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Earthquake Effects in Changing Damscapes: Geomorphology and Narrative at the Bonneville Dam

Background

Big Picture

How long can human structures withstand the forces of a changing earth? From the storage of nuclear waste under Yucca Mountain in Nevada to the interstate highway system spanning the American continent, federal projects have embedded the built environment onto the land, water, and airspace of the nation. This is true for civilizations around the world, erecting structures and setting stones for their buildings, monuments, and everyday infrastructure. Most of these structures crumble with time. Erosion, weather, geologic events, shifting seas, and human intervention take their toll and only a few of the human structures of the past remain intact. Oftentimes, these structures seem to us now as the most important buildings or monuments of that civilization. One need only to look to the stone relics of Easter Island, Machu Picchu, the Egyptian Pyramids, and other human-created sublimities to see the awe of long-lasting structures.

In terms of modern structures with the same physical and symbolic might, dams rank high. Types of dams range from large storage dams made of concrete to smaller irrigation dams made of earth and countless other materials and designs. The contemporary discourse around dams often revolves around large scale concrete dams that block major rivers and watersheds, such as the Columbia River in the Pacific Northwest, the Colorado River in the American Southwest, and the Bio Bio River in Chile. These high profile dams have been the subject of both worship (Bloodworth et al. 2008) and derision (Ladd 2009). Apart from their immense physical presence, status as engineering feats, and ability to generate power, dams often occupy a potent symbolic space and have since the beginning of large-scale dam construction in the 1930s and 1940s in the American West. Dams are symbols of humankind taming nature. They are commonly seen as embodiments of the process of modernization. With modernization, comes the management (sometimes framed as conquest and conquer) of the physical environment (Kaika 2006). Built primarily to provide hydropower and irrigation control to the surrounding communities, the missions and functions of dams have evolved throughout the 20th and 21st centuries as the environmental impacts of these structures on hydrosystems and ecosystems gained widespread attention (Saleth 1992). The main purpose of human-made dams is to store water, keep river levels constant, and help with flood control (Galbraith 2011). Today, dams are controversial on account of their ecosystem impacts including fish migration and sediment loading (including toxins), and dislocation of water in flood or drought-ridden areas.

Just as mighty structures of eras past have undergone radical shifts of appearance and function due to change over time (think about the transformation of the Egyptian pyramids from a place of burial to a tourist attraction or the steady erosion of the stones of Machu Picchu), dams as well have experienced great shifts in public reputation through the past century. From complete collapse to shifts in functionality, various dams have undergone transformations according to the popular mood that surrounds them. While the structures themselves may remain essentially the same (requiring periodic maintenance and updates), the rhetoric and narrative of dams has changed considerably since the time Grand Coulee Dam was coined the 8th wonder of the world (Dick 1989). These changes mark the controversies of the 20th and 21st centuries between the demand for hydropower versus the ecological and recreational losses (Rom 2012). Waterways are popular recreation sites, and dams hinder this experience by blocking rivers. While some dams actually create recreation opportunities and some, for instance the Hoover Dam (Wrobel 2011), have become tourist destinations, this is often at the expense of rafting or kayaking activities that require wild whitewater (Loomis 2002). Dams that have a recreational component are classified under "multipurpose dams," which are also used for flood control, irrigation, and power generation. Storage dams impacting seasonal flow patterns are not used for recreational purposes (Poff and Hart 2002). Dams have faced continuous controversy and scrutiny on the topic of fish migration, specifically salmon migration. Dams try to combat obstacles of fish spawning fish with fish ladders- a series of steps and pools that gradually go over the dam. Dams attempt to aid juvenile fish migrate downstream by creating alternative passageways to avoid dam turbines. In certain cases, the impact of the dam on the fish river ecosystem has been so severe that dams have been deconstructed to help fish survival (Levin and Tolimieri 2001).

Despite their gigantic stature, symbolic status, and ability to alter earth systems, dams are not made to last forever. Like all human structures, whether they be small residential neighborhoods, nuclear waste storage encasements meant to last millions of years, or religious monuments that have already lasted thousands, dams exist within a network of geologic and anthropocentric constant change. As social movements like Damnation (Knight and Rummel 2014) have called to deconstruct particularly harmful or useless dams, the alteration of dams to better accommodate the demands of environmentalists has been well covered. These are instances of human structures adapting to human society. However, the ability of human structures to adapt to geologic change such as earthquakes, volcanoes, floods, and other disasters usually ends it scenarios like Pompeii. Between social, legal, political, physical, geological, ecological, and climate change, for dams to remain standing in good standing for multiple generations requires careful maintenance, public relations management, and risk management. This is the framework of our study: how high profile human structures (such as federal dams) are managed to adapt over time.

This question deals very broadly with the longevity of human structures and the evolution of their narratives. Many of the large dams in the United States were built in the 1930s and 1940s and therefore are reaching the end of their predicted lifespans. As discussed previously, the social changes surrounding dam function, dysfunction, and symbolism are far more popularly discussed than the potential for geologic or climate change to alter dams. For our purposes, we wish to explore the relationship between geologic change, namely seismic activity, on the structures, functions, and narratives of dams.

Situated Context

It is important to keep in mind that dams, by their placement alone, are inherently situated in culture, history, geography, geology, language, and discourse. Each dam has its own unique relationship with its context. While there are similarities and broad concepts to be made about dams on global and national levels, as we do in the background relating to symbolism and longevity, the bottom line is that every dam is different (Committee on Seismic Aspects of Dam Design 2012) and comparing dams across culture, type, place, and time is a difficult and imperfect endeavor. We have chosen to situate our research at Bonneville Lock and Dam on the Columbia River. Bonneville is a 60-meter-high run-of-the-river dam located 40 miles east of Portland, Oregon. Opened in 1938, the Bonneville Dam is among the generation of high-profile federal hydropower projects that dominated the major rivers of the west through the 1930s and 1940s. Today, Bonneville Dam is used for hydropower generation through Bonneville Power Administration, recreation at the visitor's center and local waterways, and fish migration through fish ladders that aid salmon and steelhead in their migration upstream to spawn (Bonneville Lock and Dam 2013). The dam and its campus is owned by the Army Corps of Engineers and the Bonneville Power Administration. In 1987, Bonneville Dam Historic District was designated a National Historic Landmark District. Today, much of the dam's visitor center is dedicated to displaying the fish ladder, fish hatchery, and other infrastructure involved in assisting migrating fish through the dam (To Save the Salmon 1997). Hydropower remains paramount to the dam's purpose, but recreational opportunities and fish rehabilitation are embedded within the dam's contemporary advertising and public image.

The entire region of the Pacific Northwest, including Portland and the Bonneville Dam, is situated along the Cascadia Subduction Zone, a plate boundary prone to large earthquakes. Because the most recent Cascadia earthquake occurred in 1700 and severity of the Pacific Rim earthquake was not realized until the 1980's, the infrastructure of Portland was not built with knowledge and policy that reflects the seismic character of its location (Ashford 2015). Thus, Portland and the surrounding areas are susceptible and unprepared. Building codes were updated in the latter part of the 20th Century, but many legacy structures, including the Bonneville Dam, were constructed without earthquake precautions. On the recovery side of the potential earthquake, the Oregon Resilience Plan was not finalized until 2011. This plan roughly outlines likely impacts of the magnitude 9.0 earthquake, acceptable timeframes to restore infrastructure functions, and changes in practice and policy that will allow Oregon to reach desired resiliency, if implemented in the next 50 years (Oregon Seismic Safety Policy Advisory Commission 2013).

A hypothetical model of the fallout after the upcoming 9.0 earthquake predicts that Portland will be out of power for approximately 2 months. Many bridges will have collapsed and access to the I-5 will take two weeks to be cleared of debris (Gilles 2012). John Vidale, Debbie Goetz, and Sandi Doughton state that "liquefaction will harm almost every industrial area" as well as fuel lines and energy infrastructure being severely damaged (Jepson 2015). Energy infrastructure is particularly at risk according to a study done by the Oregon Department of Geology and Mineral Industries (Wang et al. 2012). Even since the development of the Oregon Resilience Plan, public agencies, private businesses and individuals are not adequately prepared for the impending earthquake. Because of the uncertainty around when, where, and how large to earthquake might be, it's difficult to incite the cultural, legal, and social impetus needed to inspire a culture of preparedness (Ashford 2015).

While the earthquake is likely to initiate off the West Coast and trigger a tsunami, the Bonneville Dam is located 140 miles upstream and inland. This is relatively far from the epicenter and might indicate that the location of the dam is safer. While it's true that different regions (coast, city, agricultural valley) must confront different hazards and risks in the case of an earthquake, the Bonneville Dam has a unique geologic placement that situates it in a hazardous area. The Columbia River Gorge has been the site of a number of historic landslides, including the great Bonneville Landslide of the 15th Century which actually blocked the course of the Columbia River for a time at the location of the Bridge of the Gods (Pierson 2014). This is precisely where the Bonneville Dam lies; it's northern foundation is on the toe of an ancient landslide. While the origin of the landslide is still unknown, geologists "have classified the Bonneville landslide as a large rockslide-debris avalanche, meaning it represents a complex downslope movement of rocks and soil that probably first slid along joints (fractures) and bedding planes and that then began to tumble and flow chaotically as it moves farther downslope and rapidly toward and into the Columbia River" (Pringle 2009). More recently, geologist Thomas Pierson has researched the movement of different landslides within the Bonneville Landslide complex. As recently as 2008, the Red Bluffs landslide just upstream of Bonneville has shown signs of movement (Pierson 2009). These geologic preconditions, which made the Bridge of the Gods an ideal spot for a dam, perhaps pose the greatest hazard to the Bonneville Dam in the event that earthquake shaking instigates occurrences of mass wasting around the dam.

