Sediment in Reservoirs

a Literature Review
for a
Masters in Soil and Water Science
University of Florida

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July 26, 2018

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Overview of Reservoirs and Dams

Dams have been built all through history. The reservoirs they have impounded have made many contributions to modern society in the forms of reliable water supply, flood control, debris containment and more recently, hydroelectric power. Climate change and population increases have made water management more critical and more difficult. We now have many reservoir dependent societies, and sustainable management of these reservoirs is critical.

Water Supply

The human need for reliable water has fueled some of the greatest historic feats of engineering. The Roman aqueducts are vestiges of ancient water supply systems and so is Hezekiah's tunnel. These waterworks allow us to farm in places where it does not reliably rain, giving access to rich soils that would otherwise be uncultivated. Some irrigated soils are the most productive in the world such as those in the central valley of California. The waterworks allow us to live in deserts and to expand our populations throughout the world. No modern city is without a water system, they are essential for food preparation and sanitation. Many cities and towns depend on the use of reservoirs, canals, and dams to supply the tap water that they need. Water usage splits up into three main categories like this, 69% agricultural, 23% industry and 8% household ("Sustaining water. Population and the future of renewable water supplies. | popline.org," n.d.). We are seeing now the need to acknowledge the present but often overlooked fourth category, ecosystem needs.

Because the world's population has increased dramatically this last century, water supply has become a critical limiting factor ("World Population Clock," n.d.). Population clock numbers show global population counts at 2.8 billion 1955 and 7.6 billion in 2018. These numbers are forecast to grow, and with that we face the challenges involved in supporting more people with innovative water management. The uncertainties of climate change increase the difficulty of concurrently protecting our civilization with consistent water supplies and nurturing our planet.

Flood Control

Another important function of dams and reservoirs is flood control. Many metropolitan areas have been built around trading. This commerce has been typically centered on major waterways because the waterways provide conduits for transportation. Floods are hard to predict and can cause these waterways to be un-navigable and cause destruction in the communities built around them. Dams have done a lot to mitigate these disasters.
Before flood control was implemented typical homes in old Sacramento were built with the living areas one floor above ground level to allow for annual floods. Today the loss of the use of roadways in the state capitol on an annual basis would be problematic. The larger floods fueled flood control measures.
For instance, in 1969 flooding caused 40 counties in California to be declared disaster zones. This and other events fueled the dam building frenzy that followed. Flood control allows our society to continue to run in various weather conditions. It provides safeguards against the powerful forces of nature.

Hydro-power

Hydroelectric power is another benefit of dams. With our burgeoning modern society, the need for electricity has grown. The biggest source of electricity is fossil fuel, followed by nuclear energy. Fossil fuels are a nonrenewable resource that contribute to global climate change and nuclear fuels produce radioactive waste. Although hydroelectric power creates only 5.8% of our energy, it is the largest contributor to green energy. Water generates power by its flow. The power generated by water is enhanced and harnessed by the structure of the dam. InCalifornia it is the second most common reason to build a dam (Thornley, Nov. 10, & 2009, n.d.).

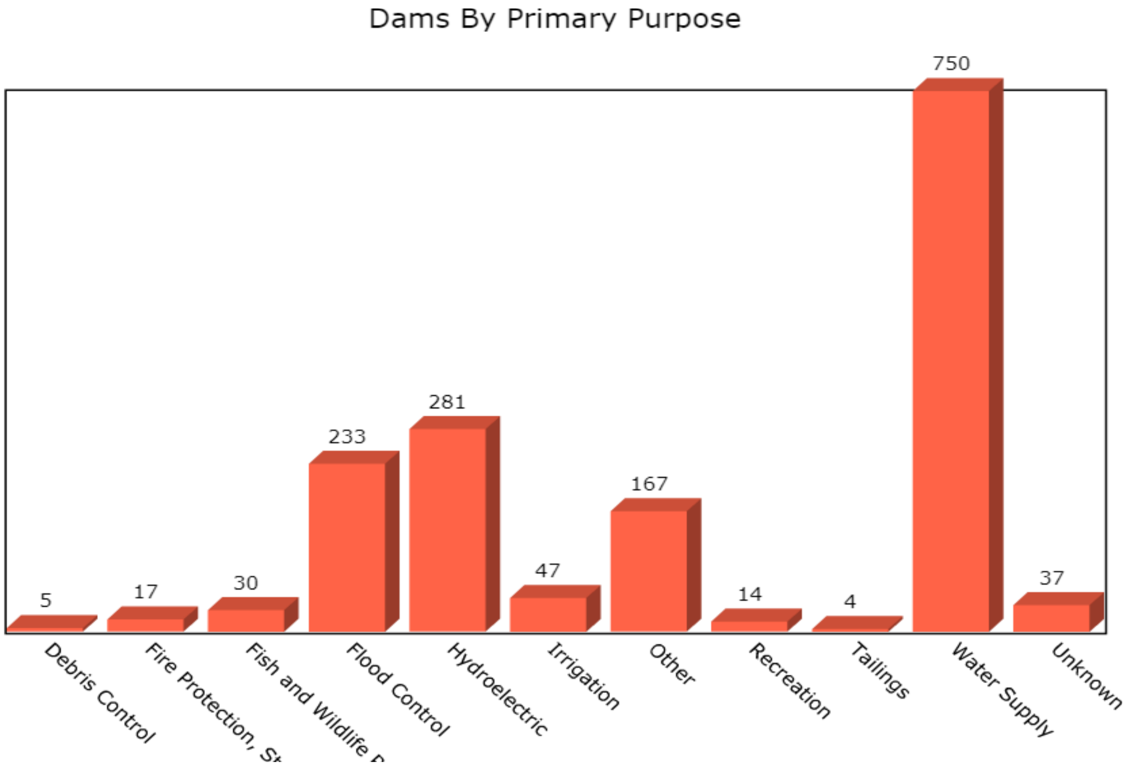


figure 1: In this bar graph we see dams in California sorted by their purpose. The most common reason is water supply, followed by hydroelectric power and then flood control.(“NID by State,” n.d.)

Debris Dams

Although debris dams represent a small percentage of the picture in California, as seen in figure 1, they play a major role in the Sierra Nevada Foothills. According to geographer Allan James in his paper entitled “Sediment from Hydraulic Mining Detained by Englebright and Small Dams in the Yuba Basin,” sediment released from hydraulic mining in the Yuba river watershed, between 1853 and 1884 totaled $344\text{x}10^6$ m^3. In contrast between 1892-and 1950 the numbers came in at at $3.1\text{x}10^6$ m^3 (James, 2005a, p. 8). This marked difference was caused by new laws. The grand total of hydraulic mining debris is 10^9 $\text{m}^{3,}$ however, most of the tailing were not added to the watershed but rather are stored in vast tailing and fan deposits in the Sierra Nevada Mountains (A. James, n.d.). During the huge depositions of hydraulic mining much farmland was buried, up to 17 feet of sediment was deposited on farm fields. Waterways filled with debris and became un-navigable. As a result, the clogged waterways flooded in unmanageable ways. These sediment flows remain so significant that this year's (2018) Professional Association of Soil Scientists tour went to see the *Cherokee* formation, now a geologic feature near Chico, California. This formation, produced by hydraulic mining, is composed of white sand gravel and mud. It overlays alluvial farming lands and has a distinct edge. The white gravelly sediment overlaps black alluvial farmland, and today creates a distinct diverse farming practice.

Sediment was distributed all the way through the watershed leading to the partial (30%) filling of the San Francisco bay. The threat of these sediments filling and thereby closing the Golden Gate to international trade led to the federal appointment of leading American geologist Carl Grove Gilbert ("Grove Karl Gilbert, 'A Captain Bold' – National Geographic Blog," n.d.) to study the situation (Gilbert, 1917).

Before Gilbert studied the science, the farmers went to court to defend their lands. This led to the Sawyer injunction of 1884 that prohibited tailings from being discharged into downstream waters. By 1892 the Caminetti Act was passed. As a result, the California Debris Commission was formed to permit hydraulic mining on the contingent on concurrent installment of on-site waste disposal such as debris dams ("The California Debris Commission: A

History," n.d.). Debris dams were built all up and down the Feather, Yuba and American river watersheds and they remain largely unmapped (James, 2005).

Many of these were built with sticks and logs and broke quickly, others leave vestiges today and a few still stand tall. Clementine Dam is 155 feet tall with an initial storage of $1.8\text{x}10^{6}\text{m}^{3}$. Its cousin, Englebright dam is the largest debris dam in Yuba watershed. Englebright stands at 280 ft tall with an initial water holding capacity of $8.6\text{x}10^{7}\ \text{m}^{3}$(Snyder et al., n.d.). They were completed in 1939 and 1941 respectively. These structures were completed to help revitalize hydraulic mining. But the mining never started again in any significant way. These dams have continued to catch any residual mining debris moving through the watershed. It has taken one hundred years to stabilize this mining sediment, and much of it still lies in these debris dams.

Distribution and Occurrence

As a result of the National Dam Inspection Act of 1972 the US Army Corps of Engineers created a National Inventory of Dams. This database includes all structures that meet minimal criteria for height, acre-feet of storage and hazard potential. The data base is meant to include all structures of significance. In California alone, the count by the National Inventory of Dams is 1,585 as of 2016. 85% of the inland waterways within the continental United States are now artificially controlled (Poff et al., 1997). A map from the National Inventory of Dams shows the large frequency and concentrated distribution of these structures in California.

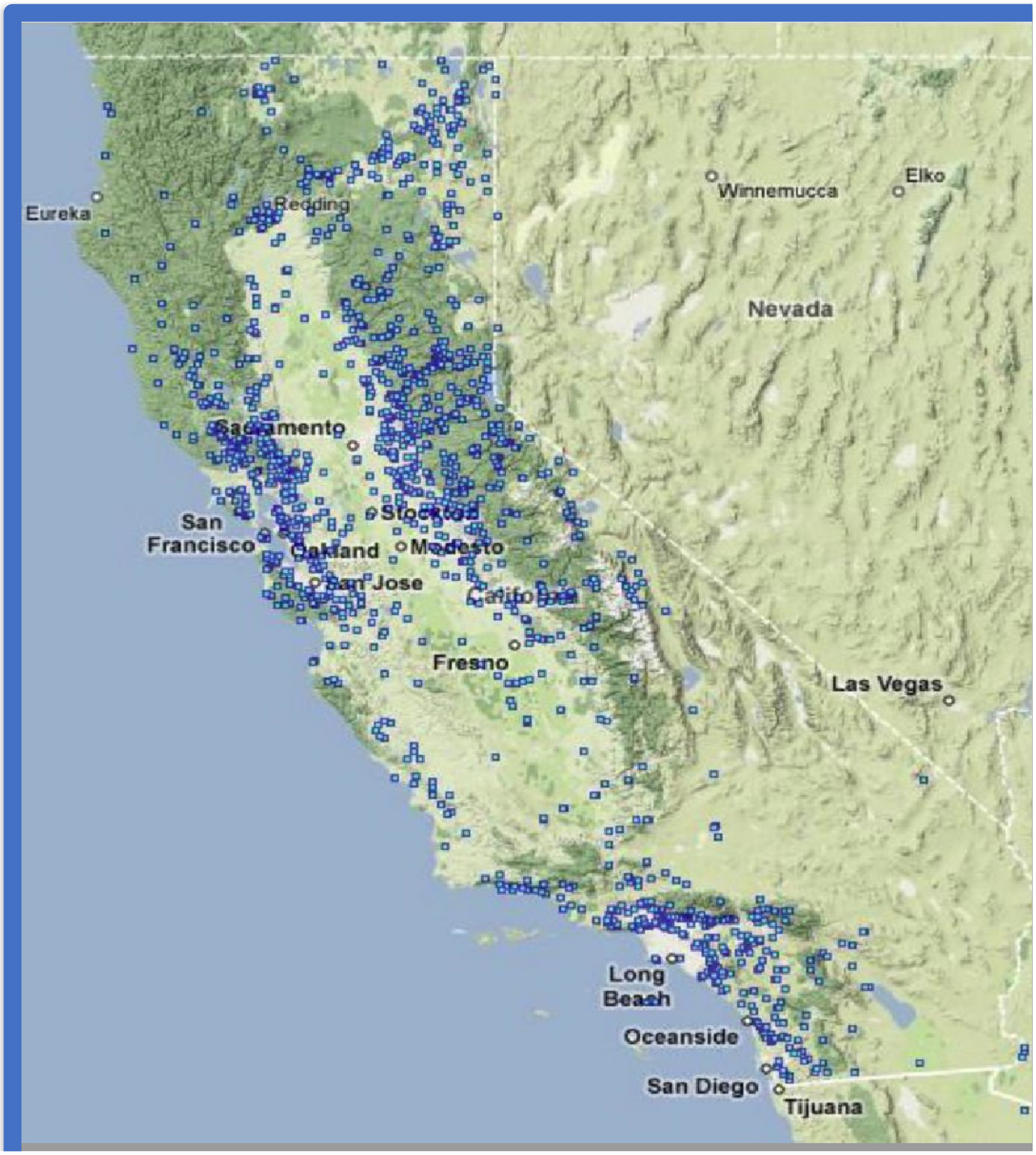


*Figure 2: m*ost dam structures in California are in the mountains of the Sierra Nevada, the Coast Ranges or the Transverse Ranges ("NID by State," n.d.-a).

Aging Infrastructure

Since most of the dams in the USA were built between 1950 and 1969, they range in age from 49 to 78 years old. This graph from the National Inventory of Dams chronicles reservoir completions in California.

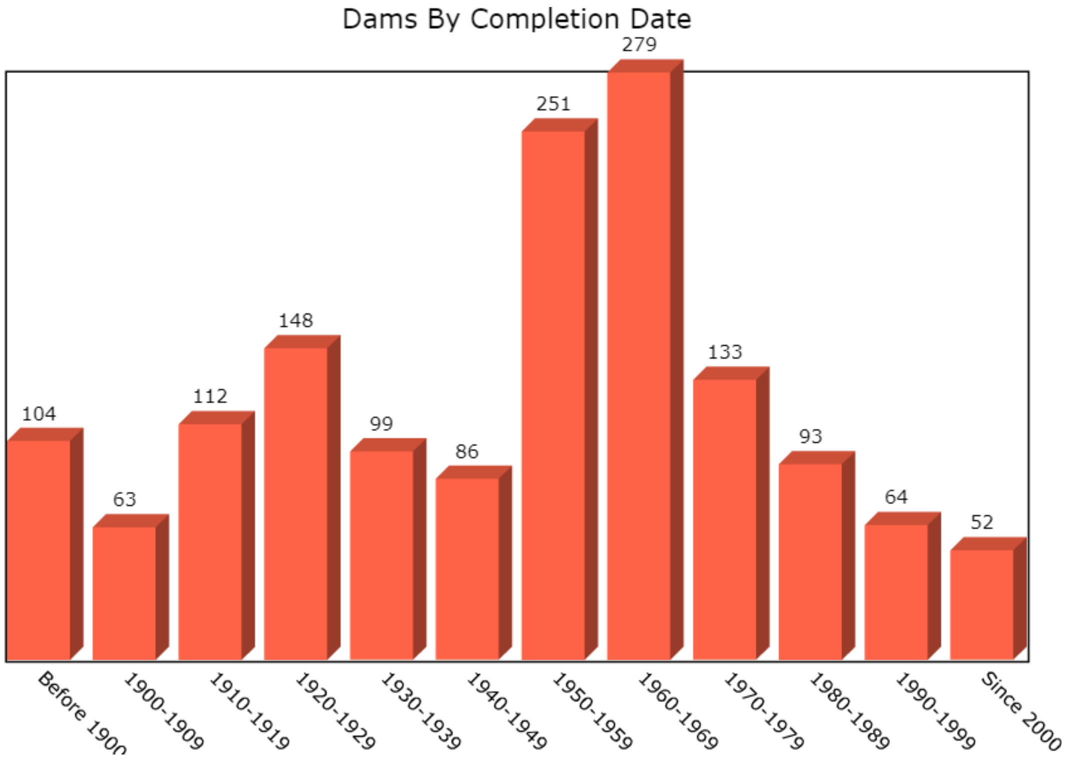


Figure 3: more than 200 dams are over 100 years old and most are over 50 years old ("NID byState,"n.d.-a).

Unfortunately, these older structures carry several functional concerns. Among them are sedimentation, ecosystem blockage and mechanical failure.

