describe all manner of sizes of dams. A quick comparison between run of river dams with storage dams is followed by a summary of different facilities of interest to the Energy Transitions project..

Run of river dam	**Storage dam**
Small hydraulic head	Large hydraulic head
Small storage volume	Large volume of stored water
Short hydraulic residence time	Long hydraulic residence time
Little control over the release of impounded water	Control over the rate of water released at all times
Energy provided is base-load and associated with the natural flow of the river*	Energy provided is controlled by the release of stored water and can meet peak demands*

Poff and Hart (2002)

* IPCC (2011)

The Mactquac generating station is located upstream from Fredericton, NB on the Saint John River. Built in the mid 1960's, the facility has the capacity to generate 660 MW of electricity, which provides New Brunswick with approximately 12 percent of its power. The dam at the Mactaquac generating station has an approximate height of 58m above the foundation and created a head pond approximately 96km long. The facility is described as a run of river hydro-electric facility by NB Power, and the dam is zoned as an embarkment dam with 'a central core of clay till and external shells of rockfill' (Tawil and Harriman, 2001) and has a foundation of stiff glacial till under which lies an aquifer with a strong artesian pressure. The generating station began its operation in 1968. Cracks began to appear in the concrete about 10 years after construction first began and in the mid-1980's the cause of these cracks was determined to be alkali-aggregate reaction (AAR). This condition does not affect the earthen dam it does reduce the lifespan of the powerhouse and spillway, which is now expected to end by 2030

The proposed Site C dam would be located on the Peace River, approximately seven kilometers southwest from Fort St. John, BC. This facility would consist of an earthfill dam approximately 60m high and 1050 m wide and create an 83 km long reservoir. Due to the topography of the area, the reservoir would cause the Peace River to be flooded 2 to 3 times its regular width, though the tributaries would experience greater rates of inundation. Classification of the dam is not available for this proposed facility however it proposed to install 183 MW generating units which could provide electricity to 450,000 homes each year.

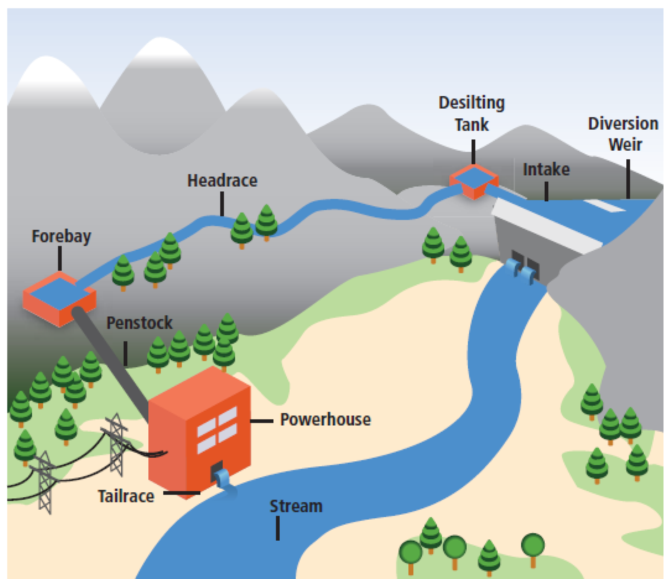
Classification by facility

Run of river

Run of river dams are typically small facilities that only use the river's natural flow for power generation. This often results in the dam diverting a portion of the stream flow for generation while the rest of the water remains in stream and free flowing. There is no impoundment in this type of facility leaving the power generation susceptible to low flows and reduced capacity. This type of facility has a minimal impact on the ecology of the river system as both sediment and water is able to flow uninhibited.

Image from: http://ontarioriversalliance.ca/about/dam-types/

Run of River with Modified Peaking



To increase the reliability of power generation, run of river facilities often have a small storage capacity. This allows for power generation during high demand regardless of the river's natural flow and for the storage of water when demand is low. As the facility has limited capacity, power generation is still largely dependent on the flow regime of the river, precipitation and run off. The natural stream flow of the river is modified by the demands for power generation, which can vary depending on the size of the reservoir and the required electricity for peak production.