From our research, we have found no evidence that the Bonneville Dam is at risk of complete, spectacular, catastrophic failure due to the seismic hazard of the Cascadia Subduction Zone. Seismicity is usually a larger issue for smaller, earthen dams such as the Fujinuma Dam in the Tohoku event (Pradel et al. 2012) or larger storage dams that might experience cracks or overtopping from their reservoirs (CSADD 2012). In fact, because Bonneville is under 100 feet and a run of the river dam which holds no significant reservoir behind it, the risks of even a complete dam failure are relatively low (CSADD 2012). We also found that the hazard of the tsunami will likely have no effect on a dam since it is so far upstream (Strauth 2015). This brings us to an important distinction between risk and hazard. Hazard is a potential source of harm. In this case, the earthquake is a hazard, the dam failure is a hazard, landslides are hazards, tsunamis are hazards, etc. Risk in the other hand describes the likelihood that a being or object will be harmed by the hazard. Risk describes where events intersect with people and/or infrastructure and subsequently creates problems.

The Oregon Water Resources Department ranks the Bonneville Dam as a high hazard dam, meaning that in the case of dam failure, loss of one human life is very likely (Dam Inventory). According to the U.S. Army Corps of Engineers, the likelihood of catastrophic dam failure is low. However, "one of the most effective risk reduction measure for such an event… is an effective evacuation plan" (Clemans 2016). While predictions have been made about the effects an earthquake will have on the power the Bonneville Dam supplies, little has been done to see how the actual dam will perform in a quake event. The Federal Emergency Management Agency has developed certain methods, including chain-of-events probability charts to help estimate potential failure modes for dams in seismic events (Brand et al. 2014). Department engineer Keith Mills, believes that earthquake studies on dam safety are out-of-date given the seismic danger predicted (Manning 2015). According to the Army Corps, "dams were built to the seismic standards of the day; the agency is now conducting studies of all its dams to better understand their vulnerability to a Cascadia-level event. Experts expect that at least some Corps dams would sustain deformation and other damage – including damage to spillway gates, regulating outlets and/or powerhouses – that might impact the Corps' ability to manage downstream flows, but may not necessarily lead to a catastrophic dam failure," (Clemans 2016). There is very little research published about the seismic hazards and risks at dams in the Pacific Northwest. We could not find an emergency action plan for the Bonneville Dam. The significance and need to assess the hazard and risk of the Bonneville dam can be summarized as this: "the impact of earthquakes on public safety and the national economy can be reduced through improvement of the built- environment to resist earthquake effects such as ground shaking. Reduction of the economic impact on individuals and the nation can also be reduced by additional means such as earthquake insurance" (USGS 2016).

While we don't possess the technical expertise to assess the Bonneville Dam for specific pathways of failure or probabilities of risk, we explored the potential locations of change in the infrastructure, landscape, and function of the Bonneville Dam as a result of a high magnitude earthquake.

With its historic and symbolic status, relationship with both geologic and ecologic systems, multiple uses and uncertain hazard futures, the Bonneville Dam is an apt structure to probe for information regarding longevity and change. We ask: how might the function of the Bonneville Dam be altered in the event of a Cascadia earthquake? The structure of the Bonneville Dam is not likely to completely fail in the event of an 9.0 Cascadia quake event. However, certain aspects of the function, including its salmon rehabilitation efforts, recreation opportunities, and energy production may be at risk or at least subject to change in the face of the impending earthquake. This study has the potential to provide insight into how human structures and the institutions that manage them might survive disasters through physical, functional, and symbolic adaptation.

Methods

To assess how an earthquake might alter the functions of the Bonneville Dam as a site of hydropower generation, recreation, and fish rehabilitation, we conducted the following methods:

geologic hazard mapping using existing layers in state databases, chain of events analysis, and informal interviews of key engineers and staff persons.

Geologic Hazard Mapping

In order to describe which events following an earthquake might affect specific functions and location within the Bonneville Lock & Dam site, we situated the Bonneville Dam within the various zones of Cascadia earthquake hazards. For the Oregon data, we used the Oregon Department of Geology and Mineral Industries Statewide Hazard View portal for each of these layers (DOGAMI). For the Washington data, we used the Washington State Department of Natural Resources Geologic Hazard Maps. For Washington, we specifically examined the Washington State Seismic Hazards Catalog for the Cascadia (not the Cascadia North) scenario (Washington Department of Natural Resources). Using the interactive interface, we examined Cascadia event shaking predictions, landslide inventory, and soil liquefaction for the river banks adjacent to the Bonneville Dam on either side of the Columbia River. As well, we mapped the Cascadia Subduction Zone slab depth across the Pacific Northwest to illustrate the extent of the zone and its increasing depth inland as context.

Chain of Events Analysis

In order to estimate the management response to an earthquake, we created event trees from information found in FEMA's "Selecting Analytic Tools for Concrete Dams Address Key Events Along Potential Failure Mode Paths" (Brand et al. 2014). Event trees outline the decisions that are made following an event, in this case a 9.0 earthquake with an epicenter off the coast of Oregon or Washington. We made three event trees to show the decisions that need to be made and in what order they will be made after our hypothetical catastrophic earthquake. Using the emergency and evacuation information collected in our case studies and our background research as well as specific procedural information about the Bonneville Dam procured from Amy Echols, Deputy Chief, Public Affairs of the U.S. Army Corps of Engineers, we made event trees for Bonneville hydropower, recreation, and fish safety.

Event trees are usually accompanied with a quantitative element to show the probability of the likelihood of a decision. Because of limited information and little transparency in the Bonneville Dam emergency systems, we were not able to create these probabilities.

Interviews

We knew that it would be necessary to talk to integral staff and administration at the Bonneville dam in order to further understand how the dam would alter in the event of the earthquake. We called the Emergency Operations Center, the Bonneville Power Administration, and the Oregon Office of Emergency Management. After calling many numbers, we were placed in contact with Amy Echols, Deputy Chief, Public Affairs of the U.S. Army Corps of Engineers. We had a long over-the-phone interview with Echols that aided us greatly in the execution of our research.

We also reached out to Professor Elizabeth Safran, who directed us to important background geologic information which can be found in our situated context.

Results

See here for an easy view of results and figures together: https://ds.lclark.edu/hannahsmay/projects-2/bonneville-dam/results/

Figure 1: Cascadia Subduction Zone Depth

This map shows the slap of the Juan de Fuca plate as it subducts at increasing depth under the North American Plate. The depth of the subducting plate ranges from about 0-5 kilometers at the subduction zone offshore of the west coast to about 100 kilometers as the Juan de Fuca plate merges with the upper mantle of Earth. Large earthquakes (7.0-9.0 on the Richter scale) are possible throughout the entire subduction zone at each depth. However, depending on where precisely the hypocenter of the earthquake is across the three dimensions illustrated in this map, the implications for Bonneville Dam and other structures and regions vary widely. From our preliminary research, the locations in the zone that are most likely to slip next are along the shallower part of the subduction offshore.

Figure 2: Oregon Cascadia Expected Shaking

This map shows the expected shaking of the area surrounding the Bonneville Dam in the scenario of a 9.0 Cascadia event. Directly to the south of the dam on the Oregon side, the slope as a rating of "severe" shaking, as does a large swath of the slope just upstream from the dam. Although the Oregon data does not explain the specific force behind the shaking ratings, the stronger the shaking indicates the higher probability of structural damage. Bradford Island itself, where the Bonneville Lock & Dam visitor center is located along with other structural aspects of the locks, dam, hydropower, and fish ladder systems, is predicted to have "very strong" shaking.

Figure 3: Washington Predicted Shaking

All along the Washington side of the Columbia River adjacent to the Bonneville Dam, the shaking is predicted to be "strong" or about 6 on the Modified Mercalli Intensity (MMI) scale. The Modified Mercalli Intensity (MMI) scale is a seismic scale that measures the effects of an earthquake on the earth's surface, humans in the area, objects, and structures. The scale ranges from 1 (not felt) to 12 (total destruction). The description of MMI 6, derived by the Washington State hazard view map from the Association of Bay Area Governments Resilience Program, is the following: "Objects fall. Felt by all. People walk unsteadily. Many frightened. Windows crack. Dishes, glassware, knickknacks, and books fall off shelves. Pictures off walls. Furniture moved or overturned. Weak plaster, adobe buildings, and some poorly built masonry buildings cracked. Trees and bushes shake visibly." While this is considered strong and a threat to structures, the shaking by itself does not pose a serious threat to the concrete structure of the dam. However, it would affect people in the vicinity and other buildings and structures nearby to varying degrees.