Sedimentation

As water descends from the mountains it carries suspended solids with it. The amount of solids, or turbidity varies with erosion properties of the watersheds and the amounts of falling rain. The rivers carry silt and debris, especially during major storm events. When this water pauses its flow down the mountain at the reservoir, many of the suspended solids precipitate to the bottom and slowly fill it. The rate of accumulation varies, but the standard dam was built with knowledge that someday the reservoir would be full of sediment and no longer hold water. Unfortunately, no provision has been made in most structures to account for this inevitability.

Sedimentation rates vary with watershed erosion, soil types, land use and rainfall. The average reservoir is expected to lose capacity at 1% per year with the outcome of a 100 year lifespan (Morris & Fan, 1998, p. 13). In the unusual case of the Camre Reservoir in Venezuela all available storage space was lost in 15 years (Morris & Fan, 1998). Other reservoirs last much longer. Even with only 30% siltation many structures are compromised in their ability to function.

Most dams in California are at risk of functional loss by sedimentation. All reservoirs are subject to the need for sustainable management and eventual decommissioning. Unfortunately, most of these structures were built to continuously trap sediment without any provision for sustainability. Thus, our global water storage capacities are shrinking gradually, one particle of silt at a time. The problem is worse because although dams can come and go, sites for building them are limited. A dam and reservoir site needs the perfect blend of geography, topography and existing water flows. Because of the limited number of good sites for reservoirs and our society's dependence on them sustainable management practices are crucial.

Figure 4: The fully cemented Camare irrigation reservoir in Venezuela. This reservoir filled with silt in only 15 years(Morris & Fan, 1998, p. 45).

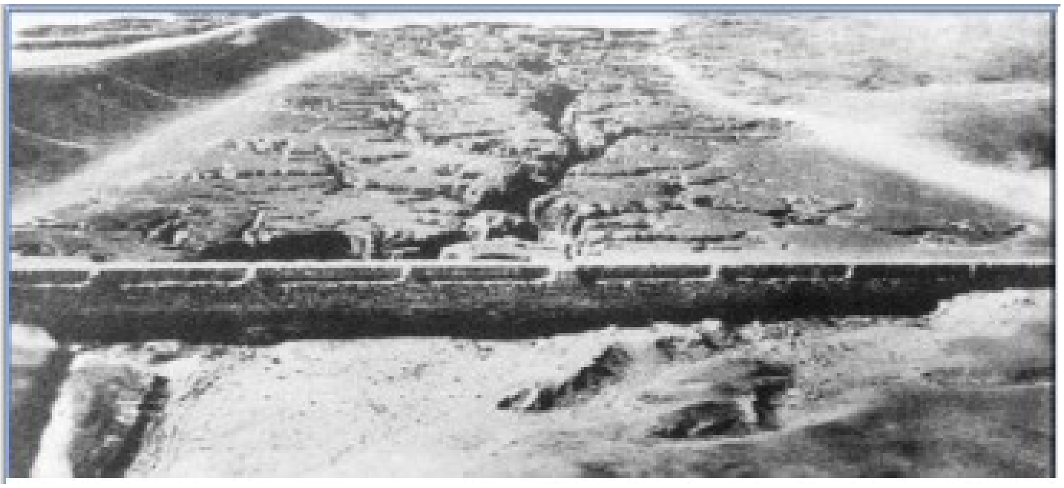


figure 5: The Harbaqa Dam constructed by the Romans shows that centuries of erosion do not remove reservoir siltation (Morris & Fan, 1998, p. 45).

Mechanical Failure

The NID (National Inventory of Dams) considers 833 of the 1585 dams in California to have a high hazard potential, meaning a failure could result in loss of life. For instance, in heavy rains the Oroville Dam emergency spillway failed, and although there was no loss of life, there were mass evacuations. This earthen overflow spillway at the Oroville Dam had never been used, demonstrating the impact of unusual weather events and climate change on safety (McDonald, 2017).

Federal Energy Relicensing Committee (FERC)

In the United states, The Federal Energy Re-Licensing Committee (FERC) is charged with inspecting and issuing licenses for hydroelectric nonfederal dams. 2,500 dams in the US are regulated by this commission ("2016FERC Office of Energy Projects Division of Dam Safety and Inspections," n.d.). The dam safety division is only one branch of the large federal agency. Structures are inspected every five years and licenses renewed in a thirty to fifty-year cycle. In 1994 FERC declared the right to demand decommissioning when considering a project for re-licensing. FERC has demonstrated that if a dam has a profound negative impact on an ecosystem it can revoke the operating license. The process of decommissioning can take up to 20 years of paperwork and inter agency coordination from multiple stakeholders before ground work even begins.

Reservoir Sediment Characterization

Distribution

There are several patterns for reservoir sediment distribution. The main characteristic of all sediment patterns is that the larger particles fall out of solution with quicker flows. Thus the gravels and sands tend to deposit wherever currents are the strongest and the silt and the fine clay are the last to precipitate doing so where water stands the longest. Each sediment pattern represents a different water current flow within the reservoir (Morris & Fan, 1998, p. 294).

SEDIMENT DEPOSITS IN RESERVOIRS

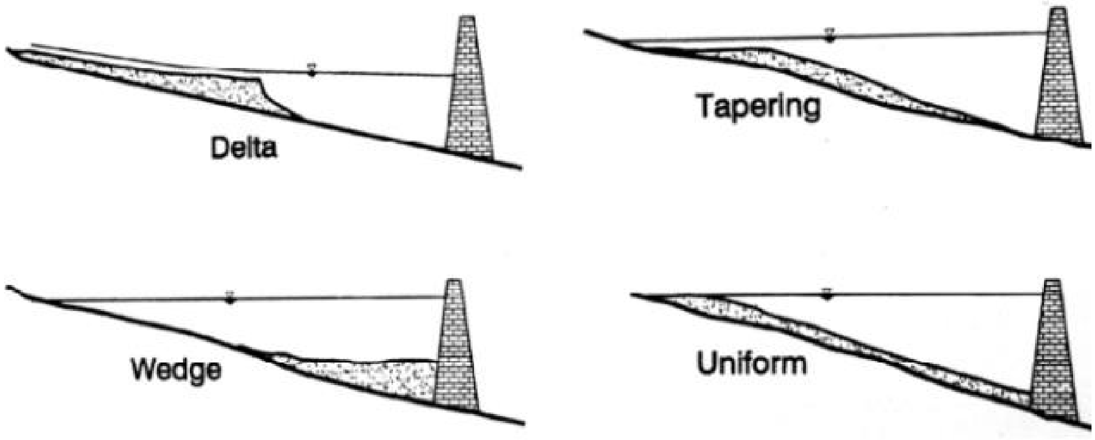


figure 6

Figure 6 shows longitudinal patterns of sediment deposition in reservoirs. Multiple patterns can exist simultaneously in different areas of the same reservoir. The delta deposits contain the coarse sand and gravels but can also have finer sediments. Wedge shaped deposits are a result of turbidity currents within the reservoir that carry sediment to the dam. Tapering deposits are more common in long reservoirs held at higher water. Uniform deposits are rare, found mostly in long reservoirs with frequent water level fluctuations and small fine sediment loads (Morris & Fan, 1998, p. 294).

The Delta pattern is the most typical. With time the delta in the reservoir grows, eventually reaching the dam itself. Here is an example of delta growth: (Morris, n.d.-a, p. 6)

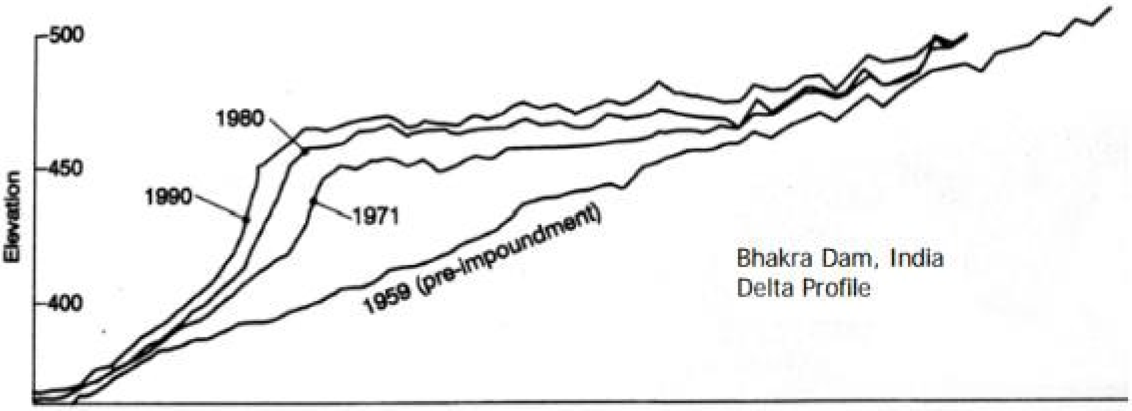


figure 7: The pattern of delta growth upstream of Bhakra Dam, India. The Delta slows its movement toward the dam as the reservoir itself deepens and widens (Morris & Fan, 1998, p. 298).

Here are some landform maps showing the common Deltaic formation in the now empty lakes Aldwell and Mills in the state of Washington.

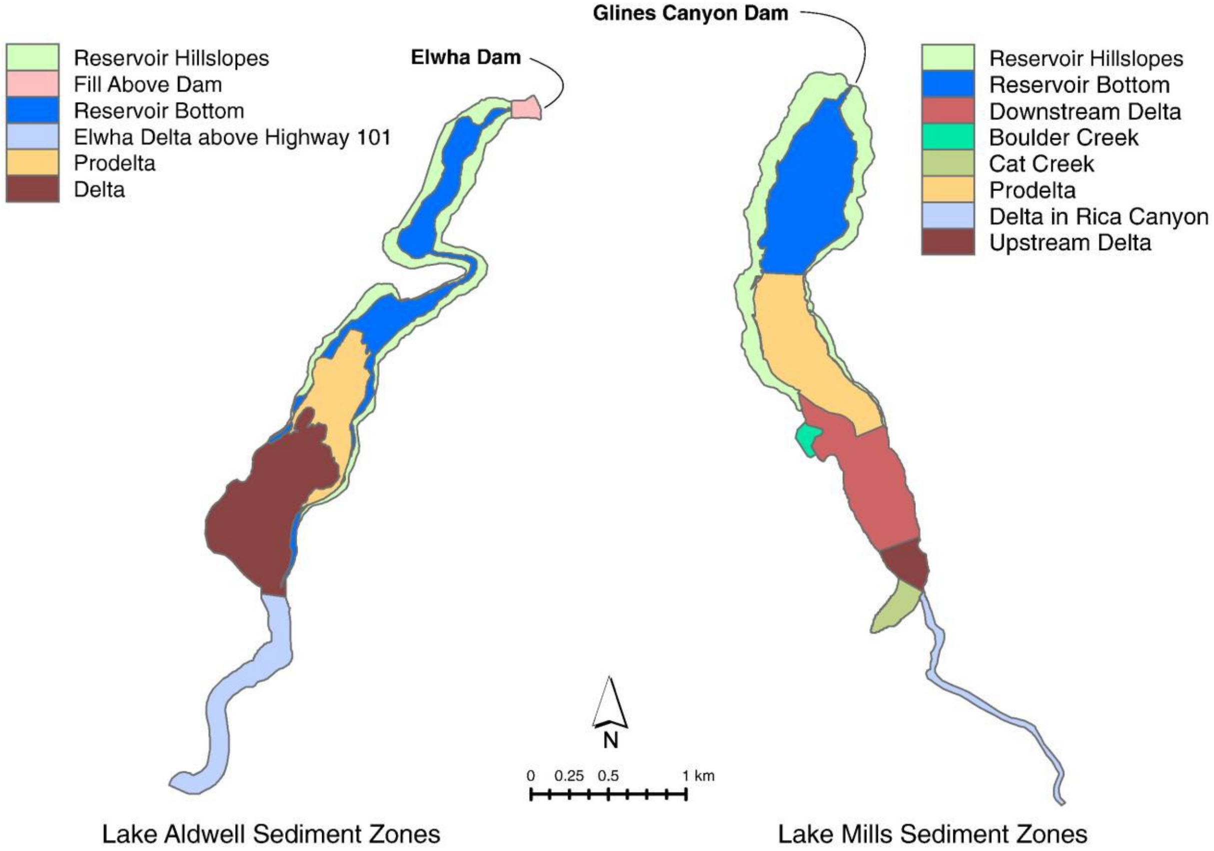


figure 8: These images clearly delineate the deltas that formed behind the reservoirs. Sediment in the darkest red was found to be 30 meters thick (Randle, Bountry, Ritchie, & Wille, 2015a, p. 7).

These images clearly delineate the deltas that formed behind the reservoirs. Sediment in the darkest red was found to be 30 meters thick (Randle, Bountry, Ritchie, & Wille, 2015a, p. 7).

Another example of the same thing is found in Englebright Lake. This lake is in the California Sierra Nevada Foothills. The 2001 bathymetric survey showed the greatest sediment accumulations in the mid to upper reservoir. Here the sediment is up to 35 meters thick. This lake is in the California Sierra Nevada Foothills.

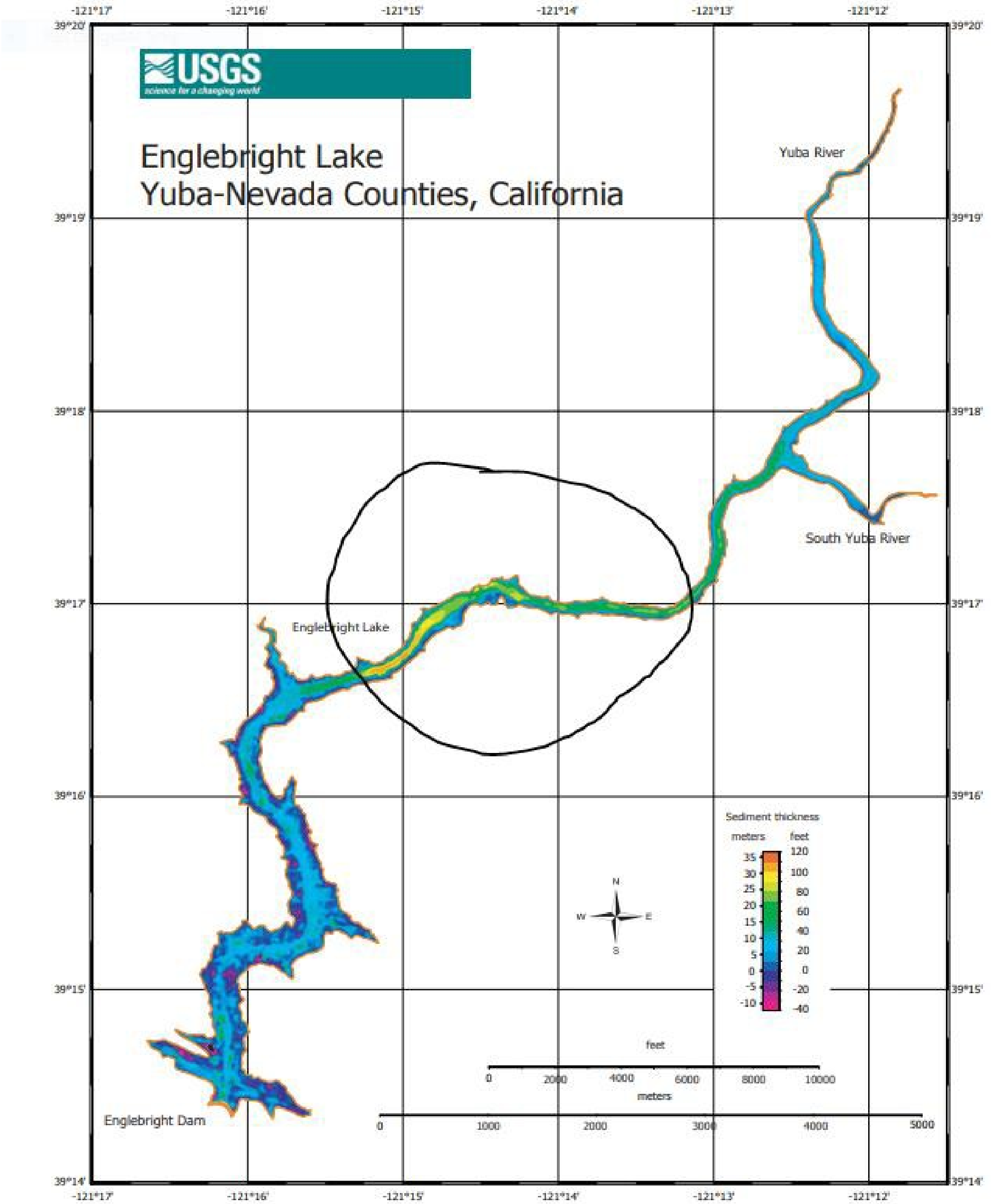
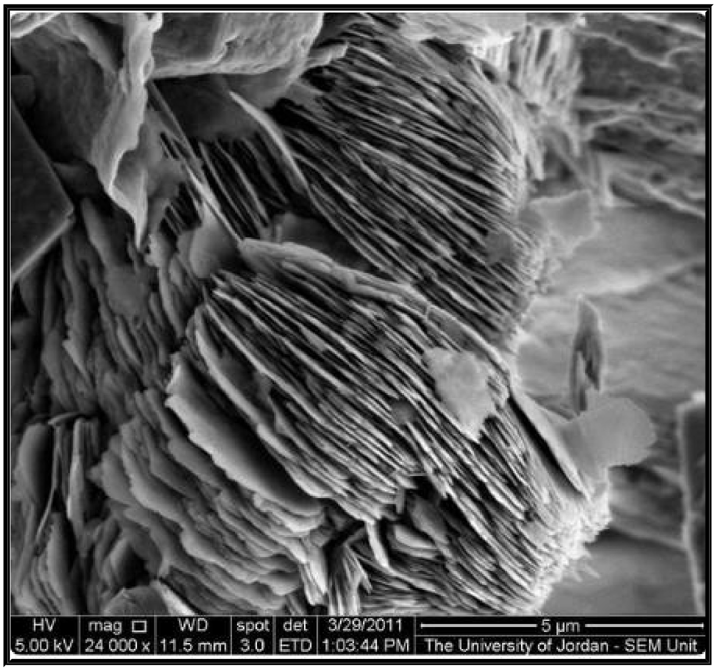


figure 9: Although this lake is 26.4% filled with sediment, it has a long way to go before accumulations with be significant at the dam itself (Snyder et al., n.d.) (Childs, Snyder, & Hampton, n.d., p. 10).