Image from: IPCC (2011)

Reservoir Storage

Dams with reservoirs are not dependent of the river's natural flow as they have large storage capacity to hold water from one season to the next. The area inundated becomes an artificial lake and which is holds water from the spring floods for periods of high demands later in the year – typically the winter months when power demands are highest. The large storage areas provide flexibility for power generation but have detrimental impact on river systems as the river flow regime is severely altered, impacting the ecology downstream.

Pumped Storage

The pumped storage facility pumps water from a low reservoir to a higher reservoir during off-peak hours so that water is available for power generation during high demand periods. These systems operate at loss in net energy production and are designed to meet peak demands for electricity.

Kinetic Hydro or In-stream Technologies

These technologies place turbines directly within the streams or on land using a piped water supply to harness natural flow or tidal flow for energy production. They can also be used to adapt existing structure (weirs, barrages, falls, etc.) for the production of electricity. They are most often small in scale and used in remote locations to help meet local energy demands.

Classification by size

There appears to be little consensus on how dams should be classified by size as different jurisdictions have different criteria. Current dam classifications tend to distinguish between large and small dams, though due to inconsistent criteria, the same dam can fall into different classifications depending on which organization's conditions are used. For example, below is a quick comparison of current (200?) classification for two different associations

US Army Corps of Engineers	**International Commission on Large Dams**
Height > 7.6m and a reservoir > 18,500m^3	Height > 15m
Height > 1.8m and a reservoir > 61, 700m^3	Height 5 - 15m and a reservoir > 3,000,000m^3
High hazard potential; likely loss of life if dam fails	

From Poff and Hart (2002)

Regardless of size, dams can impact the ecology of a river system. Dams with high hydraulic head and increased residence time can resulted in changes in the temperature of the water released (cold in summer, warmer in winter) as well as changes in the nutrient cycling as anoxic and anaerobic conditions can develop within the reservoir. This combined with the changes in sediment load and natural stream flow can greatly impact the composition of the stream bed and the ecology of the region downstream from large hydro-electric dams.

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Retrieved from: http://ontarioriversalliance.ca/about/dam-types/

Appendix 2: Dam removal videos

A compilation of online videos about dam removal and remediation post-dam.

Taking a Second Look: Communities and Dam Removal

Posted by AmericanRivers

Length: 23:30

Interviews with people from three communities in Maine, after small dams were removed from each of their urban streams a bit dated but the assumptions about dam removal are similar. The interviews summarise people's concerns about what they perceived the outcome would be compared to what the area surrounding the river means to them now. Includes information about what is required for communities to be on board. There are before and after shots of the areas that were inundated, at different times after removal, highlighting some of the changes and the time required.

https://www.youtube.com/watch?v=cCQiaT1KcPo

White Salmon Restored: A Timelapse Project ~ documenting the removal of condit dam

This is a detailed blog containing multiple videos of the White Salmon River. Notably the removal of a conduit dam itself – includes numerous time lapse videos of downstream areas flooding and the upstream area as large volumes of sediment were evacuated after the dam was suddenly removed.

http://whitesalmontimelapse.wordpress.com/category/dam-removal-updates/

Condit Dam removal leaves 'river of dust' for residents

KOIN 6

Published on Aug 14, 2012

It's been almost a year since the Condit Dam was removed, and people with lakefront homes are stuck in a dust bowl. Criticism of the lack of remediation process and how this has impacted homeowners around reservoir.

http://www.youtube.com/watch?v=yp-tvviGJWo

Freeing the Elwha: Glines Canyon Dam removal, April 2012 update.mp4

Two dams were removed on the Elwha River- one of which as high as 70m dam (...well 64-70m depending on the reference). They diverted the water and then drilled down the retaining wall, and it seems the last thing they did was blast out the remaining bit. This releases the water slowly so there isn't that same rush of water and sediment and debris all at once.

https://www.youtube.com/watch?v=vNP5KgNZhjk

Removal the Edwards dam in Augusta, ME.