Figure 4: Oregon Liquefaction (soft soil) Hazard Map

Liquefaction, the event of loosely packed and moist sediments act as a liquid substance, can occur during the intense shaking of an earthquake. The liquefaction hazard for the area adjacent to the Bonneville Dam on the Oregon side as well as on Bradford Island is moderate. Buildings and infrastructure, such as the visitor's center, are sitting on these soft soils and are likely to be severely damaged in an earthquake if liquefaction does occur.

Figure 5: Washington Liquefaction Susceptibility

On the Washington side and according to the Washington scale, the liquefaction susceptibility of the area just downstream of the dam is high whereas the Bridge of the Gods area upstream of the dam is rated moderate. Both of these ratings indicate that the land on other side of the Bonneville is susceptible to liquefaction due to its looseness and moisture content.

Figure 6: Oregon Landslide Susceptibility

This layer was created to identify areas in Oregon where landslides might occur in the future. The data depicts landslide susceptibility at a 10-meter resolution and used the Oregon Lidar Consortium and USGS NED to map elevation (DOGAMI). This elevation data was converted into slopes, and a multi-pronged analysis process used these slopes, geology and mapped existing landslides. The banks of the Columbia River on the Oregon side are rated as "very high" for landslide susceptibility because landslides already exist on these steep slopes. Bradford Island and the outer areas of the Bonneville Lock and Dam property have moderate and high susceptibility, meaning that landsliding is likely or possible throughout the entire complex.

Figure 7: Washington Landslide Map

On the Washington side of the river, two landslide features dominate the area adjacent to the Bonneville Dam. The green shape is a collection of mass-wasting deposits, mostly landslides, from the current geologic period (Quaternary). The purple shape is the Bonneville Landslide, a deep-seated historic landslide that is currently being researched by the Washington Division of Geology and Earth Resources. Both of these preexisting landslides are areas of liquefaction susceptibility, and if they are measured in the same or similar way that Oregon landslides are, it's likely that they would be rated "very high" in earthquake susceptibility.

Figure 8: Event Tree for the recreation of Bonneville Dam

Recreation around the dam consists of water activities, hiking, and the dam as a tourist attraction. Because of this, many post-earthquake effects can damage and hinder recreation, so we decided to focus on the potential for a landslide. The first "decisions" that happen in this tree are whether the landslide happens or not and whether it harms Bonneville recreation or not. While recreation can still be damage without a landslide, we are assuming that a landslide happened and damaged recreational areas for the parameters of this tree. Bonneville has a series of assessments their emergency team can do immediately, and it is most likely that the dam will close all recreational areas. In order to fix the damage, Bonneville dam then applies for emergency federal funding.

Figure 9: Event Tree for the hydropower of Bonneville Dam

If damage is found to the economic and infrastructure risk assessment, Bonneville will shut off the turbines. If risk is found in the public safety risk assessment, Bonneville's team will shut down the visitor center, gates, and travelling opportunities. In the case of hydropower, Bonneville would dispatch the Emergency Management Agency and the EMA would do their own assessment on the dam. After the results of this assessment and if there is damage and risk found in the dam, Bonneville would again apply for emergency federal funding. This map regards only the internal turbine hydropower infrastructure and not the external infrastructure of power lines transmitting hydropower away from the dam.

Figure 10: Event Tree for fish of the Bonneville Dam

As with hydropower, Bonneville would do an economic and infrastructure risk assessment. Their second assessment, however, would specifically look at damage to the fish ladders, elevators, and rigging systems. Again, Bonneville would dispatch the EMA who would do their own assessment. Like the recreation and hydropower event trees, Bonneville would apply for emergency federal funding in order to fix the damage caused by the earthquake.

Figure 11: Simplified version of all three event trees.

Interview Results

Our interview with Amy Echols helped us, not only with our event trees, but also in understanding more about how the dam is run and operated. Echols revealed to us that she thought of the Bonneville Dam as "an icon that represents development in the PNW and a leader in allowing for development and providing energy in a smart way." She told us that the Bonneville Dam is constantly changing, and that they are always trying to improve with the little money that is available. She spent a good part of her interview making it clear that Bonneville is always trying to make the dam safer for the fish that pass through. Although the Bonneville Dam may seem huge in size and symbolism, Amy grounded us by placing it in comparison with every other dam and large infrastructure in the world. She made it clear that the dam would be low on a long list of priorities if aspects of it were to fail due to an earthquake or any other natural disaster.

Discussion

Discussion of Results

Through our methodology, we examined the ramifications of both Bonneville Dam's geologic location in the case of a 9.0 Cascadia earthquake and the emergency response possibilities under the current management of the dam by the Army Corp of Engineers. Between severe shaking and high probabilities of liquefaction and landsliding at Bonneville Dam and the surrounding area of Cascade Locks, there is near certain to be change created by the earthquake. To address our question of how the function of Bonneville Dam might be altered in the event of a Cascadia earthquake, we will first explain the possible effects of the various earthquake hazards on hydropower operations, salmon rehabilitation, and recreation opportunities. Landsliding, liquefaction, and ground shaking each have the power to disrupt the integrity of structures from the visitor center on Bradford Island (Figure 12) to the concrete dam itself. Because of inherent uncertainties about the location and strength of any future earthquake and a lack of seismic research regarding the site of the Bonneville Dam, it is nearly impossible to predict which specific structures will be affected. However, using our maps and background research about the layout of the Bonneville Dam, we speculate how earthquake geology might alter the functions of the dam.

For the hydropower operations of the dam, energy is generated within the infrastructure of the dam through turbines and is transported elsewhere by a system of power lines. While the internal infrastructure has a low risk of damage because it is protected by the sturdy concrete dam, these external infrastructure of energy transport which traverses the steep hillsides and banks of the river is at a far greater risk of serious damage. If indeed these pieces of infrastructure are compromised by liquefaction or landsliding caused by shaking, the Bonneville Dam's ability to provide hydropower to the northwest region will be hindered regardless of the integrity of the turbines and other internal energy infrastructure. Our conversation with Army Corp employee, Echols, indicated that the repairs to the dam in the case of an emergency would be granted by the federal government only if approved. Considering the Bonneville Dam is relatively far inland and is not the only or largest supplier of energy to the Pacific Northwest, in the case of a catastrophic earthquake, Echols indicated that it is likely that funds would be allocated elsewhere to address more pertinent crises. In this case, the hydropower function of the dam could be stalled or inhibited for an extended period of time. Another possibility would be that any small cracks or damages to the internal infrastructure would experience a delay in being addressed and could potentially get worse during the aftershocks of the earthquake or during the waiting period for funds. Another possibility, of course, is that the dam continues to provide hydropower to assist in the recovery of the post-quake Northwest and the hydropower function of the dam is enhanced by loss of other types of energy and infrastructure needed to rebuild affected communities.

Regarding the fish rehabilitation infrastructure, similar barriers to specific risk prediction apply. Because the fish rehabilitation program and infrastructure has become a major source of pride in recent years, damages to this aspect of the dam might alter both the public image of the dam as an ecologically responsible operation and the upstream and downstream movements of migratory fish. Similar to the hydropower, elements of the fish rehabilitation infrastructure such as the fish ladder are situated within the dam structure. These pieces of the fish program are likely as little risk of severe damage. Contrarily, the hatchery located off of Interstate 5 at Cascade Locks exists within the zones of severe shaking, landsliding, and liquefaction risk. Similarly, the avian attack prevention infrastructure, excitedly mentioned by Echols as an important component of the assurances of fish survival, exists on the Washington side of the river in a zone of severe liquefaction. While the infrastructure of fish rehabilitation itself may not be at extreme risk of complete failure, damages to small aspects of the program such as the avian prevention sprinkler or access to the hatchery could prohibit the program from fulfilling its full potential after a large earthquake.

Another possibility for the scenario of a large landslide to move into the reservoir above Bonneville would be to block or partially block the river as happened historically with Bridge of the Gods. Any mass wasting into the reservoir might also increase the buildup of sediment on the pool and harm the migration of juvenile fish. What also would matter for fish is the timing of the earthquake. If the earthquake occurs during peak upstream migration, any barriers to their migration caused by the earthquake or damage to the fish infrastructure would have a more severe impact, perhaps, than if the earthquake occurred during a time that fewer fish pass through the Bonneville Dam. Echols explained that it's difficult to prioritize different functions of the dam because each management office would argue that theirs is most important. With federal dollars likely being spent to rebuild cities like Portland and alleviate suffering for affected human populations, repairs to the fish infrastructure are not likely to be at the top of list for fund allocation. In these hierarchies, it is perhaps necessary for human lives to take precedent over fish lives. However, this highlights how crisis response and emergency procedures are generally anthropocentric. Without human management of fish migration, salmon populations may decrease. Public image could be shifted if harm befalls the fish rehabilitation initiative at the dam because it has been a source of pride since its emergence. However, judging by the recovery from severe population collapse of the latter 20th Century that spurred so much environmental action and change, perhaps the earthquake does not pose a huge threat to salmon species via the Bonneville Dam. What is more likely is that funding for any damages incurred by the fish hatchery, infrastructure, or other aspects might be delayed until immediate needs of those affected by the earthquake are adequately met.