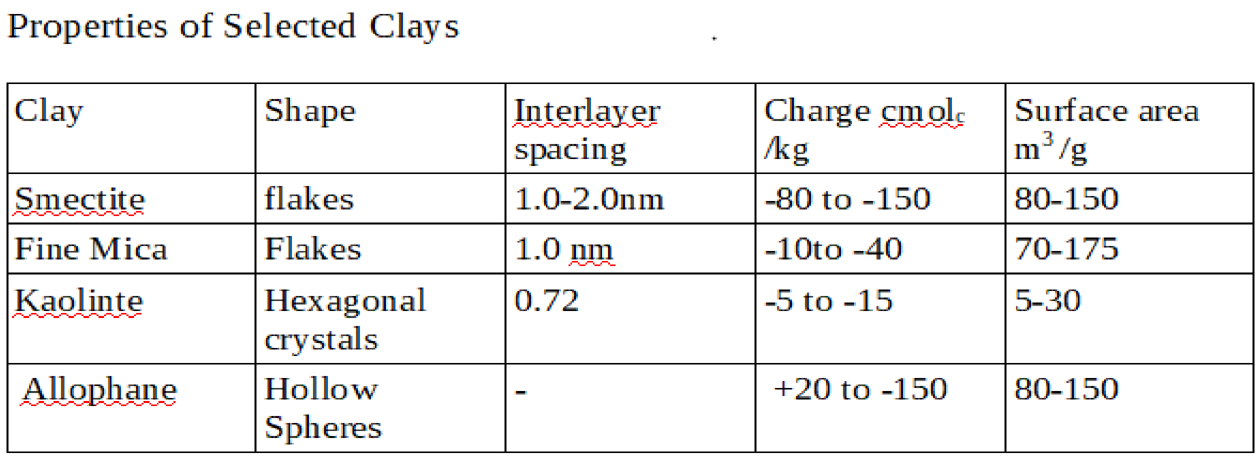
Sand Silt and Clay

Sediments consist of gravels, sand, silt and clay. Gravels are significant to reservoir management because they take up a lot of space. According to the USDA specifications, anything from 2mm to 0.05mm is sand, it is easily moved by water but does not retain water. Particles from 0.05 mm to .002 mm are classified as silt. This is smaller than can be seen by the naked eye. It tends to not hold water but like the sand still flows easily in streams. The smallest particles are clays. Clay particles are less than 0.002 mm. Clays have unique properties that make them important in reservoirs. They do not settle out quickly but tend to remain in solution. Since clay has a high surface area per quantity of material and because it is electrically charged, the presence of clay is more likely to increase pollutant accumulation in sediment layers (Çevik, Göksu, Derici, & Fındık, 2009, p. 312) (Meunier, 2005).

Figure 10: Clays are not spherical but intricate in structure. This picture at 24,000x magnification shows the microscopic paper type sheets of the 1:1 kaolinite clay and shows the many surfaces available for absorption. Kaolinite is one of many clay colloids that all have specific crystalline structures and characteristic electrical charges(Brady & Weil, 2007, p. 314) (Meunier, 2005, p. 47).



There are many structures of clays. To get an idea of the variations here is a chart from Brady and Weil (Brady & Weil, 2007, p. 313).



Properties of Selected Clays

Clay	Shape	Interlayer spacing	Charge $cmol_c$ /kg	Surface area m^3/g
Smectite	flakes	1.0-2.0nm	-80 to -150	80-150
Fine Mica	Flakes	1.0 nm	-10to -40	70-175
Kaolinte	Hexagonal crystals	0.72	-5 to -15	5-30
Allophane	Hollow Spheres	-	+20 to -150	80-150

Table 1: Some clays are flakes, others hexagonal crystals, some hollow spheres and tubes. Interlayer spacing varies as does the net charge

Characterizing the sediments into sand silt and clay is the first job of most sediment studies.

Sand silt and clay tend to accumulate in reservoirs according to the following pattern:

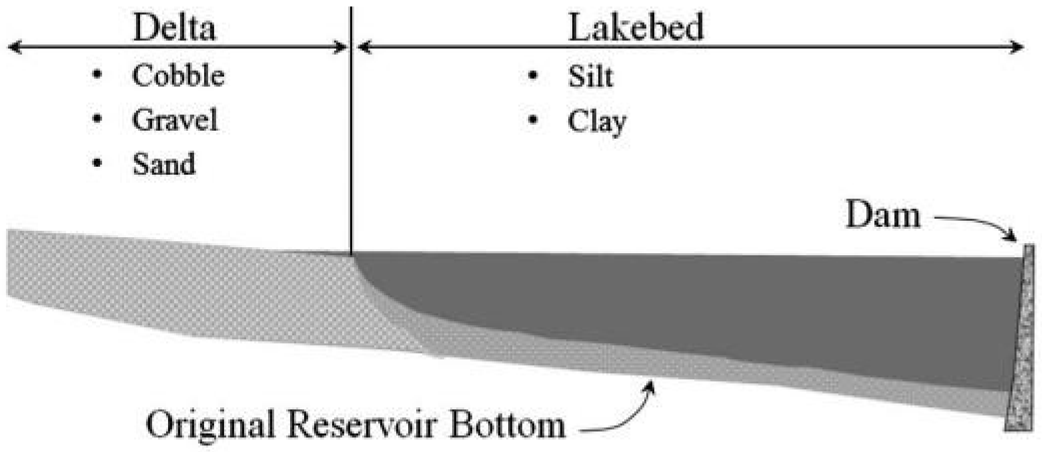


figure 12: The heavier debris flows downstream until there is not enough water current to move it. The lighter silts and clays travel further toward the dam.

Sediment Cores

Reservoir sediments can function as a hydrologic column that records depositional history related to major erosion events in the watershed. The rate of sediment accumulation can be determined by measuring the depth of deposition above an identifiable and datable horizon. One way to do this is with ^{137}Cesium. A layer of radioactive ^{137}Cesium was deposited globally between 1954 and 1964 as a result of fallout from Russian nuclear testing. The ^{137}C is strongly adsorbed to clays and can be used to trace and date sediment deposits (Morris & Fan, 1998, p. 304). Here is an example of a core correlation done on the Barasona reservoir:

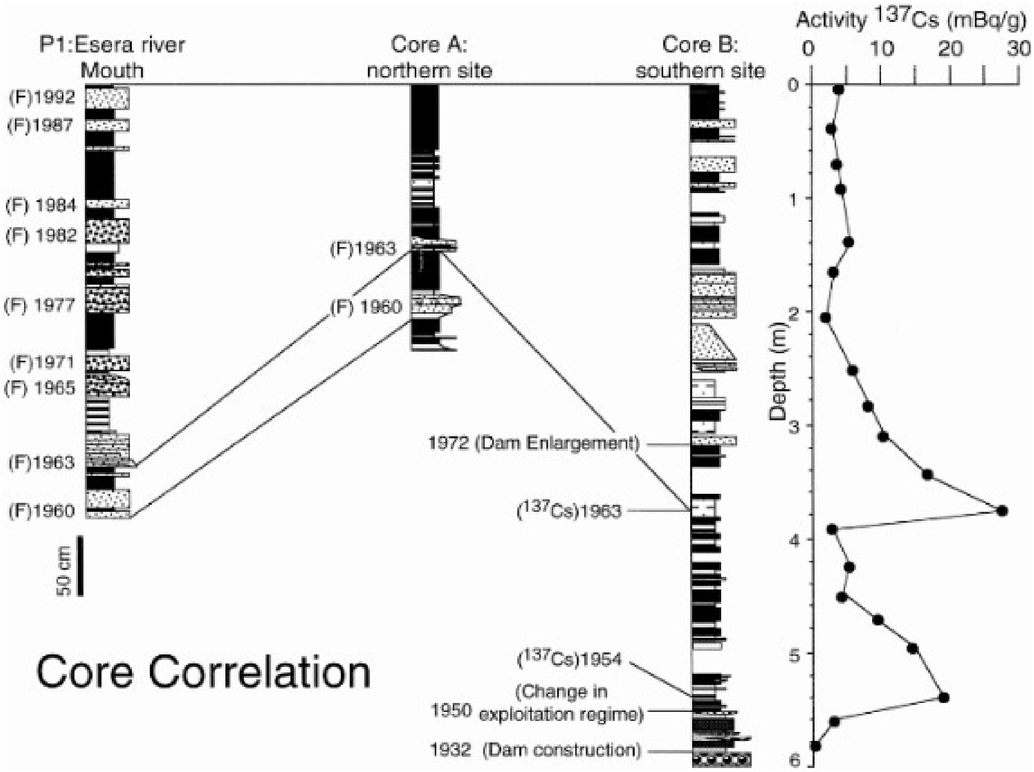


Figure 13: In this diagram a relative chronology was constructed by relating sandy silt layers to known flood events. In core B Cesium 137 levels provide milestone dates. (Valero-Garcés, Navas, Machín, & Walling, 1999, p. 16)

These sediment columns not only show a rate, but also can be traced to different parent materials in the watershed and their geographic area of origin can be traced (Valero-Garcés et al., 1999). In their paper: S*ediment sources and Siltation in Mountain Reservoirs: a case study from the Central Spanish Pyrenees*, the authors traced the origin of sediments of the Barasona reservoir to their origins in the tributaries of the watershed (Valero-Garcés et al., 1999). For example, in his paper entitled *Sediment from hydraulic mining detained by Englebright and small dams in the Yuba basin (L. A. James, 2005)* Allan James uses the percentage of quartz pebbles ≤ 50mm in samples of be material as a reliable indicator of the proportion of tailings from hydraulic mines. These sediment columns show the history of where and when erosion occurred in the watershed and they record flood events.

Nutrients

Key nutrients are not normally significantly impounded in reservoir sediments. (Teodoru & Wehrli, 2005, p. 1) In the case of the iron gate dam along the Danube river the nutrient accumulation in the sediments represent only 1% of the “missing”loads of Nitrogen and Phosphorus (N and P). The sediment accumulation corresponded to 5% Total Nitrogen 12% Total Phosphorus and 55% Total suspended solids of the incoming loading. A mass balance revealed that more N and P are leaving the reservoir than entering via the inflow thus the reservoir creates a minor source of nutrients. Nitrogen has many forms with various properties that allow it to move freely, but phosphorous moves depending on the Equilibrium Phosphorus Concentration, (EPC). If the incoming water has less P than the sediment, P will be released, if the incoming water has more P than the sediment, P will be retained. EPC also varies with changes in redox and pH.(Kim et al., 2003) So if incoming water remains consistent in its Phosphorous concentration pH and redox parameters, P concentration will not change in reservoirs.

Heavy Metals

Sediments are one of the ultimate sinks for heavy metal discharges into the environment. Heavy metals are a group of pollutants of high ecological significance. They are not removed from water by self-purification, but accumulate in suspended particulates and sediment, and then enter the food web. The metals are discharged into the watershed primarily from anthropogenic activities, volcanic activity and the weathering of rock and soil. These metals accumulate in reservoirs and enter the food chain. This is a worldwide problem; the metals are indestructible and most of them have toxic effects on living organisms when they exceed a certain concentration. Various biogeochemical processes such as pH, redox, oxygen concentration and carbon type combine with the presence of absorptive clay to create the precipitation of these metals in new solid phases into sediment. (Çevik et al., 2009, p. 2) Metals of concern are regional and depend upon the inputs to the system both anthropogenic and lithogenic. Magnesium, Iron, Copper, Zinc, Cadmium, Mercury, Chromium, Lead and Nickel are some that have been studied (Mn, Fe, Cu, Zn and Cd, and Hg, Cr, Pb, Ni)(Chabukdhara & Nema, 2012, p. 8) (Klaver, van Os, Negrel, & Petelet-Giraud, 2007, p. 9)(Çevik et al., 2009, p. 1).

According to Morris and Fan:

> *Contaminants may include agricultural chemicals such as pesticides, runoff or point source discharge from upstream industrial areas which may contain heavy metals or toxic organic compounds, products from mine drainage or tailings, or products from industrial or other spills. Some constituents may not be classified as toxins, but nevertheless may have extremely deleterious effects on downstream ecosystems, such as sediment containing high nutrient levels or organics which will exert a significant oxygen demand*
> (Morris & Fan, 1998, p. 559).

Industrial Pollutants

Zinc Cadmium, Mercury and PCB's are industrial pollutants. Zinc and cadmium are used in pesticides and fertilizers (Ghrefat & Yusuf, 2006, p. 1).

Mercury was widely used in gold mining and in the manufacture of acetaldehyde and continues to be deposited into the atmosphere by coal power plants (Ghrefat & Yusuf, 2006, p. 1)(Gilbert, 1917). Only Methyl Mercury is of concern.

Mercury can methylate under low redox conditions, and this methylmercury, now soluble, bio accumulates in fish. This form of mercury has been responsible for relatively recent mass poisonings, the most notable one being in Niigata, Japan. In this case methyl mercury was released into the ocean as a byproduct of acetaldehyde production. When 2,000 residents ate fish from this bay they were poisoned. Other mass poisonings were from MeHg treated grains in Sweden and Iraq (Meyers, Davidson, & Weiss, 2006).

PCBs or polychlorinated biphenyls were highly used in industry to make hydraulic fluids, transformers, lubricants etc… Known for their stable properties they are slow to break down in the environment. They tend to sink to the bottom of water bodies and then enter the food chain through fish. Although banned from manufacture in the US in 1977 they remain in significant quantities in fish ("PCBs in fish and shellfish," 2013).

Both PCBs and Methyl Mercury can impair cognitive function, especially in at-risk populations.

Quantification of Heavy Metals

Excessive heavy metals in sediments can be quantified by the Enrichment Factor (EF) or the Geo-accumulation Index (I_{geo}). The Enrichment factor, (EF) is a geochemical index based on the assumption that under the natural sedimentation conditions, there is a linear relationship between a reference element and other elements. Iron has been used successfully for this purpose. The EF is defined as follows: $EF = (Me/Fe)_{sample}/(Me/Fe)_{background}$ where the (Me/Fe) sample is the metal to iron ratio in the samples of interest and (Me/Fe) background is the geochemical background values of the heavy metal to iron ratio.