This is a news clip about the 10 year anniversary of the removal of the dam. The sound quality is terrible, but you can hear the former mayor talking about how the river was so polluted they actually built the downtown facing away from the water.

https://www.youtube.com/watch?v=uVBzVhukcts

Hemlock dam removal

Discusses details on how they restored the river and the return of fish habitat. Also, images from a year after removal showing the vegetation are including as well as the work was done to expedite this process and try and reduce the number of invasive species.

https://www.youtube.com/watch?v=H9wJOAtSk6s

14 days after Condit dam was breached

Shows images of a newly exposed reservoir area – the layers of sediment and the old tree stumps.

https://www.youtube.com/watch?v=hPP04exwpYo

Condit Dam Removal - Did this really help the Fish?

uploaded in oct 30, 2011, dam was removed Oct 26th, 2011

Another video criticizing of the removal of the Condit Dam on White River, is it really going to open that much river for the salmon and steelhead? At most it will open up 13 miles, and much of that has very little spawning ground.

https://www.youtube.com/watch?v=1wZSwSH7hCs

Elwha River- 101 bridge to mouth Summer 2012.wmv

Elwha river from 101 bridge to mouth showing the erosion of old Lake Aldwell – a long thirty minute video but shows downstream conditions.

https://www.youtube.com/watch?v=db_lNqkiTMA

Former Lake Mills, Now all Elwha River after dam removal: Video Dec 10,2012

Published on Dec 12, 2012

With the dam pretty much now removed, the lakebed and river are exposed. River water is clear until it hits lakebed, then it becomes turbid. Of particular interest are "cool water springs" on former lakebed with heavy iron in them making for rust-colored pools; can even smell the iron when close to the water. Large population of tadpoles in one of the pools recorded.

https://www.youtube.com/watch?v=IsCRn_J0zh0

Site C

Here are videos showing different representations of the area that will be impacted by the dam. First is the BC power video, and second is a slightly less slick view of the entire area to be flooded.
https://www.sitecproject.com/ and https://www.youtube.com/watch?v=8Rem7y28UJM

Sandbars forming at mouth of recovering Elwha River in Washington

News article describing the changes along the coast after the dam's removal which now allows sediment to be transported to the river's mouth.

http://www.oregonlive.com/environment/index.ssf/2012/12/sandbars_forming_at_mouth_of_r.html

New beaches in the making: Elwha River mouth grows as unleashed sediment flows

A second news article describing the changes along the coast after the dam's removal as sediment is once again being transported to the river's mouth.

http://www.peninsuladailynews.com/article/20140413/NEWS/304139998/new-beaches-in-the-making-elwha-river-mouth-grows-as-unleashed

Time Lapse of the evolution of the Elwha River Mouth, 1939 - June 2013

Published on Jul 16, 2013

A time lapse of the evolution of the Elwha River Mouth using geo-referenced photography in a GIS. Post dam-removal photography produced using the "PlaneCam" and is courtesy of Andy Ritchie, Olympic National Park

https://www.youtube.com/watch?v=MK4unqwzOrY

Calapooia River

Small dam removal. Benefits for watershed. Brief discussion on how restoration and community involvement in complex science projects help facilitate the success of these projects.

https://www.youtube.com/watch?v=rZNW-rg0ZZY

Lake Mead: Clear and Vital

Video discussing water quality within Lake Mead, of specific interest is how nutrients (Phosphorous and pharmaceuticals) are being monitored within the watershed to avoid overloading the reservoir.

https://www.youtube.com/watch?v=ka-qqJAnDd4

Dam Removal Begins on Maine's Penobscot River to Revive Historic Salmon Runs

http://newswatch.nationalgeographic.com/2012/06/12/dam-removal-begins-on-maines-penobscot-river-to-revive-historic-salmon-runs/

Atlantic Salmon Restoration in Maine: Orrington Dam Removal

Makes mention of the importance of consultation with the community to understand their needs.

https://www.youtube.com/watch?v=ammi9DCsdlk