While effects of the earthquake to hydropower and fish infrastructure is grounded in existing infrastructure, the possible effects on recreational opportunities at Bonneville Dam is less tangible. The three recreational activities focused on here are access to the visitor center on Bradford Island and use of the river for boating, swimming, and fishing recreation. First, the earthquake effects of liquefaction, shaking, and landsliding are all possible on Bradford Island, creating a risk for visitors to be frightened by the earthquakes effects. Falling objects and unstable structures within the complex of the visitor center could also cause damage to both the facilities and visitors. The dam visitor center and surrounding recreation sites are accessible by highways on either side of the river. Between the landslide hazard and the liquefaction, it seems likely that these arteries of transportation will be disrupted, thus cutting off access to the dam by visitors and rescue and repair crews until the roads are repaired. Access would be the main immediate and short-term effect of an earthquake on recreation at Bonneville Dam. Long term effects might include altered layout of recreation facilities due to geomorphology. Additionally, if the dam survives, which it likely will, history of the earthquake might be included in the visitor center materials and exhibits illustrating the strength and resilience of a dam in large seismic events. Since the dam is a national monument, it's possible that new plaques or areas of interest will be developed in remembrance or interpretation of the events of the earthquake.

After speaking with Echols, we were able to gain a better understanding of potential outcomes of a 9.0 earthquake in the PNW and possible next steps that would be taken at the dam. The information gathered in our interview allowed us to speculate about what can be done at the dam to better prepare for the impending Cascadia earthquake. We learned that although there is new advanced research and knowledge of earthquake risk at the dam and surrounding area, the funding can't keep up with it. In order to get sufficient funding to make updates to the dam to ensure earthquake safety, a disaster must occur first. If a natural disaster like an earthquake did compromise the dam, there is emergency funding potentially available. However, if an event like this took place and other areas were compromised, the area with greatest risk would get the most money. Those risks would be weighed first at the district level of district dams and then taken to the division level. After risk levels were determined, the list of issues would have to be taken to Congress with a specific plan proposal and estimated cost in order to receive emergency funding. Not only would Bonneville Dam be competing with about 600 other dams, but Bonneville would also have to compete for funding against hospitals, highways, water filtration, and hundreds of other structural services in the case of an emergency. It is a challenge across the country to get enough money to keep dams up to standard as better technology, science, and earthquake detection emerge. The Bonneville Dam is not the only dam with earthquake hazards or aging infrastructure, and the Portland Army Corps will never be the only ones asking for money to make improvements. While small repairs and low-cost updates can be made for the short term, funding for long-term changes seems to be a waiting game for structures.

Broader Implications

For our framing question, we inquired how high-profile dams are managed to adapt over time. By asking this question, we must consider the ways in which dams adapt and over what period of time. When we talked on the phone with Amy Echols, she told us that the lifespan of the Bonneville Dam, when it was first built, was predicted to be about 75 years. The Bonneville Dam is now around 80 years old, and said that this is definitely apparent when looking at the aging infrastructure. Although the Bonneville Dam is considered to be structurally sound, it was not built to stand earthquakes, and there are many functions of the Bonneville that may be compromised in the case that one occurs. There have definitely been improvements to Bonneville since it was originally built, however there isn't enough federal funding to keep the dam up to current regulation. The Cascadia earthquake, while holding a large amount of threat, is not the only natural disaster that could affect structures in the United States, or the world, making Bonneville's importance, as a run-of-the-river dam with high hazards but low risks, even less likely to be at the top of the list for federal funding.

In terms of symbolic implication, human-made dams are inherently fragile if they can be tested by natural forces. Since dams are given a "lifespan" when they are created, they become systems that need substantial care, especially when that lifespan has expired. Because there is not an unlimited amount of money to fund these federal structures, it is important to consider what may alter their function or landscape, and how best to cope with these adjustments. By preparing for disasters, realizing that each dam adapts differently, and taking into account lifespans, life-threatening structural failure could be managed or minimized. Our research trickles down to our ultimate question: how do human structures evolve through change over time? Nearing the end of its functional life, the Bonneville Dam has always been a symbol of development in the Pacific Northwest. At the same time the dam's primary function is to provide renewable clean hydroelectric energy. Through our study, we predict that if little damage is made to the dam, then the dam will remain a powerful symbol of expansion and development. The conclusions of our research are concerning, however, because dams like Bonneville do not have the resources to make the necessary precautions in case of an earthquake. This perhaps indicates a need for a change which will allow funding to be precautionary rather than reactionary, a problem that even talk-show hosts bemoan (Oliver 2015). Instead, infrastructure waits for the disaster to happen and then surrounding communities start rebuilding and picking up the pieces. In the rare chance the Bonneville Dam completely fails and perhaps takes human lives with it, what will the impact be on the cultural significance of this structure? If the dam fails, a dam symbolizing the power of humans over nature, we can only imagine the implications this might have on federally-funded infrastructure.

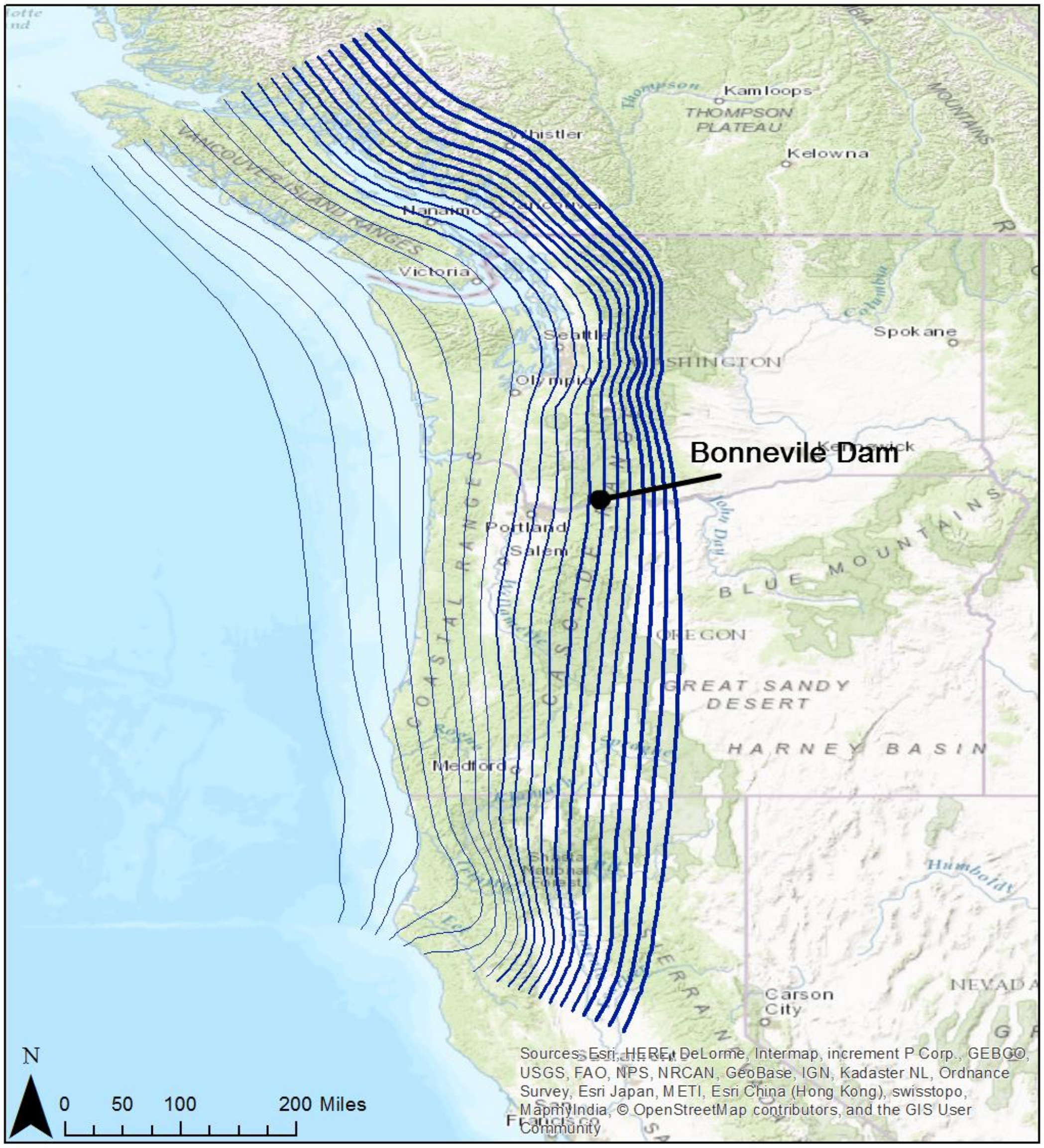
This problem of infrastructure funding doesn't just apply to the Bonneville Dam. In fact, this dam is a very small player in the network of dams providing hydropower in the Pacific Northwest. If dams holding back huge reservoirs fail, the failure could result in extreme flooding. If a dam producing a lot of hydroelectric power fails, then that failure will lead to an electricity deficit. Dams in the Pacific Northwest will not be able to make precautions to prepare for the earthquake, and will instead be applying to emergency federal funding all together. On top of that, they will be competing with highways and hospitals. Whether a bridge was taken out by a tsunami or a road was uprooted by a tornado, all of this infrastructure is repaired by applying for federal aid, and then making the necessary repairs. It would be interesting to conduct an economic analysis to evaluate if the federal government saves money by taking precautionary measures or by fixing infrastructure after disasters.