The geo-accumulation Index (I_{geo}) compares current and pre industrial concentrations of sediments.(Chabukdhara & Nema, 2012, p. 4)(Çevik et al., 2009, p. 6)

Sediment in Reservoirs can hold these toxic substances indefinitely. They can mobilize with changes in the water such as pH, redox, temperature or turbation. The composition of this accrual needs to be considered when removing sediment or taking down dams. The dam removal process will release whatever is in these sediments to the downstream environments. It can cause great harm.

Ecosystem Effects

Not only are these aging structures less safe over time. They are filling with sediments. They have also had ecosystem effects such as shoreline erosion, channel incision and habitat disruption. The riverbeds below the dams coarsen without the fine sediments to balance them out.

Dams stop many of the ecosystem functions of our rivers. The greatest one is the connectivity that a river can provide to lands without the blockage of the dam. The river imports nutrients and exports toxins. Seeds and other genetic information are shared up and down an undisturbed river. The river brings nutrients upstream with fish such as salmon which can grow to over 100 pounds each. Salmon are a keystone species, they bring nutrients back from the seas to the forest thereby nourishing plants and animals. A free-flowing river will take many toxins and waste products out to the ocean where they are diluted and dispersed. With a dam in place, toxins stay in place on the land instead of being discharged into the sea (Bednarek, 2001, p. 6). This retention is actually one of the reasons to leave a decommissioned dam in place.

Coastal Shoreline Loss

Because sediment loads from the watershed are held in dams instead of nourishing wetlands at the deltas, sediment loads to the river deltas are reduced. River mouths are constantly being eroded by oceanic influences and without continual deposition of sediment from the watershed, the balance between deposition and removal of soil at coastlines is upset. The coastal wetlands act as a buffer along shorelines and often develop at the deltas where the river meets the sea. The reservoirs only add a part to this complex problem. Climate change causing sea level rise makes its contribution. Subsidence due to ground water withdrawal or peat oxidation after wetland drainage also plays a part. Other waterworks such as channelized flow and the use of levees reduce the area of influence of the river. Coastlines lose their wetland buffers and seawalls are built. It has been shown that living shoreline withstands erosion and hurricanes much better than seawalls or abrupt land to water interfaces.

Shoreline loss is a significant problem in places like Louisiana where, according to the USGS, 2,006 square miles of land have been lost since 1932. ("USGS: Louisiana's Rate of Coastal Wetland Loss Continues to Slow," n.d.) In Louisiana they measure shoreline loss at 1.3 miles per day. 24 of the world's 33 major deltas are currently shrinking because of reservoir sedimentation. (Morris & Fan, 1998, p. 27)

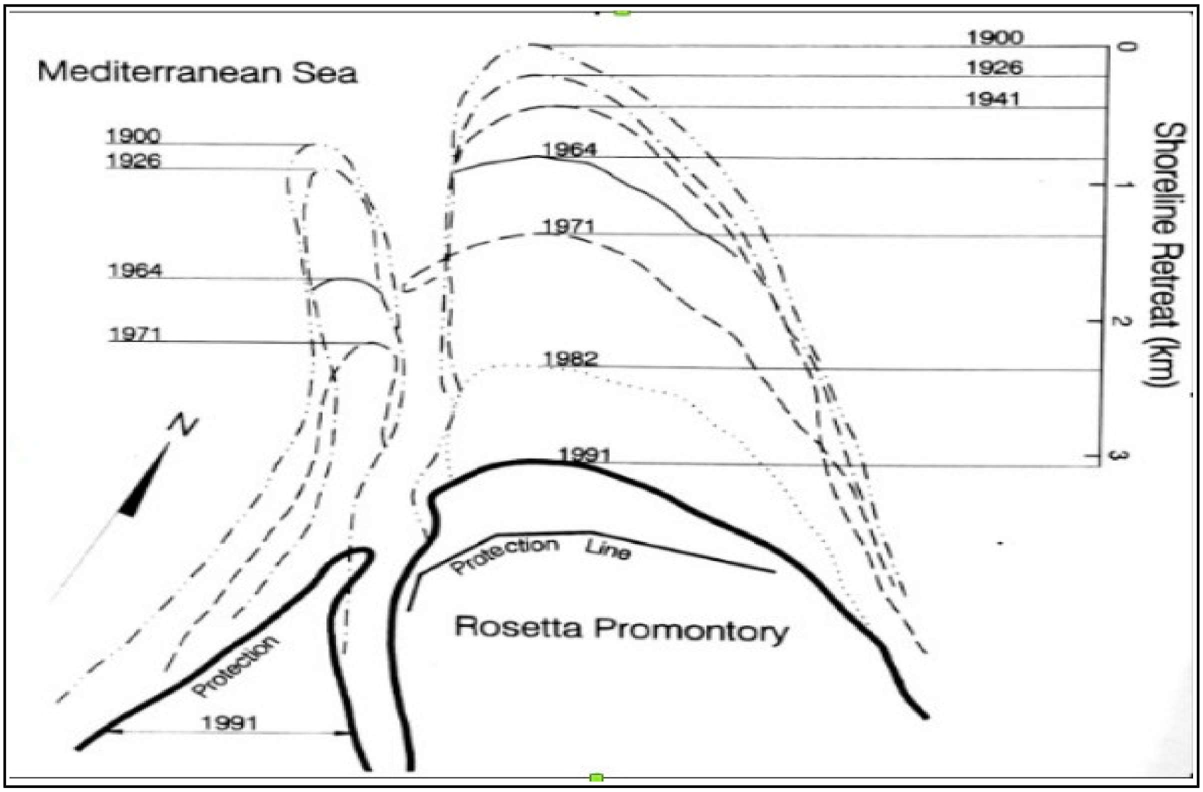


Figure 14 : The erosional history of the Nile delta. The first Aswan dam was completed in 1902 and the Aswan High Dam in 1967 (Morris & Fan, 1998, p. 27). Shoreline erosion began with the early dam but was greatly accelerated with the presence of the larger structure.

Habitat

An impact of dams is the disruption of the habitat of wildlife. Fish are prevented from spawning in upstream waters, macro-invertebrate communities are diminished, and with that, the birds that feed on them are diminished as well. The overall community structure loses diversity. Large dams function as walls that keep fish from moving freely in the rivers. The loss of once lively waters has had economic impacts on people who used to fish for a living. The changes in temperature, water quality, or blocked migrations may be of overriding importance (Baxter, 1977), but we cannot overlook the alteration of the natural flow regime, or hydro pattern that supports biodiversity by its seasonal ebbs and flows. Normally water flows higher in the rainy seasons and less in the dry ones. Many species depend on these seasonal variations for their life-cycle patterns. A regulated river will have flow rates inconsistent with natural patterns, and incompatible with many wildlife life cycles.

In their study on habitats in impounded versus free-flowing water entitled, “Effects of Multiple Low-Head Dams on Fish, macroinvertebrates, Habitat, and Water Quality in the Fox River, Illinois, Santucci, Gephard and Pescitelli quantified their results as follows:

	Free flowing water	Impounded water
IBI index of biotic integrity	46/60	<31/60
MCI macroinvertebrate condition index	>415/700	<210/700
QHEI quality of habitat evaluation index	>70/100	<45/100
DO dissolved oxygen	Less flux	2.5-18 mg/l wide flux to low
PH acidity of the water	Less flux	7 – 9.4 middle to high
Water quality standards	met	Not met

Table 2

The results are summarized in table 1(Santucci et al., n.d.). They found that the index of biotic integrity, the macroinvertebrate index and the quality of habitat evaluation index were all significantly lowered with impounded water. Dissolved oxygen and pH had more fluctuations in impounded water than in free-flowing water, and impounded water did not meet water quality standards.

Harmful Algal Blooms

Reservoirs can be subject to harmful algal blooms (HABs). These do not occur in every system, but the slowing and deepening of the water, which lessens its mixing with oxygen, coupled with excessive nutrient loads can result in a tendency in nutrient laden watersheds to HABs. The algae grow as a result of available nutrients and their decomposition requires oxygen.
Oxygen is depleted in the HAB zones and can create anoxic waters that lead to dead zones where fish are killed.

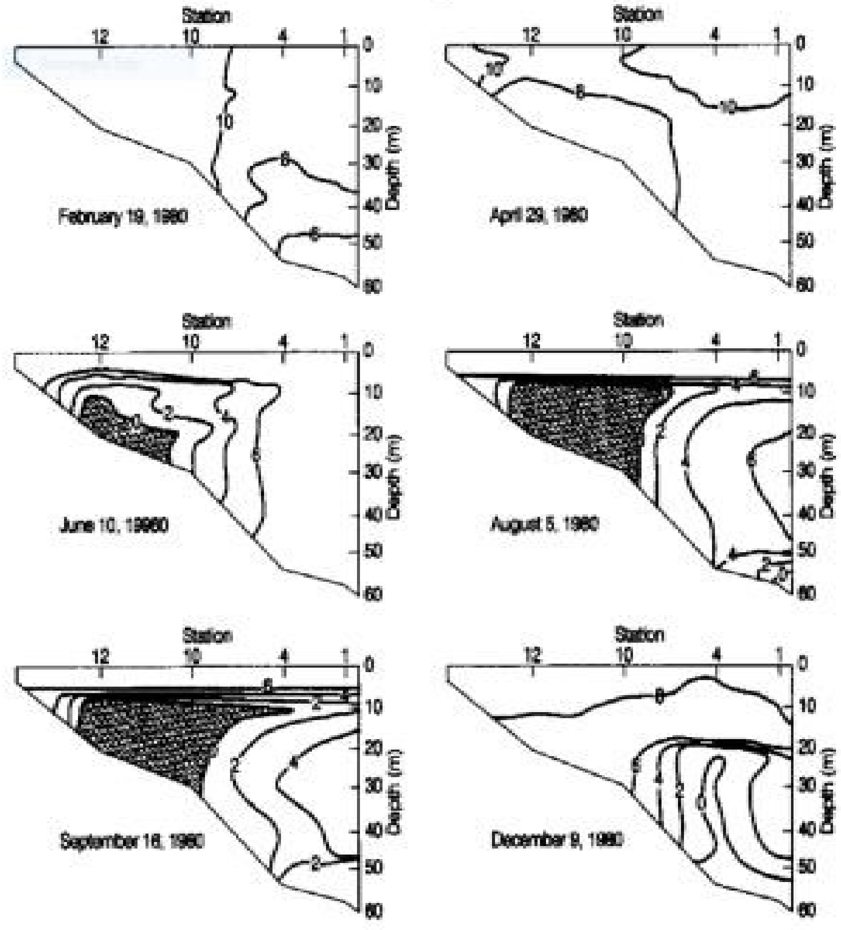


Figure 15: Seasonal variations in dissolved oxygen distribution in Lake DeGray, Arkansas. The upstream zone receives the highest rate of organic loading (Morris & Fan, 1998, p. 86). Black shows where there is no oxygen in the water and therefore shows where fish can't live. Dead zones like this are a significant environmental concern.

Water Diversion

Although not a direct result of the reservoir as a structure, many reservoirs divert water. In California there was the complete loss of the large but shallow Tulare lake that used to set along highway 5 near Coalinga. The water diverted from Owens lake left it dry, and now that area experiences toxic dust storms. Two major rivers have lost their connection to the sea. The Colorado, which traverses seven US states and part of Mexico has been a vital source of water for 40 million people. It hosts an extensive system of dams, reservoirs and aqueducts that divert in most years its entire flow. Since 1960, the mighty Colorado has rarely reached the sea. The delta is only a fraction of its former size and delta is no longer a suitable habitat for many sea animals that used to live there. In a cooperative effort between the US and Mexican governments.
52,000-acre feet of water were released in a pulse flow and the river once again met the sea with the aim to revitalize wetlands in the area. The event was called Minute 319, and for 8 weeks in 2014 water traveled through the desert in the old riverbed finding its inevitable discharge in the waters of the Pacific. This pulse was only a fraction of the original 16.3 million acre feet/year (52000/16,300000 =4%) ("Colorado River," 2018). The agreements on water rights to this river are laid out for flood or drought conditions. The one-time pulse is far from the ecosystem boost needed to recover a land from a dried-up river.

Another missing river is the San Joaquin, once the major southern input to the San Francisco bay, the San Joaquin river languishes as part of a government 're-watering project'. Engineers calculate seepage patterns and groundwater impacts on nearby orchards in an attempt to restore flows in pieces of the river. The major tributaries to the San Joaquin are the Merced river, the Tuolumne river and the Stanislaus river. Historically these mighty waters created a burgeoning ecosystem that include king salmon, elk, grizzly bear and vast wetlands that support waterfowl. Today it provides drinking water to 4.5 million people, 3000 megawatts of power and supports some of the most productive and profitable agriculture in the world. The cost is more than 100 miles of the main stem river being dry for over fifty years. (Rivers, 2016). The river is endangered and the impacts are severe.

Evaporation

An unintended side effect of reservoirs is that the reservoir increases evaporation of river runoff by 15%. we know that lakes do this too, but we have created conditions conducive to evaporation with our reservoirs.

Channel Incision and Reduced Floodplain Inundation

Other unintended effects are channel incision and reduced floodplain inundation (Ligon, Dietrich, & Trush, 1995). Although flood control is one of the major benefits of dams, the resulting river banks are limited. The incised channel supports woody vegetation or no vegetation, and the benefits to water quality of wetland cycling are lost. The incised channel does not create groundwater storage, support riparian vegetation or wildlife. Projects have been undertaken to conserve water resources through meadow restoration and stream bed restoration. These projects slow the water, let the soil clean it, let the soil absorb it to recharge groundwater, support growth of vegetation in a wider corridor, and consequently support the wildlife that corridor sustains. An example of a restored riverbank is the McCarran Ranch preserve along the Truckee river in the Nevada Desert. The Nature Conservancy began this project in 2006. Severe channel incision that was part of a flood control project had lowered groundwater beyond the reach of riverside vegetation. To restore the river they filled in the deep channel and reconnected the river to its floodplain. They also established native plants. In the restored river water meanders and life flourishes bringing a corridor of green to the desert ("McCarran Ranch Preserve - The Nature Conservancy," n.d.).

Sediment Management

Sediment management consists of proper financial planning and an array of sediment removal techniques. Typical removal strategies include: Reduction of sediment yields (i.e. watershed management,) sediment routing, sediment flushing, and sediment removal (Palmieri et al., 2001, p. 4).

Cost Benefit Analysis

One of the dysfunctional pieces in sediment management process is the initial Cost Benefit Analysis (CBA) done for the dam. The way the CBA is traditionally set up, costs incurred after 30 years for any project are neglected. Because the CBA does not consider the long view, the true cost of the reservoir is not calculated. Any sustainable reservoir management plan needs a budget that includes the whole cost of the dam (Palmieri, Shah, & Dinar, 2001, p6). This would provide for the costly ongoing sediment management and the eventual repair or take down of the structure. These costs are typically given to future generations, and no money is allotted for ongoing sediment removal. For reservoirs to be sustainable this type of planning is essential.

Sediment Reduction

The reduction of sediment yields can be accomplished two ways, either prevent erosion or trap the eroded sediment before it enters the watershed.

Erosion Control

Erosion prevention closely resembles good soil management practice. In good soil management the practice fits the soil. In other words, topography and soil type are considered when putting in roads, cutting forest and laying out farm fields. Soil disturbance is minimized by conservation tillage by the farmers, reasonable road layouts by the loggers, and avoiding to much tractor work in the rainy seasons by the developers. Roads and farm fields consider terracing, flow diversion, cross drains and try to use a low channel slope in a protected (grassy) channel for concentrated flows.

A simple practice is to keep the soil covered. Whether with straw, a vegetative canopy or ground level vegetation, covered soil is not prone to erosion loss.

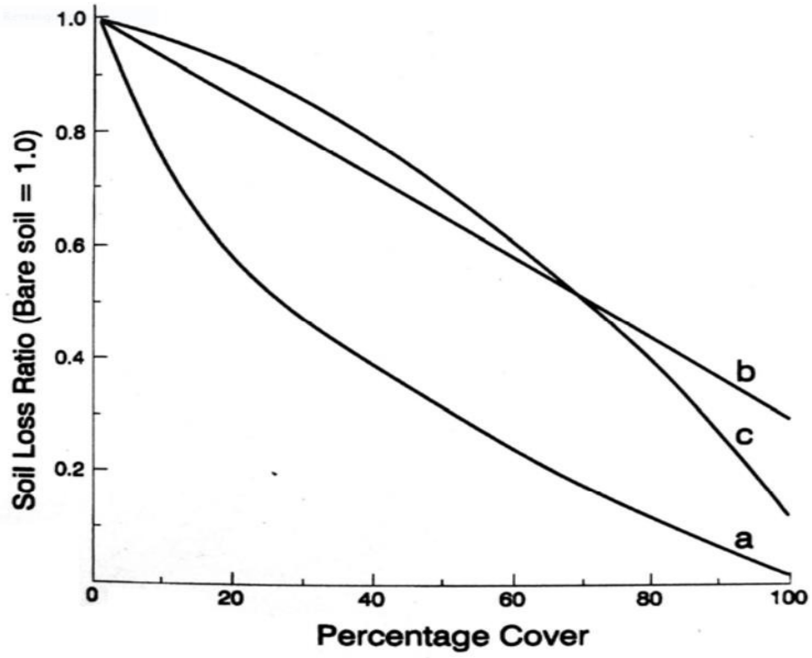


figure 16

A = ground level vegetation b = vegetative canopy c= oat straw mulch (Morris & Fan, 1998, p. 366).

High infiltration rates of water into soil also discourage erosion and increase soil retention. These rates can be raised with good root structures in un-compacted soils.

Along with erosion control measures, sediment trapping may be a consideration to reduce loads to reservoirs.

To trap sediment on site riparian buffers can be used as can small sediment basins. The riparian buffer is a vegetated strip along the waterways. The roots of these grasses and trees hold back soil from entering the waterways. The small sediment basin is a depression in the landform that lets the water pool and infiltrate slowly rather that rushing to the river.

For larger flows sediment detention ponds can be a good choice. They will fill in time, but tend to be smaller, and easier to manage or relocate.

The most important part of erosion control soil management is to monitor the results and adjust when needed. For instance, a small sediment basin could develop an eroded side thereby not retaining water. Monitoring the system is the key to success.

Sediment Routing

When it comes to sediment routing there is a Chinese slogan: "Discharge the muddy water, impound the clear water." (Morris & Fan, 1998, p. 418) This can be done with a sediment pass through, an off stream reservoir or a sediment bypass tunnel (Morris, n.d.).

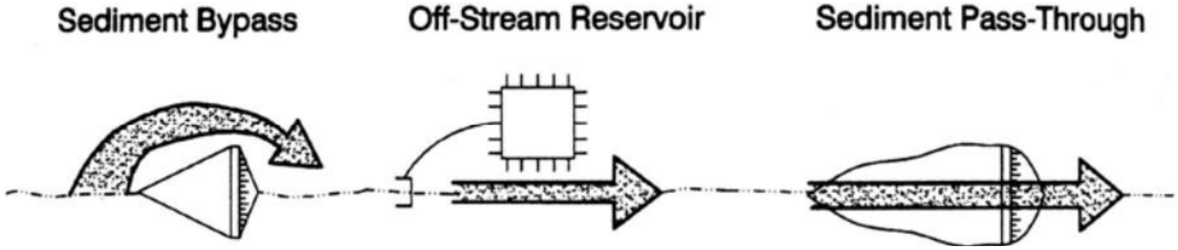


figure 17: Types of sediment routing

All routing requires a lot of water which is the main disadvantage. The advantage is that routing is more environmentally benign than flushing.

Pass through routing is accomplished by letting the water pass quickly through the dam (keeping the water levels low) when the incoming water is muddy. The reservoir is operates like a switchable train track keeping the water or letting the water pass depending on conditions at hand.

The off-stream reservoir is created to fill with more turbid waters and expected to fill with sediments. This can save a more valuable structure downstream, but it will fill eventually, and other measures will have to be taken.

The sediment bypass works on the principle that more turbid waters can be drawn down and passed through from the bottom of the reservoir. The study of turbid density currents is beyond the scope of the paper but can be important in understanding how to manage turbid waters.

Flushing

The tool of Flushing involves a reservoir draw down and the opening of a low-level outlet to flush the eroded sediments through the reservoir. These tunnels are built into the dam itself. This system does not allow multi-year water storage, and larger debris still can accumulate behind the dam (Morris & Fan, 1998, p. 506).

Mechanical Removal

Sediment can be managed by a variety of Mechanical Removal processes. It can be done with wet or dry sediment and consists of tractor work or dredging. Although costs can be significant, mechanical removal is easy to manage.

Dry

For dry sediment removal the reservoir must be emptied. This will result in water losses and can be done with standard equipment. Dry removal tends to be costly however, the resulting sediment is in an easily manageable form.

Dredging

Dredging is the lifting of sediment out of a wet reservoir and piling it somewhere else. For wet sediment removal there are three kinds of dredges.

Clamshell

The first type type of dredge is the clam shell bucket to a scow- this apparatus works better for coarse debris, finer silts and clays are not retained by the clamshell.

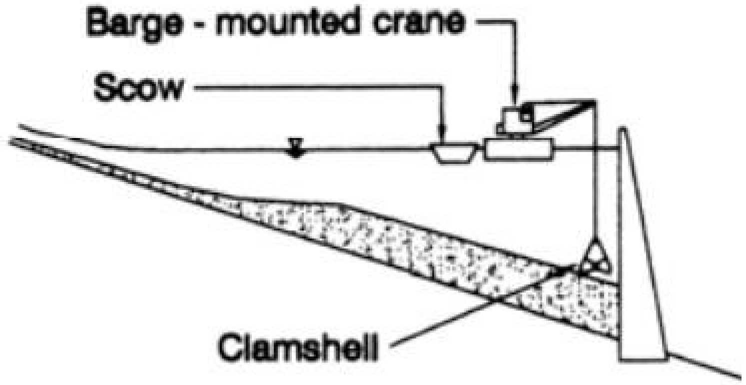


Figure 18: clamshell dredge

The clamshell is raised and lowered from the barge and the sediment is deposited in a scow.

Cable Dredge

A second type of dredge is the cable dredge.
The cable suspended pump moves sediment to a slurry pipeline. Considered by many to be the most versatile of the dredges it is maneuverable and can handle coarse or fine sediments.

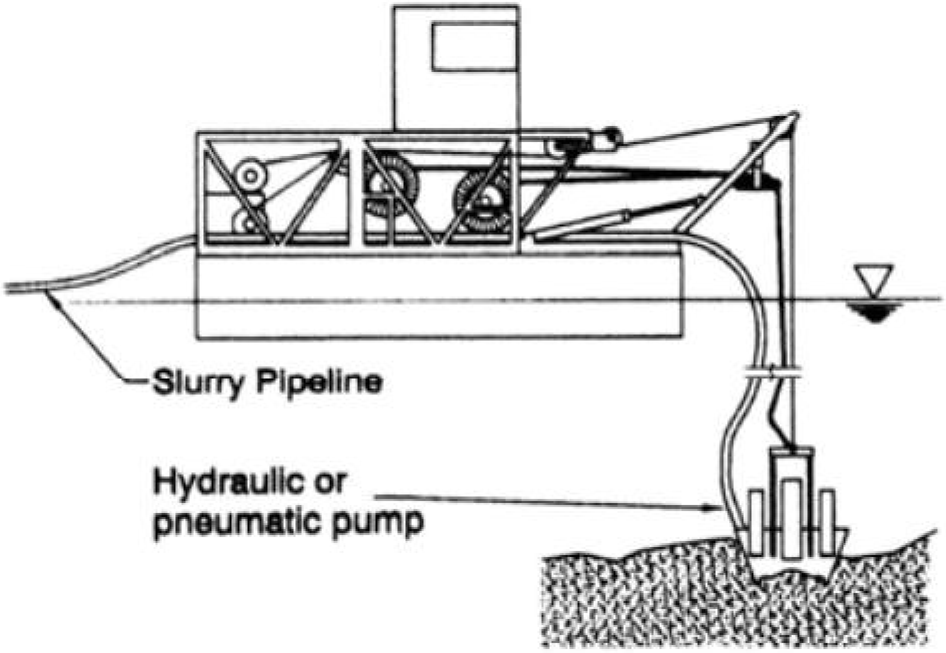


figure 19: cable dredge

The pump sits on the sediment in the bottom of the reservoir and the slurry pipe is variable in length to accommodate topography in the reservoir. The slurry goes wherever you route the pipe. Larger debris not recommended for this style of dredge.

Siphon

The last type is the siphon dredge. The siphon dredge has no pump, there is a low discharge point and the discharge line is kept under water. The difference in pressure between water at the top of the reservoir and water at the bottom moves the sediment out the discharge point located as low as possible on the dam.
Suction dredging is limited to areas closer to the dam because of the deeper water is needed to create the strong hydraulic head.

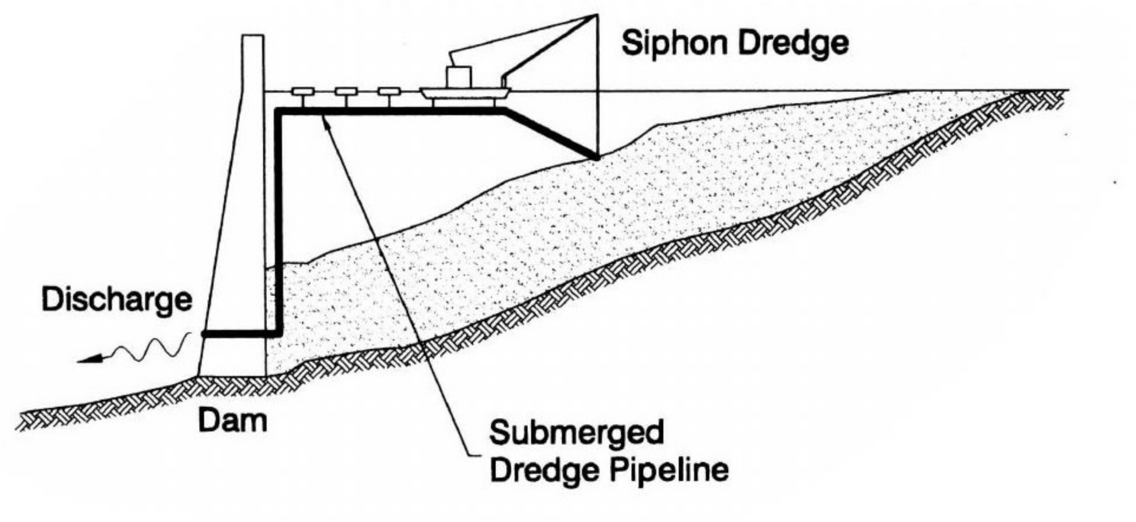


figure 20: The siphon dredge works better for smaller applications (Morris & Fan, 1998, p. 514).

Suspended Solids in Dredging

One of the issues encountered in dredging for sediment removal is that disturbance of fine sediment re-suspends toxins into the water column. In the case of Methyl Mercury this is a deadly re-suspension. Because of this the standard reservoir maintenance of sediment removal can be halted. Research is being done on the use of a coagulant to keep the Mercury form dispersing into the water (Graham, 2018). It is hoped that when dredging occurs after coagulant application the metal will stick to the sediments as they are removed from the reservoir. Once the Mercury laden sediment is withdrawn Mercury can be extracted from the removed sediment with a centrifuge and re purposed.

Adequate disposal sites are necessary for any reservoir sediment removal process. The best sites are large, nearby and not environmentally sensitive. More work needs to be done on the re-purposing of these soil materials. Very often they are piled like mine tailings near their point of origin. Sometimes they are trucked to a dump site, and other times they are hauled away for fill on other projects.

Decommissioning Dams

Overview and Occurrence

There is a growing trend toward dam removal in the United States. We lead the world in this. We take down our dams because they are a safety hazard, they no longer serve their intended purpose, and because of the scientifically documented effects they have on river ecosystems.

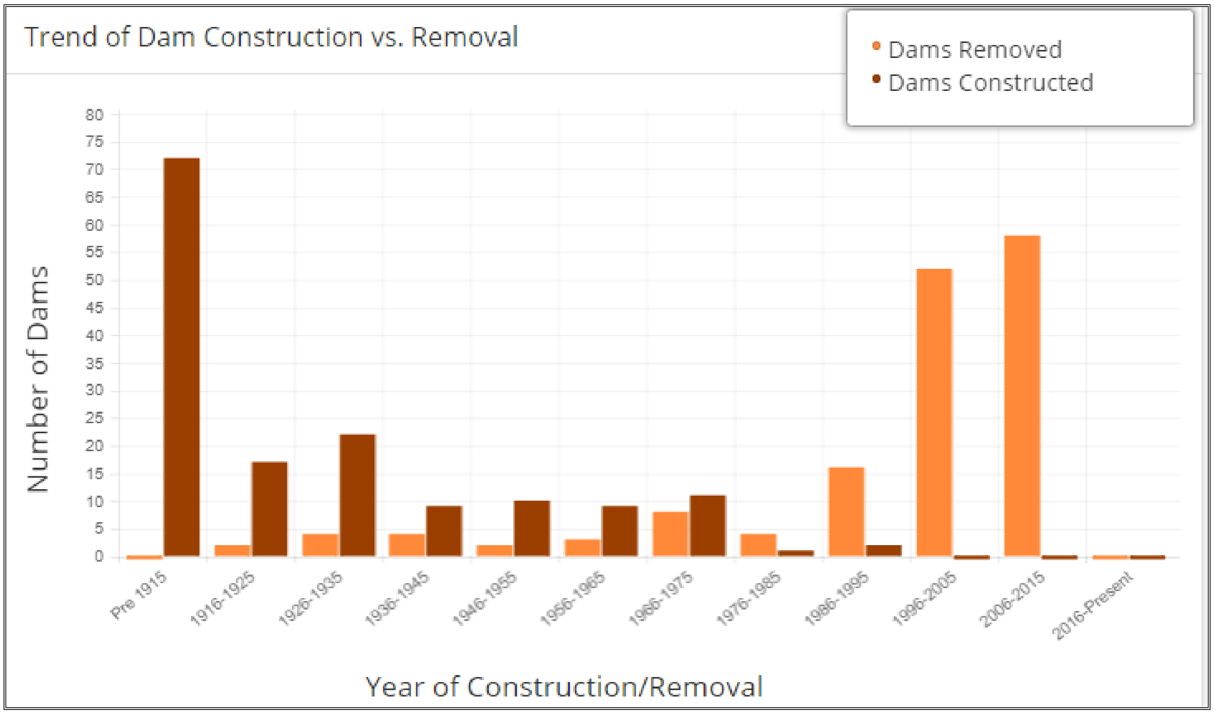
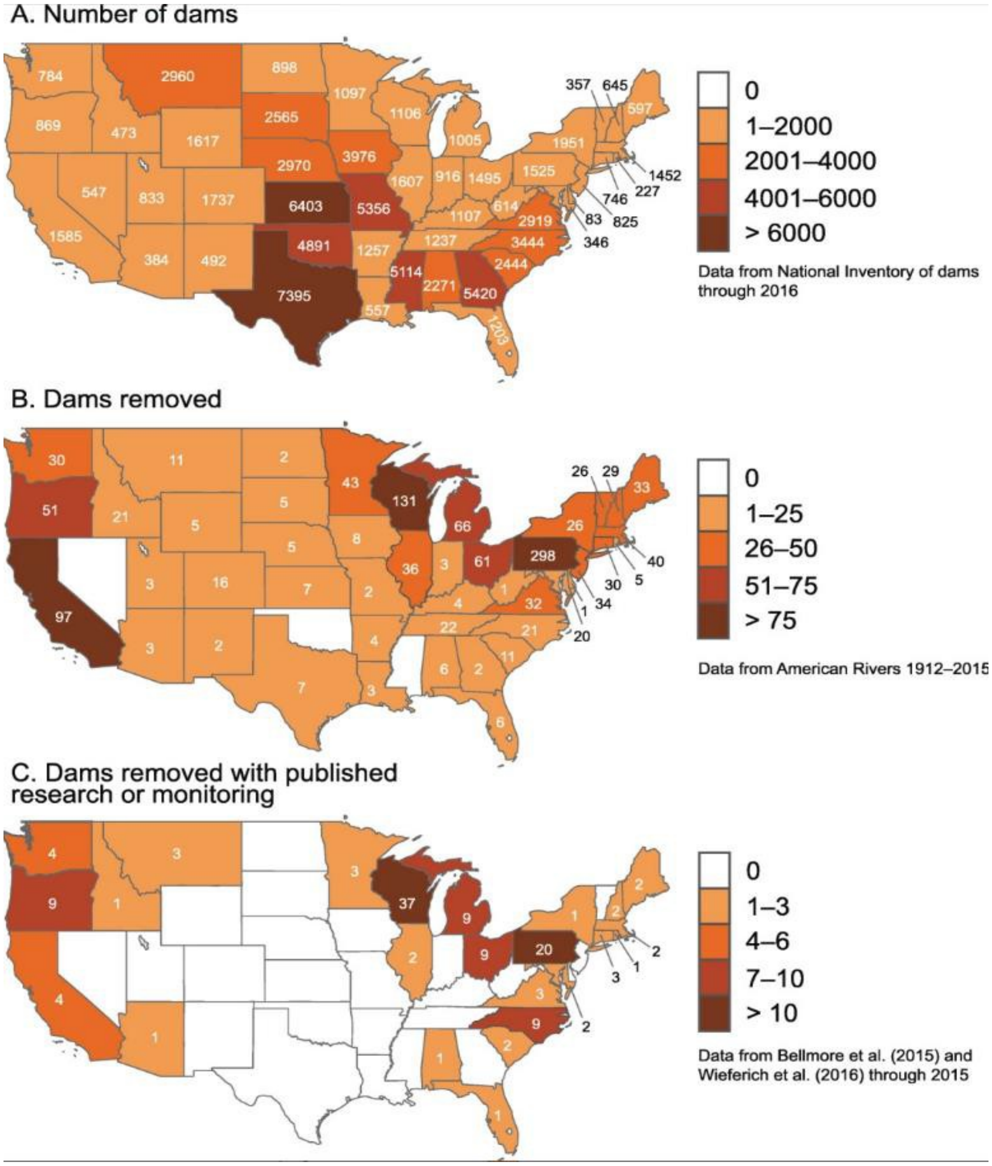


Figure 21: The trends of dam construction and dam removal for the one hundred years from 1915 to 2015. Dam removal is now eclipsing dam construction ("NID by State," n.d.-b).