Looking into the future of predicting the outcome of the Bonneville Dam, it would be interesting to create an action plan for the dam for every scenario of the earthquake and calculating its chance of failure. This would constitute a more quantitative analysis. While to create a plan for every possible scenario would be impossible, at the very least it would be helpful and reassuring for the Army Corps to create an evacuation plan for the future earthquake. Along those lines, another opportunity for further research would be assessing the range of possible damage to hydroelectric power, a network in which Bonneville Dam is thoroughly embedded, is important for broader resilience. It would also be interesting to examine an ethnographic perspective on the dam and interview people regarding their perceptions of the dam and how their image of the dam could change in the face of the 9.0 Cascadia earthquake. If we could, we would ask people from the 1930s, 1980s, 2000s, from the aftermath of the Cascadia event, and into the distant future how the Bonneville Dam is both functional and symbolic. Unfortunately, the future is opaque and we can only speculate about the diversity of temporal perspectives.

Our project is largely hypothetical and covers a range of possible futures. While this certainly inhibits our ability to speculate from real occurrences, it does provide important lessons. When planning for the future, whether it be building a long-lasting structure or created an emergency action plan for one that already exists, there are so many possibilities and unforeseen circumstances that might alter the course of action. Planning for change, particularly change by disaster, can never be guaranteed to be correct. Furthermore, the building and maintenance of structures is an investment in some belief in the future. If that belief in is a resilient structure that can overpower the earth, as dams classically are seen, then perhaps challenges to this mindset are less likely to be taken seriously. These beliefs, which inspire and sustain the structures of our civilizations, are bound to change over time. Here we see the shift from wonder of the world, to ecological misstep, to responsible and functional historic monument. What's next for the Bonneville Dam? If the Bonneville Dam poses a lesser problem than others, how will its function adapt to events that greatly affect its context? Broadly, how will the structures of our civilization be remembered and how do geologic events influence that perspective? Perhaps sometime in the next fifty years, the Cascadia earthquake will contribute to the many answers to these questions.

Figure1:

Cascadia Subduction Zone Slab



Legend

Cascadia Subduction Zone Slab Model Depth (km)

- 5.000000 - 20.000000
- 20.000001 - 40.000000
- 40.000001 - 60.000000
- 60.000001 - 80.000000
- 80.000001 - 100.000000

Figure2:

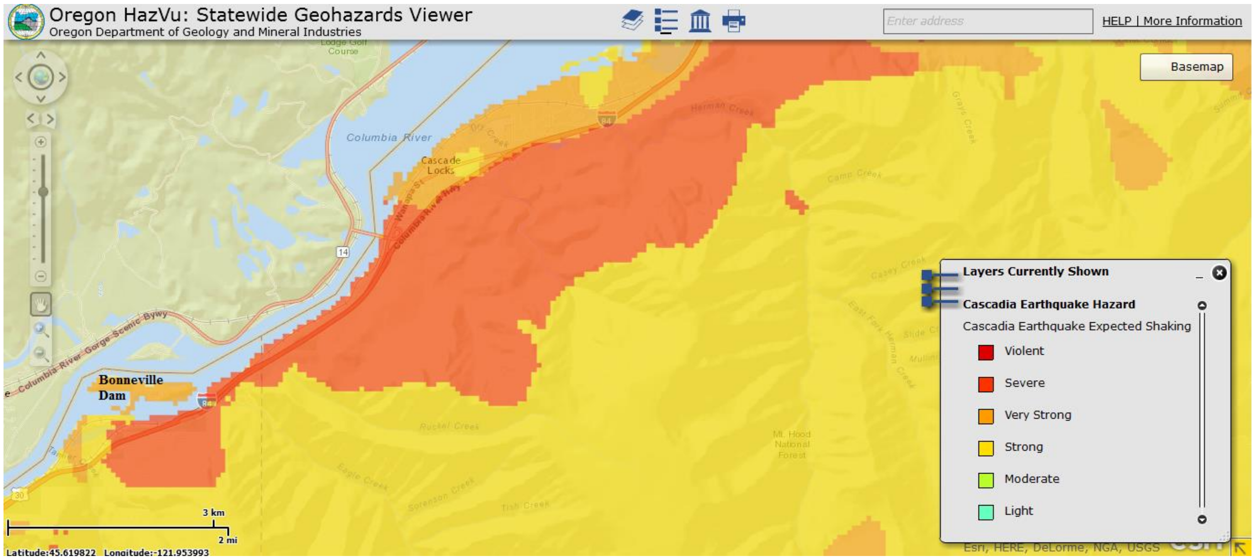
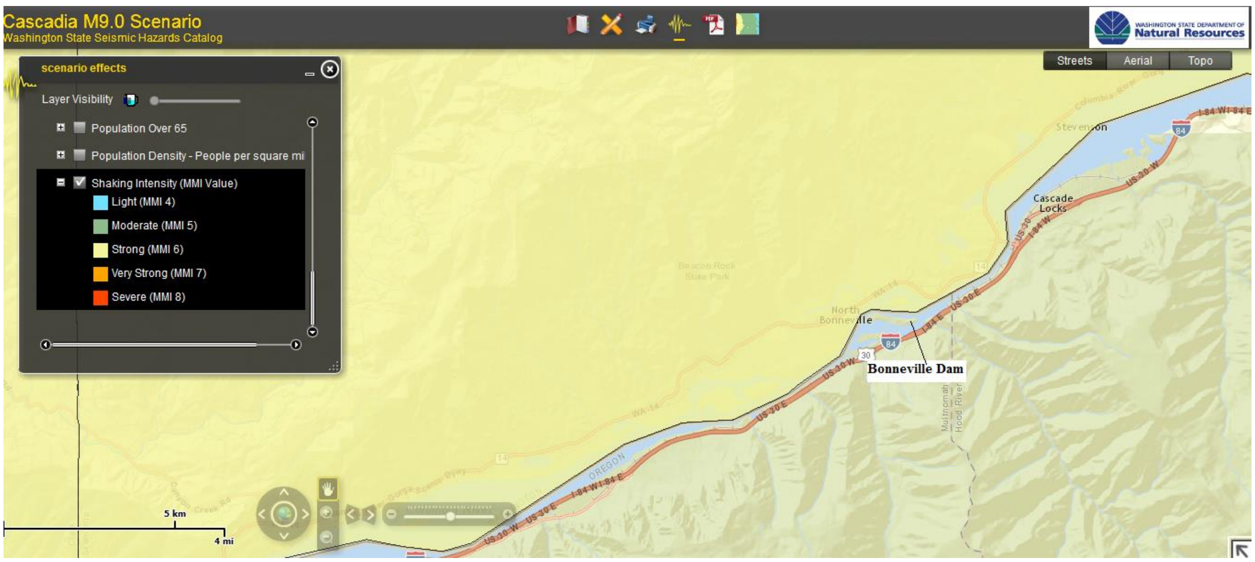


Figure3:



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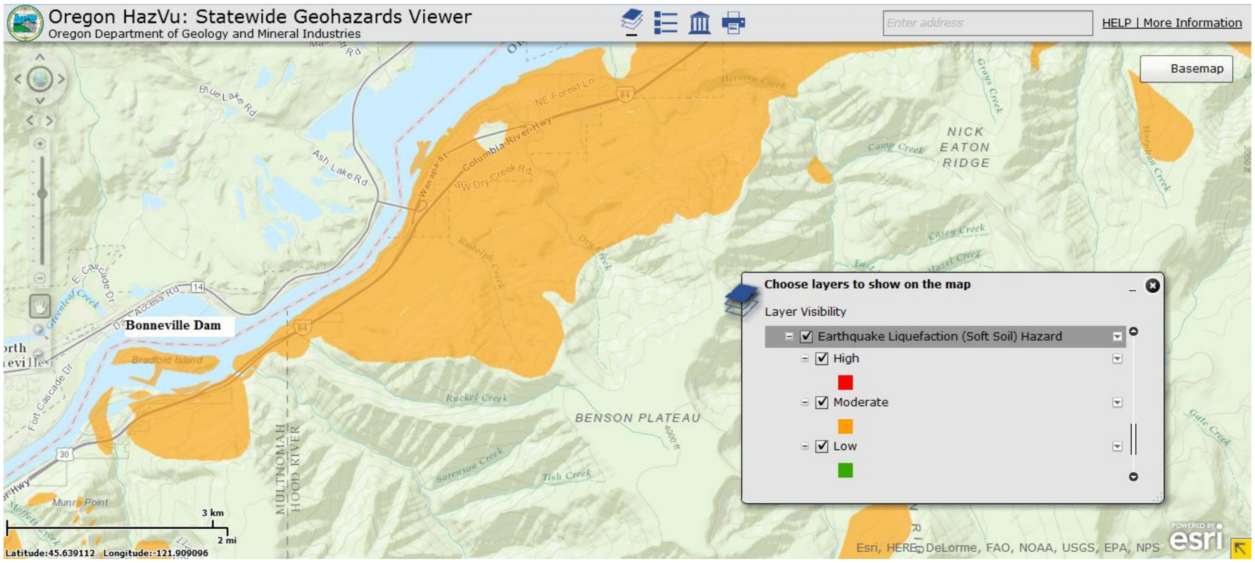