Many of the 80,000 dams in the United States have found themselves outdated. The myriad of original purposes have been served and are no longer relevant. For instance, some were built to provide power for milling grain or lumber, some were built to halt debris flows from the now defunct hydraulic mining industry, some were built to control flooding in places where river channels have once again been widened and can manage the greater hydrologic flows. In addition, these structures have started to crumble and pose safety hazards and liability threats to their owners. Now that we have a better understanding of the way ecosystems work and function as a whole unit, many are anxious to see dams removed. ("Impacts and Alternatives," n.d.) All of us depend on the healthy forests, clean water and the resilience of biodiversity that our world is going to need to fight climate change and move forward. When they start counting the real costs of maintaining dams, many dam owners are finding dam removal to be their most sensible option.

So far the dams removed have either been quite small, or in the case of the Condit, Elwha, and Glines, they have been located in pristine environments near the Pacific Ocean. Foreseeable projects like taking down Englebright dam, at 280 feet tall, far from the ocean and known to have high levels of mercury in the sediment will be informed as these relatively easier projects progress. (O'Connor, Duda, & Grant, 2015) ("Map of U.S. Dams Removed Since 1916," n.d.)

Our research on sediment flux in dam removal is informed by the work on sediment flow from hydraulic mining. The mining debris sent downriver in the Sierra Nevada watershed exceeds that from any dam release so far. As mentioned earlier, sediment released from hydraulic mining in the Yuba river watershed between 1853 and 1884 totaled at $344x10^6$ m^3(L. A. James, 2005). The largest dam removal to date released $21x10^6m^3$ (Warrick et al., 2015). Although the mining debris was released over a longer period, the similarities are striking. Both events are mainly concerned with ecosystem and land form flux.


A. Number of dams

Data from National Inventory of dams through 2016

B. Dams removed

Data from American Rivers 1912–2015

C. Dams removed with published research or monitoring

Data from Bellmore et al. (2015) and Wieferich et al. (2016) through 2015

Figure 22: the number of dams, dams removed, and dams removed with studies in the US through 2015 ("DRIP - USGS," n.d.). Wisconsin has the most removals and the most studies, followed by Pennsylvania. The largest number of dams are in Texas and Kansas. Texas has 7,395 dams only 7 of which have been removed.

Ecosystem Response

Ecosystems respond quickly to dam removal, but actual recovery takes time. The work of dam removal itself can take several years as the river channel is switched back and forth while sediments are removed or flushed slowly downstream and the structure itself is removed one part at a time. The biggest cost and the biggest concern is the fate of the sediment. Timing of dam removal with seasonal considerations is important, this too extends timelines. During major rainstorms river turbidity is already high, so removal pauses to ease the strain on downstream ecosystems.

Sometimes the lake draw down is done slowly, over a period of years, other times it is rapid. In the case of the Condit dam draw down was only 30 minutes. The lake bed is made of something that resembles cement when dry, slurry when wet, and many things will not grow in it at first. Vestiges of the old growth forest before dam construction dot the landscape and contribute to debris flows as they disentangle themselves from the soil. With the lake gone, groundwater re calibrates. Soil too will express an unspecified morphology as the ground settles to its new shape. As the huge sediment fluxes make their way to the ocean they make their own history. Seeds spread up and down the river, both native and invasive plant species flow in the river. Birds, fish, and all living creatures adapt, move in, spread along or move out of the system depending on habitat gains and losses.

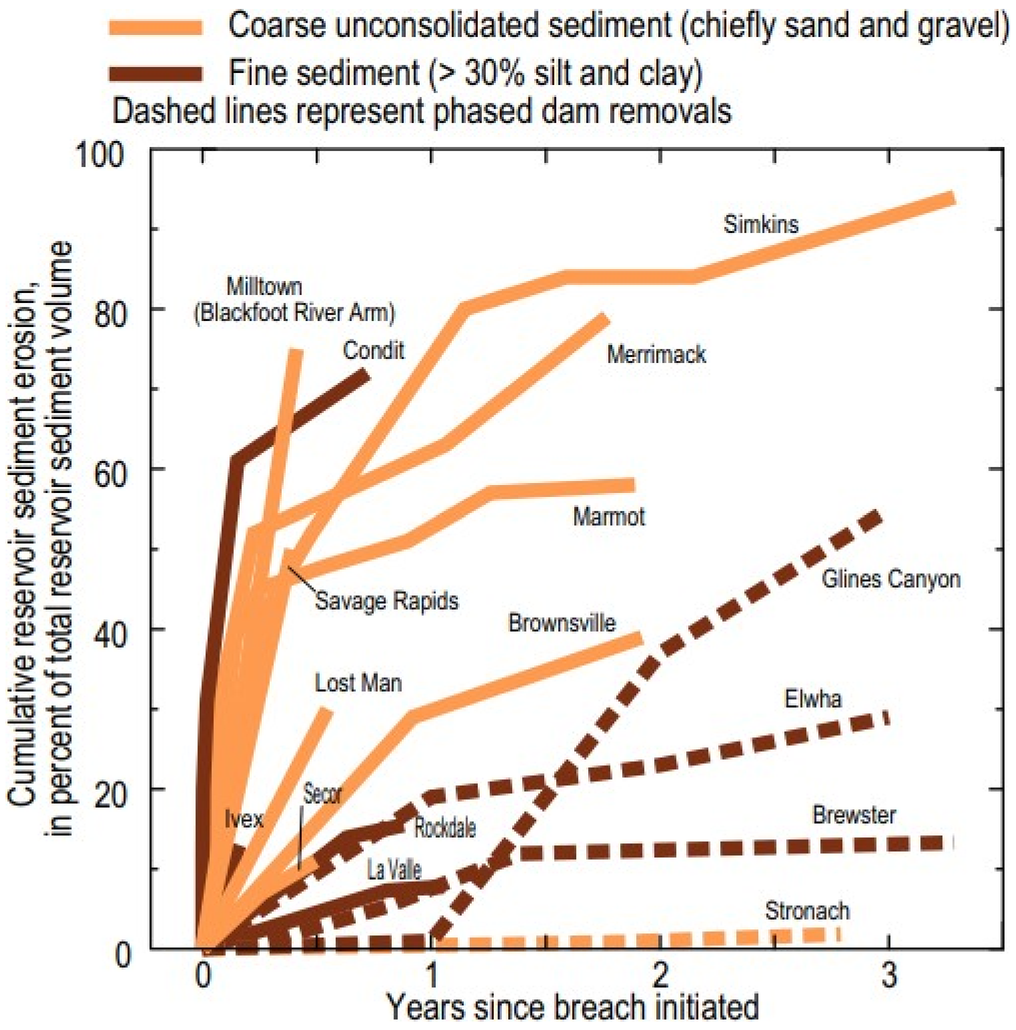


figure 23

Figure 23: The Percentage of reservoir sediment eroded with time after dam removal(Foley et al., 2017) . As you can see, in two and a half years, most sediment is still up in the breached reservoirs, with only one river, the Simkins, completely eroding its sediment within three years. This graph illustrates the time it takes for these changes to settle in.

The ecosystem itself will remain in flux for quite some time and it will take years, we don't know how long, to re-vegetate. The response is rapid, but recovery requires patience. We have found that pre-dammed conditions may not be possible (Foley et al., 2017). Many things contribute to the changes, current watershed uses and climate change play a role in the newly birthed ecosystem.

The rivers have responded in unexpected ways, but the most dramatic changes have occurred at the places where the river meets the sea. The delta regains life as 100 years of pent up sediment are added to the estuary. The new sandy beach not only looks beautiful, it prevents shoreline erosion and provides a safe nursery for many forms of life. Saltwater intrusion is halted and the flora and fauna adjust to the new situation. The changes are many and profound (Foley et al., 2017).

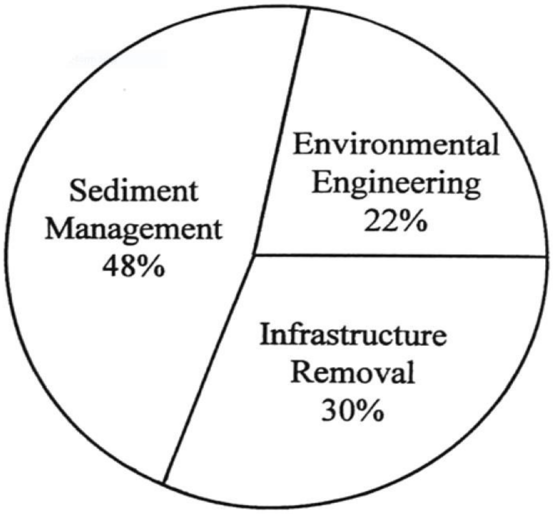


figure 24: Removal costs broken into three categories, the largest is sediment management, followed by infrastructure removal and then environmental engineering.

Infrastructure Removal

Infrastructure removal has three basic options, leave the dam in place, partial removal or complete removal.

Leaving the dam in place is more attractive if the sediment can cause downstream ecosystem harm. Entombed toxins are less damaging than released ones. It is also attractive because of the low investment required. If the structure doesn't crumble prematurely the end result would resemble the completely sedimented dams in figure 4.

Partial dam removal slows the sedimentation process but can the same long term problems of sediments accumulating behind the remaining dam. Partial removal may be the best option in many cases, as the cement structures can be mounted on cliffs or other hard to reach places. Case by case, as these projects are considered, weight must be given to the balance of the difficulty of an entire removal against the sediment retention capacity of a partial removal. The Glines canyon dam is a partial removal, part of it still clings to the towering cliff above the river.

Complete dam removal can be accomplished with staged breaching by calculating the water to sediment loads and spreading out the discharge of reservoir sediments over time. It can also be done quickly sending one huge sediment pulse downriver with a large but short lived ecosystem effect. Each structure, site and system will interplay call for a unique draw down tactic that will likely take great ingenuity. Dam removal, especially complete dam removal is tricky.

Sediment Management in Dam Release

Options for sediment management in dam release are: non-disturbance, natural erosion, channelization, staged erosion or the complete removal of sediments. In practice a variety of styles used for in each project. But in every case sediment management is the largest part of the budget and the biggest concern.

Non disturbance is the is the result of leaving the dam in place. The success of this depends on sediment inflow to outflow balance: water and what it carries must flow through the existing reservoir without erosion.

Natural Erosion lets the river do the work. This needs to be controlled because excessive amounts of fine sediments can create downstream environmental consequences and the release of large amount of coarse sediment can infill downstream channels causing problems such as flooding and impairment of navigation. Natural erosion's economic attractiveness needs to be balanced with downstream costs.

The incremental discharges of sediments into the river or staged erosion is the technique that was used with the Elwha river system. This balanced approach releases sediments over time in manageable amounts to downstream waters.

Sediments can also be managed by channelizing and stabilization. In this technique the straight channel or the meandering channel may be used. The channel is protected against shore erosion (Warner & Pejchar, 2001, p. 8) and the river is routed through it. One way to do this is to keep the dam in place and reroute the river. The run of the river dictates how feasible this option is.

A more severe treatment is the complete removal of sediments. This method requires an emptied and dried reservoir although dredging may be a viable option for coarse sediments. Complete removal makes sense if the sediment is considered hazardous material and needs special handling.

To this end, understanding the content of the sediments is crucial to the work. According to Morris and Fan:

> *Should the sediments contain unacceptable concentrations of pollutants, such as those on the U.S. Environmental Protection Agency Priority Pollutant List, or should the sediments be classified as hazardous material, it may be more costly, more harmful to the environment, or both, to decommission in a manner that disturbs and re- mobilizes the contaminated sediments. Testing of sediments through the entire depth of the deposit to be disturbed should be undertaken for content ….(Morris & Fan, 1998, p. 559).*

Sediment management is the most significant consideration in dam removal. Contaminants can be immobilized in dam sediments and the dam removal process can release them to the environment. Much care has to be taken with these large 100 yr accumulation releases to preserve downstream life and functions.

Environmental Engineering

Environmental engineering is an important part of the dam removal process. It requires thoughtful consideration of the geomorphic effects of the reservoir release. Water table and slope erosion are going to change. Seeds should be gathered from native plants in the years before removal so they will be on hand to start the re-vegetation process. Native trees and shrubs should be propagated and grown in pots so they will be ready to transplant when the time is right (“Klamath River Renewal Corporation |,” n.d.).

Case Studies

The Condit Dam

Condit dam was built in 1913 on the White Salmon River in the State of Washington. At 12.5 stories tall, the 125 ft Pacific Corps hydroelectric dam stood until Oct 26, 2011. It originally impounded 1.6x 10^6 m ^{3} of water, however useful storage capacity at time of removal was .82x10 ^{6}m^3, about half the original volume("Condit Hydroelectric Project," 2017)

The biggest removal up until its time, the structure was also the largest in 1913 when it was built. The dam was created to provide hydroelectric power to a defunct sawmill. The power generated was still being sold. The wood stave pipeline from the reservoir to the powerhouse was in itself a remarkable feat of engineering that lasted more than 100 years. Sited a mere 3 miles from the Columbia river, the structure was a blockade to fish populations upstream in an entire tributary system. Fish ladders were constructed twice and destroyed by the elements early on. When the dam came up for FERC licensing in 1991 it failed because of its ecological impacts to the fish. From 1991 until 2011 the structure ran with a temporary permit while negotiations were in progress on the decommissioning permit and local utilities sought to save it.

FERC proposed a fish ladder that would have cost 30 to 50 million. Removal cost came to about 30 million and the annual value of the power was 4.8 million("Condit Dam removal complete," 2012). PacifiCorp opted for removal in the best interests of its customers.

To breach the dam they cut a 12x18x100ft tunnel in its base leaving the last 15 feet for the final demolition, a dredge removed woody sediment from the dams inside arc. Fish were caught and moved out of harm's way before the day of the breech. PacifiCorp's plan was to quickly flush as much sediment through the watershed as possible, thereby minimizing the amount of time the sediment plume harmed downstream life.

The project took from June 2011 until October 2012.

On Oct. 6 2011 3000 lbs. of explosives were used at the base of the dam. After months of blasting, the last ten feet of the tunnel at the bottom of the dam exploded with the words "fire in the hole!" Five stories of silt were quickly freed from behind the dam. Pacific Corps was planning for a fast release, say 5 to 6 hours, but the event largely was completed in 30 minutes.

The rest of the dam was removed painstakingly over time with tractors and ingenuity. Debris were used to reform the lake bed basin. A year later newscasters interviewed homeowners who once had lakeside homes about the effects of the lake removal. Homeowners were not happy, dust from the old lake bed had become intolerable, some folks had moved out. Fourteen wells had gone dry, and many homes were subject to damage by the settling of the land after this abrupt geomorphic change. Slope erosion was an unforeseen side effect. Pacific Corps did a re-vegetation project that met its goals, so the dust was a short term problem. By 2016, the long term ecosystem recovery was kicking in. Migratory salmon, steelhead and wild Pacific lamprey were being spotted above the old dam site. It is still early in the recovery, and researchers are watching the changes afoot in the White Salmon River("Condit Dam," 2016).

Figure 25: The release of the Condit Dam, massive black sediment filled water mixed with smoke from exploding dynamite and concrete create a black cloud.

Elwha and Glines Dams

These are the largest dam removals in US history. They occurred in the Olympic National Park in the Olympic Peninsula in the North of Washington State. Both dams were on the Elwha river that empties into the Strait of Juan de Fuca which borders Canada and the US.

In 1978 the Elwha dam failed its FERC safety inspection. In 1992 Congress passed the Elwha River Ecosystem and Fisheries Restoration Act that authorized both dam removals on the Elwha river. King Salmon fish runs that had been in the 400,000 range had decreased to 3,000. It was hypothesized that the return of this keystone species could jump start the ecosystem and the salmon were ready, after a hundred years they still beat their heads against the bottom of the dam trying to go upstream. Removal of the Elwha dam began in September of 2011 and lasted 6 months.

Removal of the larger Glines canyon dam followed in 2014. These two removals essentially freed the Elwha river. For both projects sediment flux was managed by incremental structure removal. Downstream turbidity was watched carefully and if values were too high, deconstruction was halted temporarily. This assigned the tedious work of moving 24 million cubic meters of sediment to the river itself (Randle, Bountry, Ritchie, & Wille, 2015b, p. 2) (Warrick et al., 2015, p. 17).

Elwha dam removal 2011 – March 2012.

The Elwha dam was built in 1911 and was 108 ft high. It was situated 4.9 miles from the Strait of Juan de Fuca. The work of removing the Elwha dam was accomplished in stages with ten reroutes of the river. First the water was lowered, then a diversion channel was created by blasting. With the diversion channel in place water could be shifted from side to side to allow for the progress of the work. After each channel shift sediment was dry removed and demolition acted against exposed remaining parts of the dam structure. This process was repeated many times until at last no vestige of the Elwha dam remains on the river. With this technique, most of the work could be done with tractors on dry ground.

Glines canyon dam removal 2012- 201

Glines Canyon Dam was more difficult to remove than the Elwha or the Condit. Twice the height of the Elwha it is the largest dam removal project to date. Built in 1927 it was 210 ft tall concrete arch 13 miles up from the Strait of Juan de Fuca.
The concrete arch between canyon walls left no room for tractors to be on solid ground. To remove this dam, they had a tractor with a pneumatic hammer on a barge (Angeles & Us, n.d.).

Workers prep for explosives placement on Glines Canyon Dam.

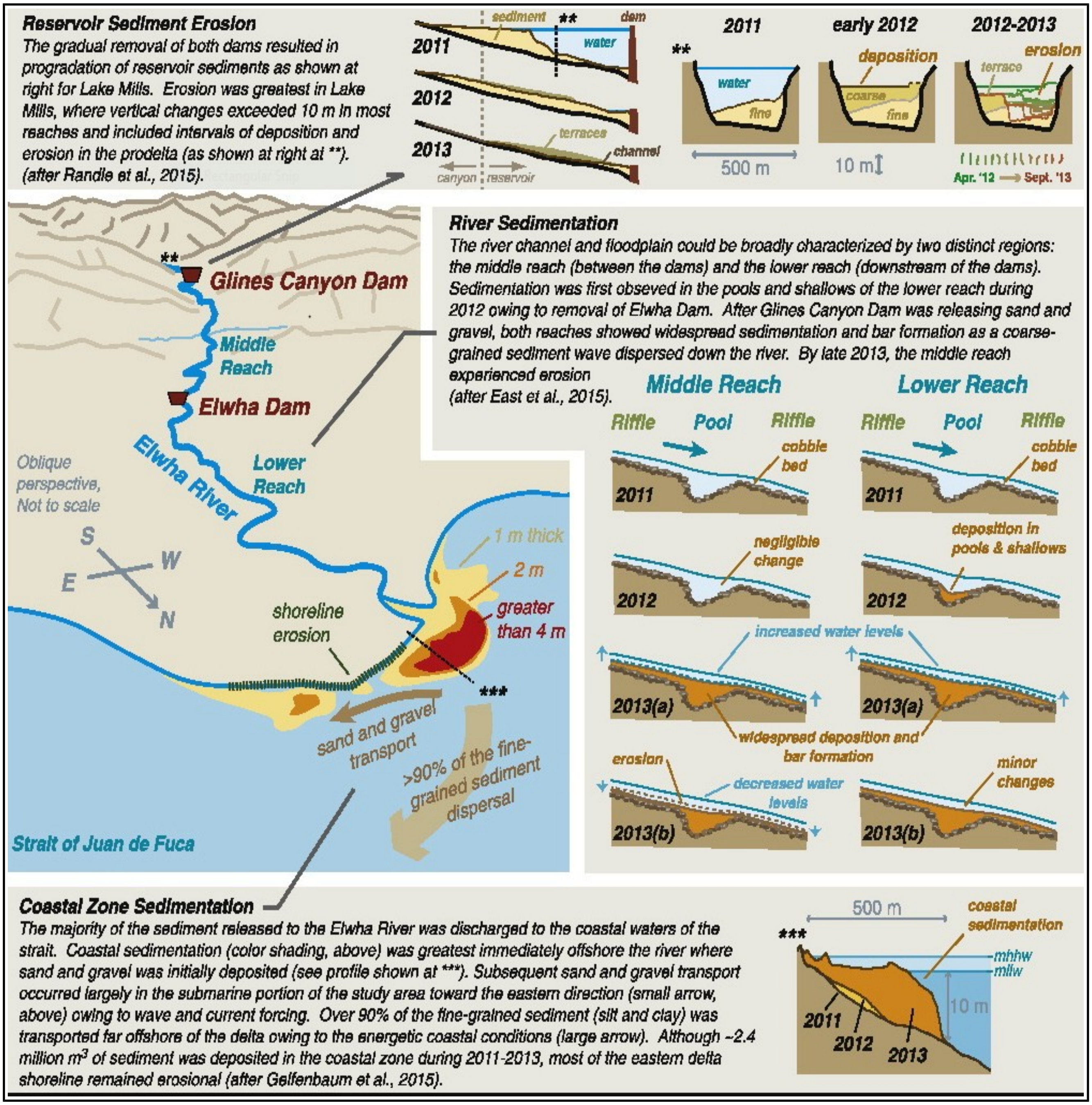
PHOTO COURTESY OF BARNARD CONSTRUCTION CO.

figure 26: Work on dam deconstruction at Glines. Despite the high hazard potential no one was hurt through the project.

They chipped the dam away underneath the barge and the lake level went down 6 inches to a foot every day. When the lake got too low to use the barge removal was finished with blasting. The final blast was August 2014.

Post Dam Sediment Flows on the Elwha

Figure 27: Sediment Flows on the Elwha river in the post dam era have been carefully monitored. With incremental reservoir draw down the pattern in the sediments is delta progradation. The delta advances to the former dam site burying fine lake sediment with its coarser debris. Loads to the downstream area and then to the sea were measured in Megatons. 9.5 Million tons. The river experienced periods of extreme turbidity but carried the most of this debris to the ocean (warrik et al.. 2015).



Reservoir Sediment Erosion

*The gradual removal of both dams resulted in progradation of reservoir sediments as shown at right for Lake Mills. Erosion was greatest in Lake Mills, where vertical changes exceeded 10 m in most reaches and included intervals of deposition and erosion in the prodelta (as shown at right at **). (after Randle et al., 2015).*

River Sedimentation

The river channel and floodplain could be broadly characterized by two distinct regions: the middle reach (between the dams) and the lower reach (downstream of the dams). Sedimentation was first obseved in the pools and shallows of the lower reach during 2012 owing to removal of Elwha Dam. After Glines Canyon Dam was releasing sand and gravel, both reaches showed widespread sedimentation and bar formation as a coarse-grained sediment wave dispersed down the river. By late 2013, the middle reach experienced erosion (after East et al., 2015).

Coastal Zone Sedimentation

*The majority of the sediment released to the Elwha River was discharged to the coastal waters of the strait. Coastal sedimentation (color shading, above) was greatest immediately offshore the river where sand and gravel was initially deposited (see profile shown at ***). Subsequent sand and gravel transport occurred largely in the submarine portion of the study area toward the eastern direction (small arrow, above) owing to wave and current forcing. Over 90% of the fine-grained sediment (silt and clay) was transported far offshore of the delta owing to the energetic coastal conditions (large arrow). Although ~2.4 million m^3 of sediment was deposited in the coastal zone during 2011-2013, most of the eastern delta shoreline remained erosional (after Gelfenbaum et al., 2015).*

Not just fine and coarse-grained sediments but also woody debris have been making their way down the Elwha river.

The changes in the river have been drastic. For the first three years the river was choked with sediment (Duda, Beirne, Warrick, & Magirl, n.d.). Debris dams spontaneously formed trapping sediment and fish, the river itself became wild moving in places to the wider braided flows, taking out roads and one campground. At one time during the project, 200,000 planted chinook salmon were choked to death by unexpected and extreme turbidity (credit, Sept. 4, & edition, 2017). The response of the Elwha river has been most pronounced at the ocean. It has been found in the case of the Elwha that 90% of the released sediment reached the sea (Warrick et al., 2015) moving in sediment waves like the type described by Gilbert 100 years earlier. (Randle, Bountry, Ritchie, & Wille, 2015) (Gilbert & Murphy, 1914) This is probably due to the steep terrain and significant flows in this watershed. The sediment decreased the slope of the lowermost river and by the second-year post dam the seafloor near the mouth of the river had raised 33 ft.

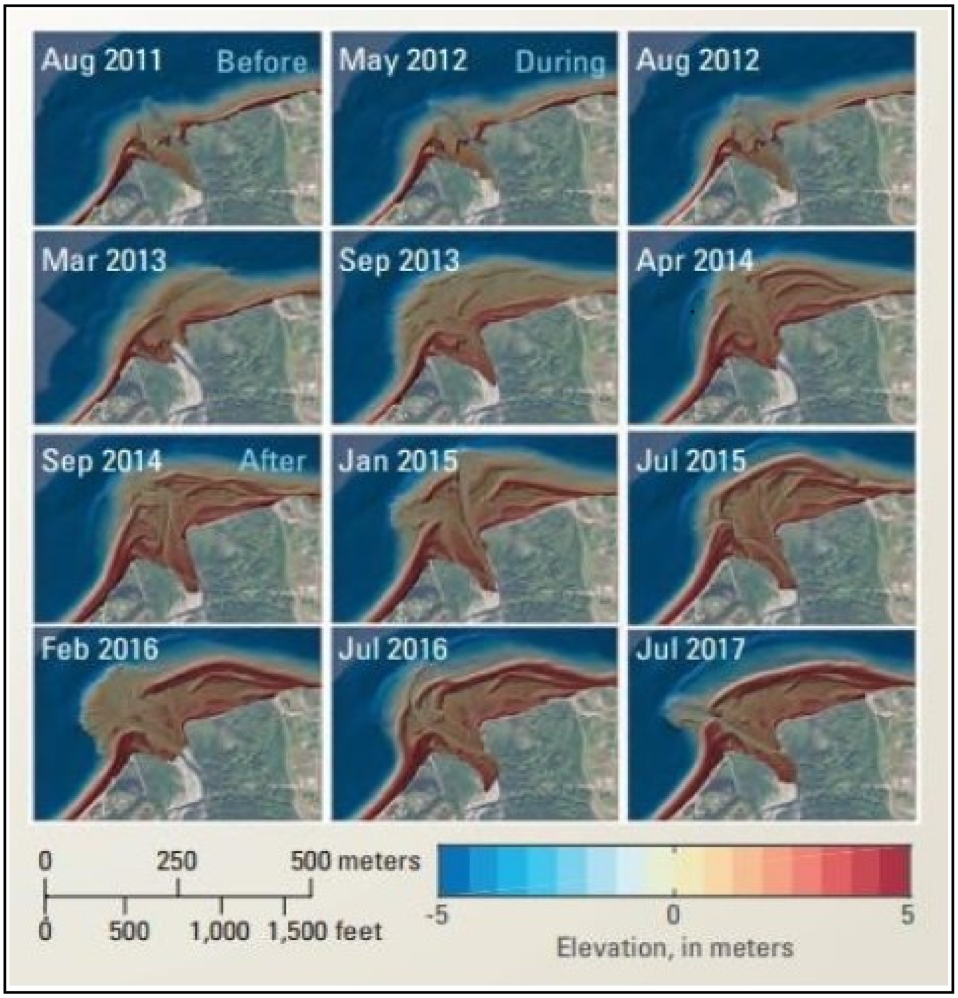


Figure 30: substantial shoreline extension from 2011 until 2017 that resulted from dam removals on the Elwha river (Duda et al., n.d.).

The old lake beds resemble a moonscape as vegetation slowly moves in. They now have a terraced sediment morphology. This is expected to stabilize but be vulnerable to large flooding events. Fish are being spotted upstream of the removed dams and are expected to increase in population with time. The enlarged estuary is an important nursery for them and other species. Plenty of sediment remains undisturbed, over 60% of the original lake bed sediment or 20 million tons (Warrick et al., 2015, p. 10) and will either assimilate into its new dry land situation or eventually move down river. The recovery of this river will take time. The return of the keystone species King Salmon, is expected to jump start the ecosystem. Many scientists are quantifiing aspects of the newly free- flowing river(Duda et al., n.d.).

Conclusion

The growing world population has presented society with many challenges. One of the most daunting is the stewardship of our water resources. To this end we have constructed multitudes of dams. Many are magnificent engineering feats that testify to man's powers of ingenuity, perseverance, and cooperation. They have protected us from floods, nourished our lands with water and provided hydroelectric power and debris control. The benefits are clear and large as are the costs.

Sediments in the reservoirs and river systems are of the greatest importance. With the sediment impounded behind the reservoirs, ecosystems suffer. The sediment is needed to prevent shoreline losses, to provide habitats for fisheries, and in general to be a part of the delicate balance of nature. As science advances, the connectivity of the river that is lost with these structures is more profoundly understood. Our attempts to add fisheries have not come close in productivity to the natural systems. Without the influx of nutrients from the fish, whole systems have lost their vitality.