Figure5:

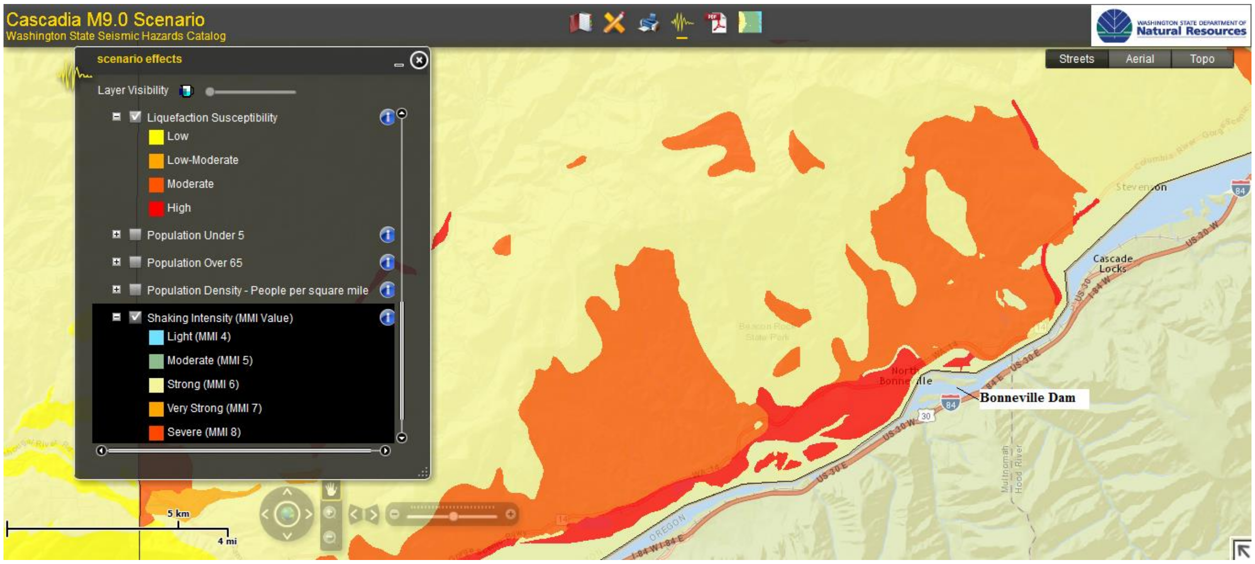


Figure6:

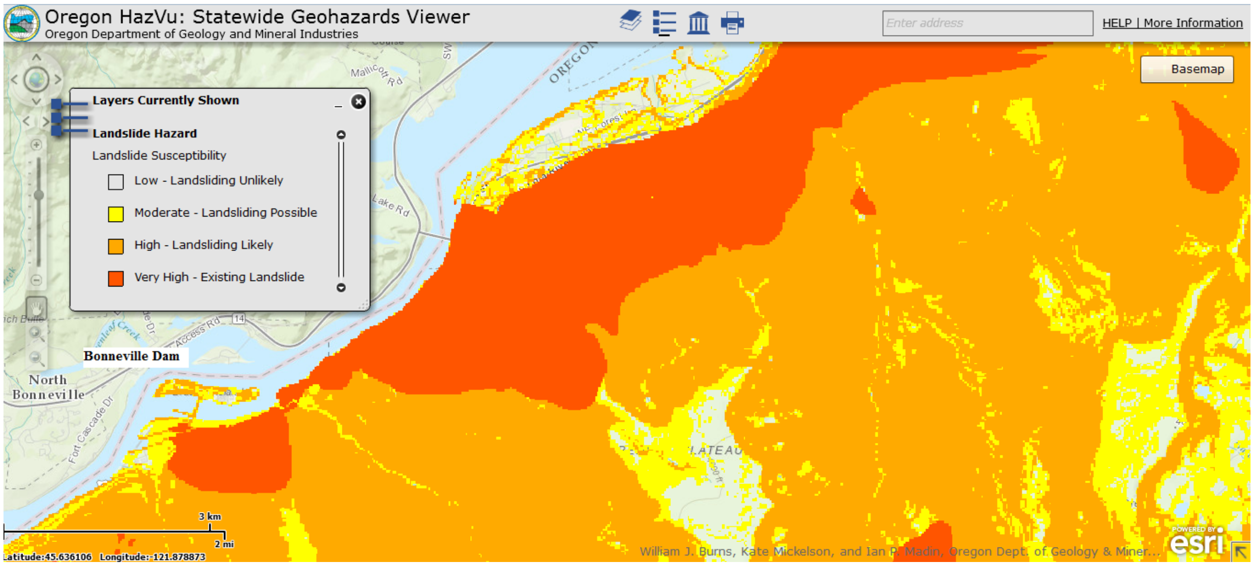


Figure7:

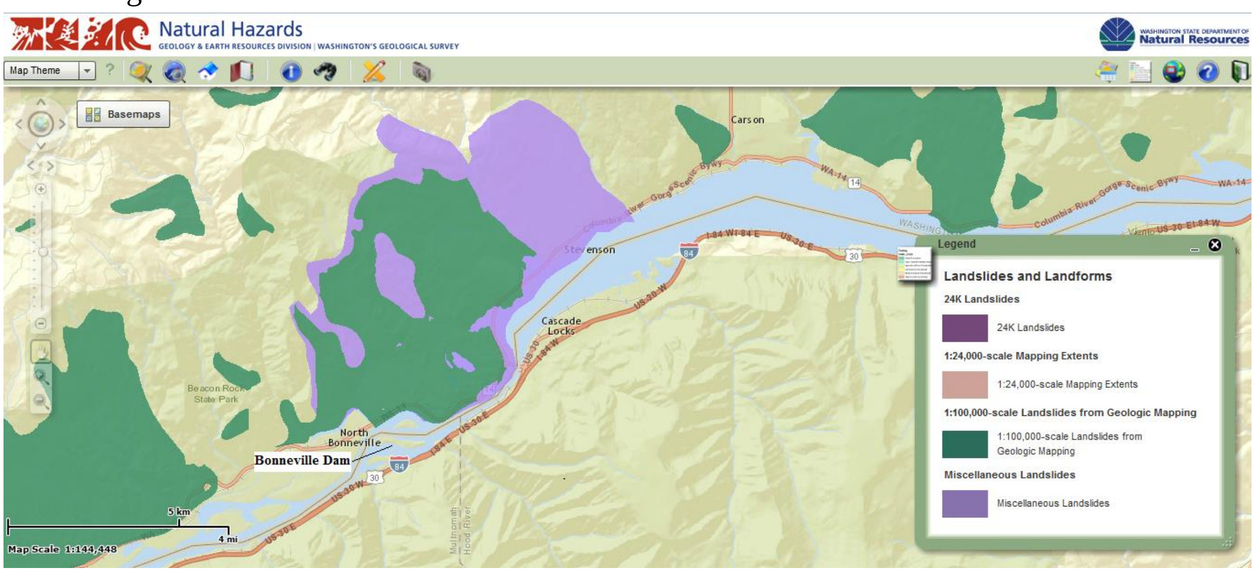


Figure 8:

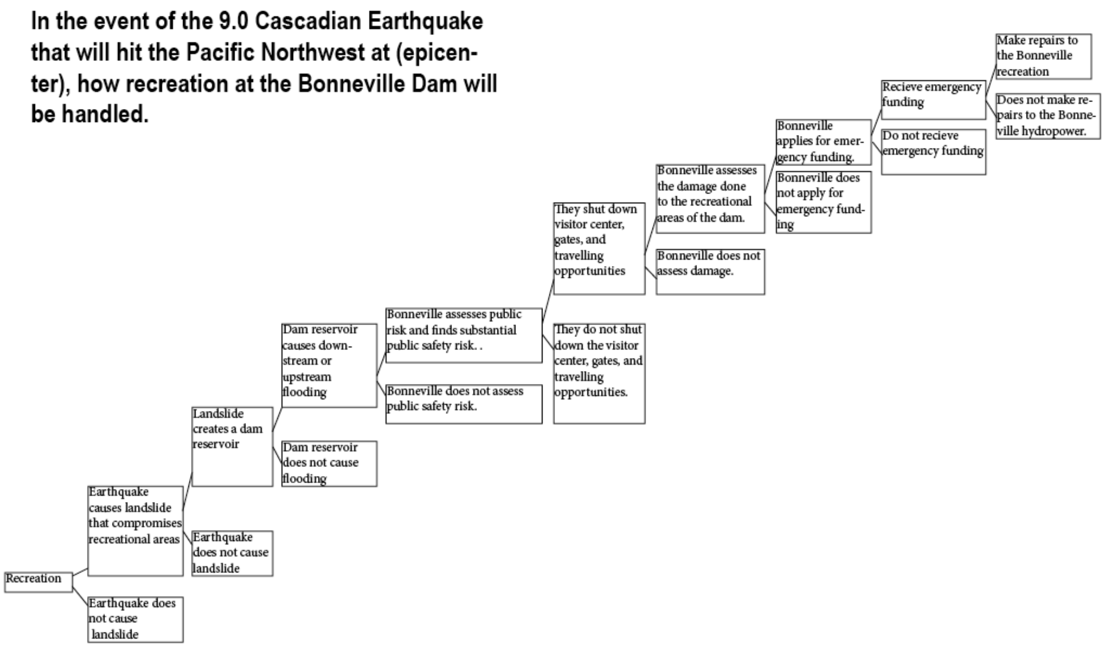

In the event of the 9.0 Cascadian Earthquake that will hit the Pacific Northwest at (epicenter), how recreation at the Bonneville Dam will be handled.
Recreation
Earthquake causes landslide that compromises recreational areas
Earthquake does not cause landslide
Landslide creates a dam reservoir
Earthquake does not cause landslide
Dam reservoir causes down-stream or upstream flooding
Dam reservoir does not cause flooding
Bonneville assesses public risk and finds substantial public safety risk. .
Bonneville does not assess public safety risk.
They shut down visitor center, gates, and travelling opportunities
They do not shut down the visitor center, gates, and travelling opportunities.
Bonneville assesses the damage done to the recreational areas of the dam.
Bonneville does not assess damage.
Bonneville applies for emergency funding.
Bonneville does not apply for emergency funding
Recieve emergency funding
Do not recieve emergency funding
Make repairs to the Bonneville recreation
Does not make repairs to the Bonneville hydropower.