The ecosystems are of primary importance, but there is another grave concern with our reservoirs. Sediment accumulation in these structures is impinging on their capacity to hold water. It is slow moving but the losses are of essential functions. The

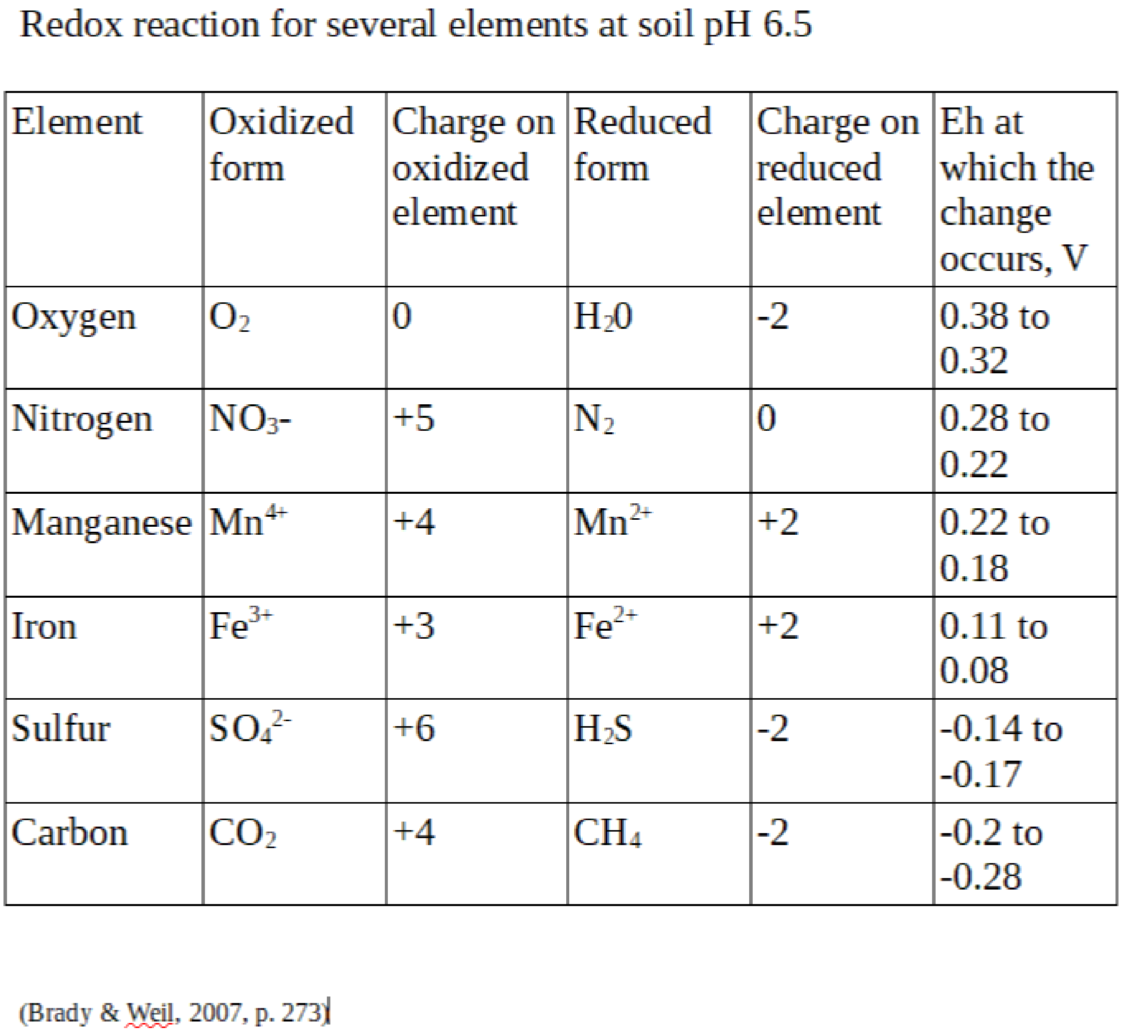
eventuality without intervention is that all the reservoirs will fill with sediments returning us to pre-dam conditions. Irrigation and tap water are at risk.

It is hoped by many that we abandon the reservoir system and move on to other things. Until then the water holding capacity of reservoirs remains essential to the way our society functions.

Sediment management needs to become a priority. The key problems of funding and toxin management will have to be addressed.

The stewardship tasks that lie ahead are enormous but the impermanent nature of the dams themselves will move us forward. We will use the same qualities we already know we have, powers of ingenuity, perseverance and cooperation. We will take down many dams and we will more carefully maintain others. To manage reservoir sediments in the future we will need to reach a consensus on priorities that are long term, renewable, good for the earth and good for its people.

Appendix



Redox reaction for several elements at soil pH 6.5

Element	Oxidized form	Charge on oxidized element	Reduced form	Charge on reduced element	Eh at which the change occurs, V
Oxygen	O_2	0	H_20	-2	0.38 to 0.32
Nitrogen	NO_3-	+5	N_2	0	0.28 to 0.22
Manganese	Mn^{4+}	+4	Mn^{2+}	+2	0.22 to 0.18
Iron	Fe^{3+}	+3	Fe^{2+}	+2	0.11 to 0.08
Sulfur	SO_4^{2-}	+6	H_2S	-2	-0.14 to -0.17
Carbon	CO_2	+4	CH_4	-2	-0.2 to -0.28

(Brady & Weil, 2007, p. 273)

Sand Silt and Clay designations from several agencies

Sand	Silt	Clay	System
>2mm >0.5	>0.05mm>0.002mm	>0.002mm	US Dept of Agriculture (Used by Soil Scientists)
>2mm>0.063mm	>0.63mm> 0.0063mm	>0.002mm	ISO (international organization for standardization)
>2mm>0.062>5mm	>0.0625mm>0.0039mm	>.004mm	Wentworth (used by Geologists)

1.

O’Connor, J. E., Duda, J. J. & Grant, G. E. 1000 dams down and counting. *Science* **348,** 496–497 (2015).

2.

2016FERC Office of Energy ProjectsDivision of Dam Safety and Inspections. 25

3.

Yin, X.-A., Yang, Z.-F., Petts, G. E. & Kondolf, G. M. A reservoir operating method for riverine ecosystem protection, reservoir sedimentation control and water supply. *Journal of Hydrology* **512,** 379–387 (2014).

4.

Warner, K. & Pejchar, L. A River Might Run Through It Again: Criteria for Consideration of Dam Removal and Interim Lessons from California. *Environmental Management* **28,** 561–575 (2001).

5.

credit, K. S. I., Sept. 4, y R. & edition, 2017 From the print. After its dams came down, a river is reborn. (2017). Available at: https://www.hcn.org/issues/49.15/rivers-six-years-after-its-dams-came-down-a-river-is-reborn. (Accessed: 18th July 2018)

6.

Rivers, A. American Rivers Dam Removal Database. (2017). doi:10.6084/m9.figshare.5234068.v2

7.

Çevik, F., Göksu, M. Z. L., Derici, O. B. & Fındık, Ö. An assessment of metal pollution in surface sediments of Seyhan dam by using enrichment factor, geoaccumulation index and statistical analyses. *Environmental Monitoring and Assessment* **152,** 309–317 (2009).

8.

Ghrefat, H. A., Abu-Rukah, Y. & Rosen, M. A. Application of geoaccumulation index and enrichment factor for assessing metal contamination in the sediments of Kafrain Dam, Jordan. *Environ Monit Assess* **178,** 95–109 (2011).

9.

10.

Chabukdhara, M. & Nema, A. K. Assessment of heavy metal contamination in Hindon River sediments: A chemometric and geochemical approach. *Chemosphere* **87,** 945–953 (2012).

11.

Childs, J. R., Snyder, N. P. & Hampton, M. A. Bathymetric and geophysical surveys of Englebright Lake, Yuba-Nevada Counties, California. 20

12.

Andre, E. Beyond hydrology in the sustainability assessment of dams: A planners perspective – The Sarawak experience. *Journal of Hydrology* **412–413,** 246–255 (2012).

13.

Olsen, K. Chemical Impacts from acid mine drainage in a dam ecosystem.

14.

Olsen, K. A. A. Chemical impacts from acid mine drainage in a dam ecosystem: an epilimnion and sediment analysis. (2016).

15.

Meunier, A. *Clays*. (Springer Science & Business Media, 2005).

16.

Morris, G. L. COLLECTION AND INTERPRETATION OF RESERVOIR DATA TO SUPPORT SUSTAINABLE USE. 10

17.

Colorado River. *Wikipedia* (2018).

18.

Condit Dam removal complete. *The Columbian* (2012).

19.

Condit Dam: Life after the breach. *The Columbian* (2016).

20.

Condit Hydroelectric Project. *Wikipedia* (2017).

21.

Graf, W. L. Dam nation: A geographic census of American dams and their large-scale hydrologic impacts. *Water Resources Research* **35,** 1305–1311

22.

Dam Removal Project Restores a National Park. Available at: https://www.enr.com/articles/38292-dam-removal-project-restores-a-national-park. (Accessed: 16th July 2018)

23.

Distribution, fractional composition and release of sediment-bound heavy metals in tropical reservoirs. 15

24.

Ligon, F. K., Dietrich, W. E. & Trush, W. J. Downstream Ecological Effects of Dams. *BioScience* **45,** 183–192 (1995).

25.

Friedman, Osterkamp, W. R., Scott, M. L. & Auble, G. T. Downstream effects of dams on channel geometry and bottomland vegetation: Regional patterns in the great plains. *Wetlands* **18,** 619–633 (1998).

26.

Rayne, S. & Friesen, K. J. *e*.

27.

Palmieri, A., Shah, F. & Dinar, A. Economics of reservoir sedimentation and sustainable management of dams. *Journal of Environmental Management* **61,** 149–163 (2001).

28.

Santucci, V., Gephard, S. & Pescitelli, S. Effects of Multiple Low-Head Dams on Fish, Macroinvertebrates, Habitat, and Water Quality in the Fox River, Illinois: North American Journal of Fisheries Management: Vol 25, No 3.

North American Journal of Fisheries Management Available at: https://www.tandfonline.com/doi/abs/10.1577/M03-216.1. (Accessed: 13th July 2018)

29\.

Baxter, R. M. Environmental Effects of Dams and Impoundments. *Annual Review of Ecology and Systematics* **8,** 255–283 (1977).

30\.

Snyder, N. P. *et al.* Estimating accumulation rates and physical properties of sediment behind a dam: Englebright Lake, Yuba River, northern California. *Water Resources Research* **40,**

31\.

OnePlan, I. Estimating Soil Moisture. (2000). Available at: http://oneplan.org/Water/soil-triangle.asp. (Accessed: 11th July 2018)

32\.

Orndorff, A. Evaluating the Effects of Sedimentation from Forest Roads. 38

33\.

Graham_Nicholas_summer2017_thesis.pdf.

34\.

Grove Karl Gilbert, ‘A Captain Bold’ – National Geographic Blog. Available at: https://blog.nationalgeographic.org/2018/01/08/grove-karl-gilbert-a-captain-bold/. (Accessed: 29th June 2018)

35\.

James, A. Hydraulic Mining Sediment in the Northwestern Sierra Nevada. 29

36\.

Gilbert, G. K. *Hydraulic-mining Débris in the Sierra Nevada*. (U.S. Government Printing Office, 1917).

37\.

James, L. A. Incision and morphologic evolution of an alluvial channel recovering from hydraulic mining sediment. *Geological Society of America Bulletin* **103,** 723–736 (1991).

38.

Klaver, G., van Os, B., Negrel, P. & Petelet-Giraud, E. Influence of hydropower dams on the composition of the suspended and riverbank sediments in the Danube. *Environmental Pollution* **148,** 718–728 (2007).

39.

Klaver, G., van Os, B., Negrel, P. & Petelet-Giraud, E. Influence of hydropower dams on the composition of the suspended and riverbank sediments in the Danube. *Environmental Pollution* **148,** 718–728 (2007).

40.

Klamath River Renewal Corporation |.

41.

Randle, T. J., Bountry, J. A., Ritchie, A. & Wille, K. Large-scale dam removal on the Elwha River, Washington, USA: Erosion of reservoir sediment. *Geomorphology* **246,** 709–728 (2015).

42.

Warrick, J. A. *et al.* Large-scale dam removal on the Elwha River, Washington, USA: Source-to-sink sediment budget and synthesis. *Geomorphology* **246,** 729–750 (2015).

43.

Legacy Mine Lands Pollute Scotchman Creek and the South Yuba River | South Yuba River Citizens League.

44.

Morris, G. L. Management Alternatives to Combat Reservoir Sedimentation. 10

45.

Map of U.S. Dams Removed Since 1916. *American Rivers*

46.

Marigold - Yuba-Sutter - LocalWiki. Available at: https://localwiki.org/yuba-sutter/Marigold. (Accessed: 29th June 2018)

47.

McCarran Ranch Preserve - The Nature Conservancy. Available at: https://www.nature.org/ourinitiatives/regions/northamerica/unitedstates/nevada/placesweprotect/mccarran-ranch-preserve.xml. (Accessed: 13th July 2018)

48.

Graham, N. Metal-based coagulant effect on sediment slurry for the Lake Combie Reservoir Sediment and Mercury Removal Project, Grass Valley, CA. (2018).

49.

NID by State. Available at: http://nid.usace.army.mil/cm_apex/f?p=838:3:0::NO::P3_STATES:CA. (Accessed: 14th July 2018)

50.

CIGB, I. Number of Dams by Country Members. *ICOLD CIGB* Available at: http://www.icold-cigb.net/article/GB/world_register/general_synthesis/number-of-dams-by-country-members. (Accessed: 12th July 2018)

51.

McDonald, C. Oroville Dam Highlights Infrastructure Risks. *Risk Management; New York* **64,** 6,8-9 (2017).

52.

PCBs in fish and shellfish. *Seafood Selector* (2013). Available at: http://seafood.edf.org/pcbs-fish-and-shellfish. (Accessed: 21st July 2018)

53.

Meyers, G., Davidson, P. & Weiss, B. Perspectives on Niigata, Japan. (2006). Available at: https://web.archive.org/web/20060505115116/http://www.seychelles.net/smdj/SECVA.pdf. (Accessed: 11th July 2018)

54.

Hongthanat, N. Phosphorus sorption-desorption of soils and sediments in the Rathbun Lake watershed. 72

55.

Morris, G. L. & Fan, J. *Reservoir Sedimentation Handbook*. (McGraw-Hill Book Co., New York, 1998).

56.

George Matthew W., Hotchkiss Rollin H. & Huffaker Ray. Reservoir Sustainability and Sediment Management. *Journal of Water Resources Planning and Management* **143,** 04016077 (2017).

57.

George, M. W., Hotchkiss, R. H. & Huffaker, R. Reservoir Sustainability and Sediment Management. *Journal of Water Resources Planning and Management* **143,** 04016077 (2017).

58.

Angeles, M. A. 600 E. P. A. P. & Us, W. 98362 P.-3130 C. Restoration of the Elwha River - Olympic National Park (U.S. National Park Service). Available at: https://www.nps.gov/olym/learn/nature/restorationoftheelwha.htm. (Accessed: 18th July 2018)

59.

Teodoru, C. & Wehrli, B. Retention of Sediments and Nutrients in the Iron Gate I Reservoir on the Danube River. *Biogeochemistry* **76,** 539–565 (2005).

60.

Huang, C., Pan, J. R., Sun, K.-D. & Liaw, C.-T. Reuse of water treatment plant sludge and dam sediment in brick-making. *Water Science and Technology* **44,** 273–277 (2001).

61.

Rivers, A. San Joaquin River. *Americas Most Endangered Rivers for 2016* (2016).

62.

Duda, J. J., Beirne, M. M., Warrick, J. A. & Magirl, C. S. Science Partnership Between U.S. Geological Survey and the Lower Elwha. 4

63.

Kim, L.-H., Choi, E. & Stenstrom, M. K. Sediment characteristics, phosphorus types and phosphorus release rates between river and lake sediments. *Chemosphere* **50,** 53–61 (2003).

64.

James, L. A. Sediment from hydraulic mining detained by Englebright and small dams in the Yuba basin. *Geomorphology* **71,** 202–226 (2005).

65.

Valero-Garcés, B. L., Navas, A., Machín, J. & Walling, D. Sediment sources and siltation in mountain reservoirs: a case study from the Central Spanish Pyrenees. *Geomorphology* **28,** 23–41 (1999).

66.

Story Map Journal. Available at: https://www.arcgis.com/apps/MapJournal/index.html?appid=4533fec4fbb148f289bf81f9cc8adbd6. (Accessed: 29th June 2018)

67.

Sustaining water. Population and the future of renewable water supplies. | POPLINE.org. Available at: https://www.popline.org/node/331603. (Accessed: 13th July 2018)

68.

The California Debris Commission: A History. 112

69.

Thornley, D., Nov. 10, published on & 2009. The Myth of Fossil Fuels, Alternative Fuels and Renewable Energies. Available at: http://www.mackinac.org/11309. (Accessed: 13th July 2018)

70.

Poff, N. L. *et al.* The Natural Flow Regime. *BioScience* **47,** 769–784 (1997).

71.

Brady, N. C. & Weil, R. R. *The Nature and Properties of Soils, 14th Edition*. (Pearson, 2007).

72.

Restoration, T. S. C. The Worst Floods in California's History | TSC Restoration, Inc. *TSC Restoration* (2015).

73.

Bednarek, A. T. Undamming Rivers: A Review of the Ecological Impacts of Dam Removal. *Environmental Management* **27,** 803–814 (2001).

74\.

USGS: Louisiana's Rate of Coastal Wetland Loss Continues to Slow. Available at: https://www.usgs.gov/news/usgs-louisiana-s-rate-coastal-wetland-loss-continues-slow. (Accessed: 13th July 2018)

75\.

World Population Clock: 7.6 Billion People (2018) - Worldometers. Available at: http://www.worldometers.info/world-population/#table-historical. (Accessed: 13th July 2018)