Figure 9:

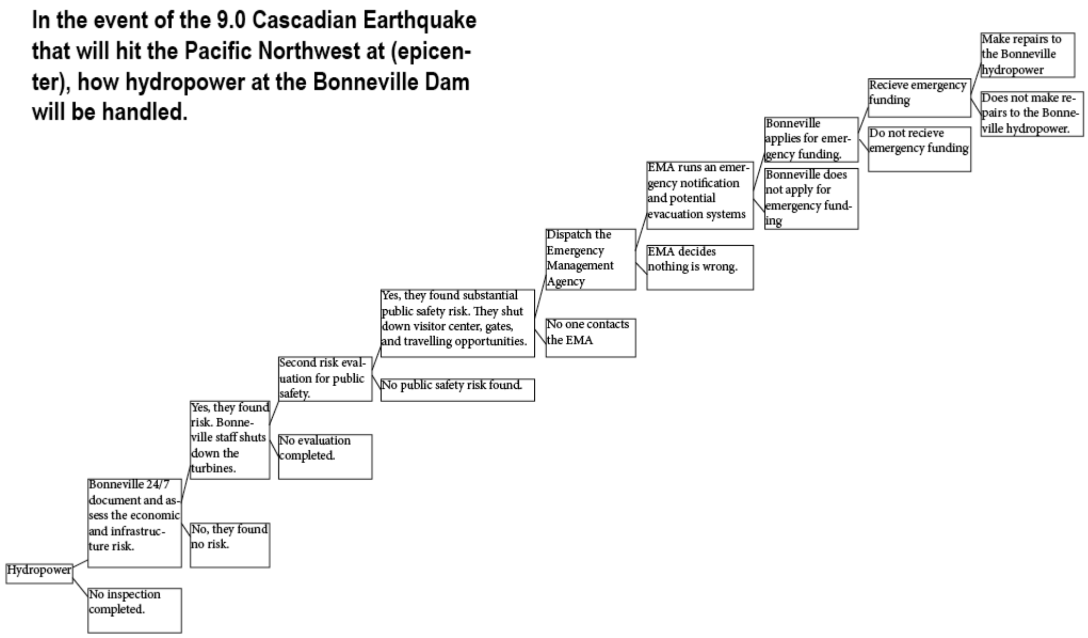


Figure10:

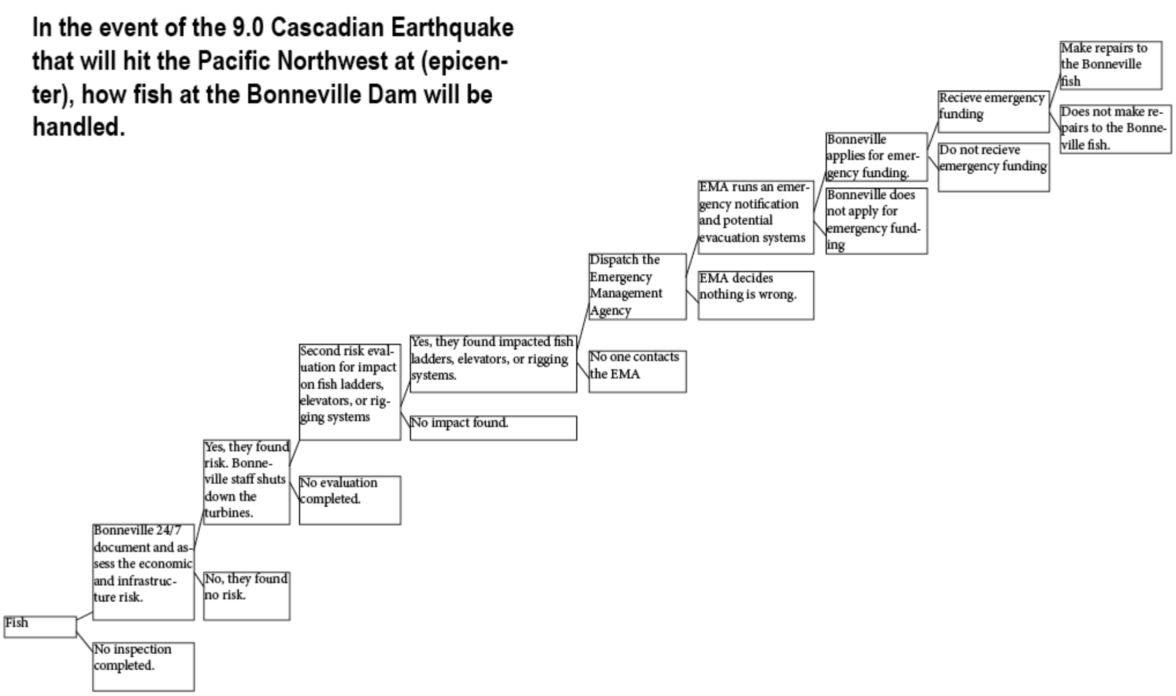


Figure 11:

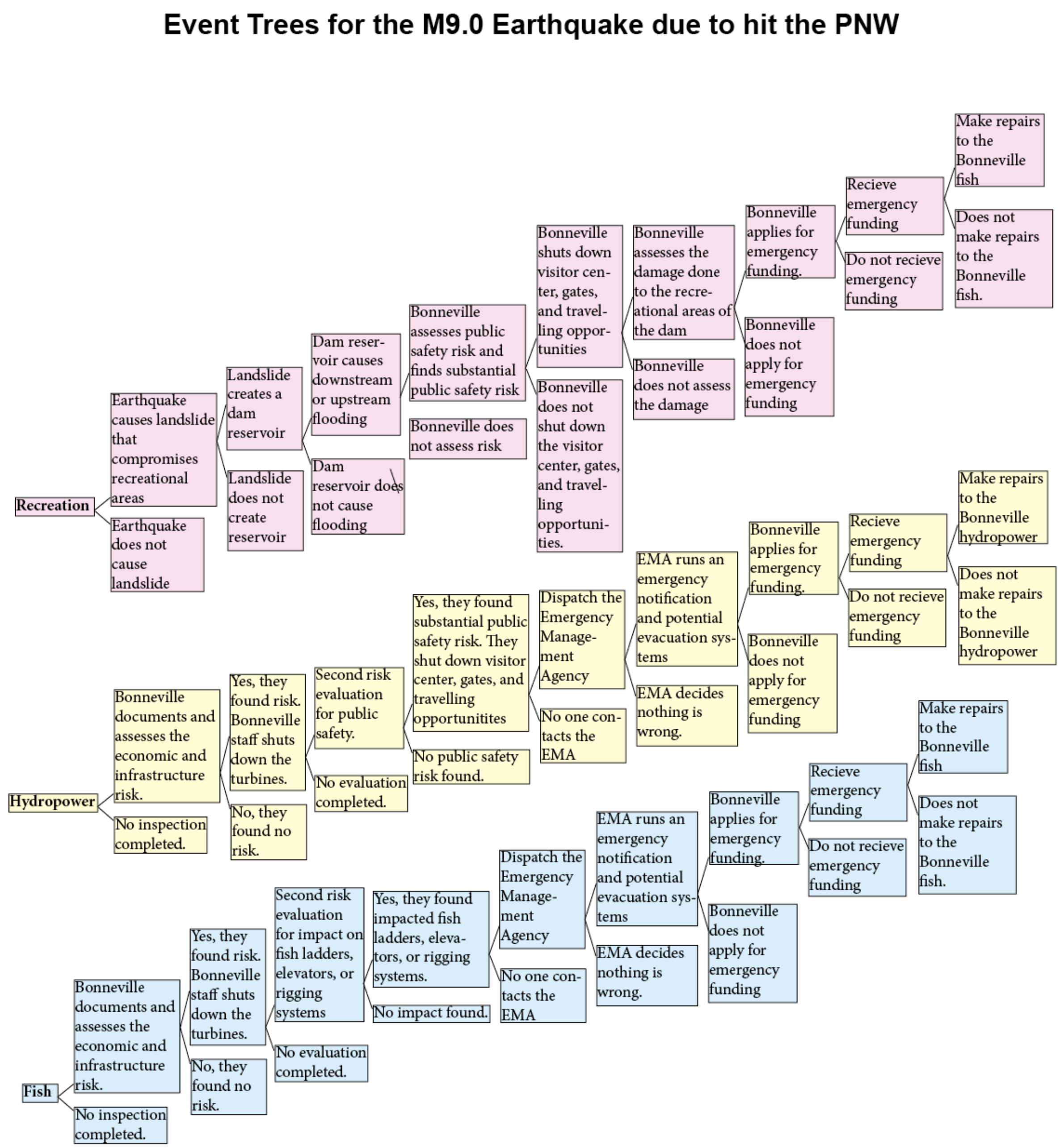
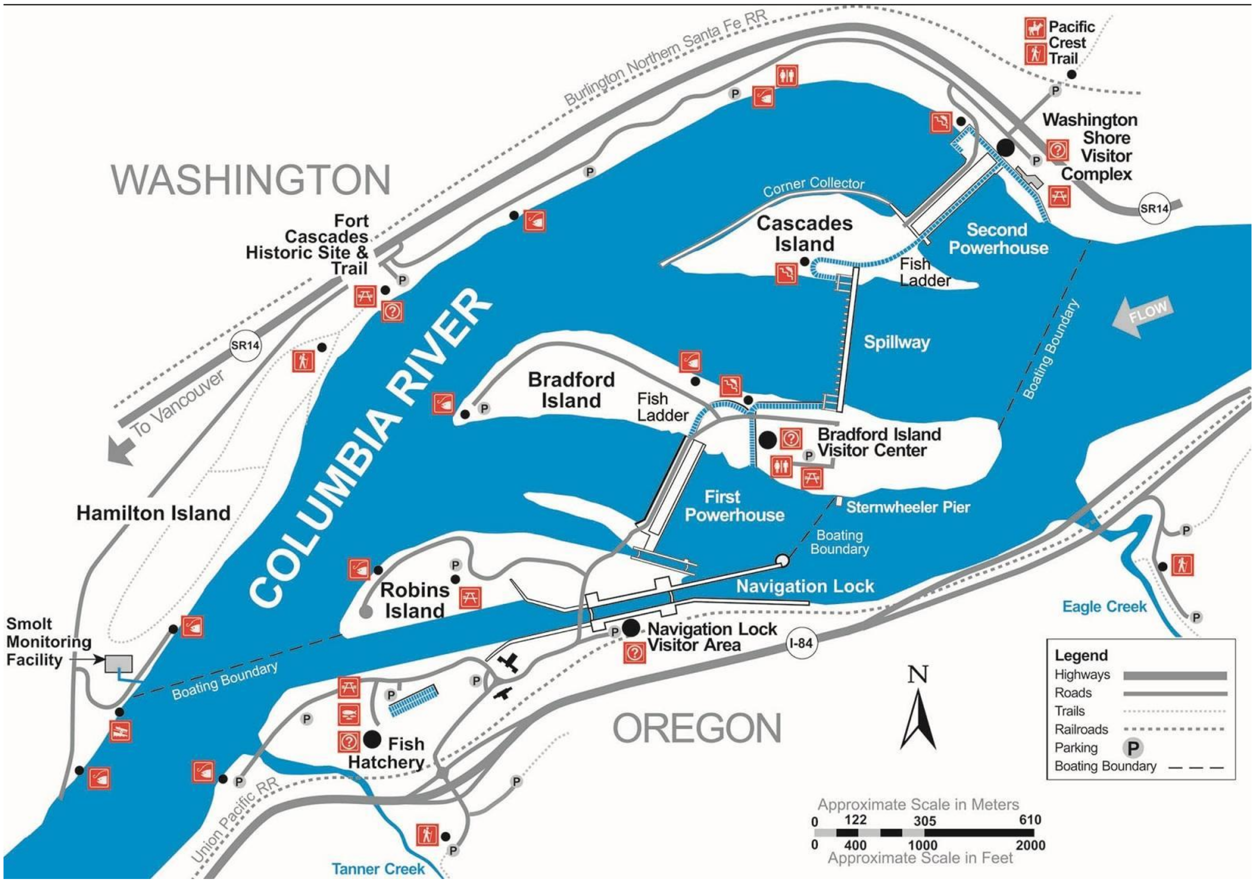

Event Trees for the M9.0 Earthquake due to hit the PNW
Recreation
Earthquake causes landslide that compromises recreational areas
Earthquake does not cause landslide
Landslide creates a dam reservoir
Landslide does not create reservoir
Dam reservoir causes downstream or upstream flooding
Dam reservoir does not cause flooding
Bonneville assesses public safety risk and finds substantial public safety risk
Bonneville does not assess risk
Bonneville shuts down visitor center, gates, and travelling opportunities
Bonneville does not shut down the visitor center, gates, and travelling opportunities.
Bonneville assesses the damage done to the recreational areas of the dam
Bonneville does not assess the damage
Bonneville applies for emergency funding.
Bonneville does not apply for emergency funding
Recieve emergency funding
Do not recieve emergency funding
Make repairs to the Bonneville fish
Does not make repairs to the Bonneville fish.
Hydropower
Bonneville documents and assesses the economic and infrastructure risk.
No inspection completed.
Yes, they found risk. Bonneville staff shuts down the turbines.
No, they found no risk.
Second risk evaluation for public safety.
No evaluation completed.
Yes, they found substantial public safety risk. They shut down visitor center, gates, and travelling opportunitites
No public safety risk found.
Dispatch the Emergency Management Agency
No one contacts the EMA
EMA runs an emergency notification and potential evacuation systems
EMA decides nothing is wrong.
Bonneville applies for emergency funding.
Bonneville does not apply for emergency funding
Recieve emergency funding
Do not recieve emergency funding
Make repairs to the Bonneville hydropower
Does not make repairs to the Bonneville hydropower
Fish
Bonneville documents and assesses the economic and infrastructure risk.
No inspection completed.
Yes, they found risk. Bonneville staff shuts down the turbines.
No, they found no risk.
Second risk evaluation for impact on fish ladders, elevators, or rigging systems
No evaluation completed.
Yes, they found impacted fish ladders, elevators, or rigging systems.
No impact found.
Dispatch the Emergency Management Agency
No one contacts the EMA
EMA runs an emergency notification and potential evacuation systems
EMA decides nothing is wrong.
Bonneville applies for emergency funding.
Bonneville does not apply for emergency funding
Recieve emergency funding
Do not recieve emergency funding
Make repairs to the Bonneville fish
Does not make repairs to the Bonneville fish.

Figure 12: (US Army Corps of Engineers)



Works Cited *(visit our project site for a complete annotated bibliography)*

Ashford, Scott. 2015. “Earthquake preparations need to start now, OSU dean advises federal officials” *Oregon State University News and research Communications*. http://oregonstate.edu/ua/ncs/archives/2015/may/earthquake-preparations-need-start-now-osu-dean-advises-federal-officials

Bloodworth, Gina, and James White. 2008. “The Columbia Basin Project: Seventy-Five Years Later.” *Yearbook of the Association of Pacific Coast Geographers* 70; 96–111.

“Bonneville Lock and Dam.” 2013. US Army Corps of Engineers.

Brand, Bruce, David Dollar, Luis Hernandez, Husein Hasan, Larry Nuss, Rex Rowell, and William Wallace. 2014. “Selecting Analytic Tools for Concrete Dams Address Key Events Along Potential Failure Mode Paths.” *FEMA*:1016. http://www.fema.gov/media-library-data/1423072356123-801ff39d781345289daa842256a31a4d/FEMAP-1016.pdf.

Clemans, Scott. 2016. “Don’t Freak out: Dams Generally Do Well in Earthquakes.” *US Army Corp of Engineers, Portland District*. http://usaceportland.armylive.dodlive.mil/index.php/2016/01/shakeout-dont-freak-out-dams-generally-do-well-in-earthquakes/.

Committee on Seismic Aspects of Dam Design. 2012. “Dam Safety and Earthquakes.” *International Water Power & Dam Construction*, August. http://www.preventionweb.net/files/15259_9694491.pdf.

Dick, Wesley Arden. 1989. “When Dams Weren’t Damned: The Public Power Crusade and Visions of the Good Life in the Pacific Northwest in the 1930s.” *Environmental Review: ER* 13 (3/4): 113–53. doi:10.2307/3984393.

Galbraith, Kate. 2011. "Hydropower's Resurgence and the Controversy Around It." *New York Times*, March 29, 2016. http://www.nytimes.com/2011/05/16/business/global/16iht-green16.html?_r=0.

“Geologic Hazard Maps.” Washington State: Department of Natural Resources. Accessed March 11, 2016. http://www.dnr.wa.gov/programs-and-services/geology/geologic-hazards/geologic-hazard-maps#landslides-and-landforms.

Gilles, Nathan. 2012. “The First Four Minutes.” *Portland Mercury*, March 14, 2016. http://www.portlandmercury.com/portland/the-first-four-minutes/Content?oid=5766214.

Jepsen, Sue. 2015.“The Really Big One and Portland: Answers from Earthquake Experts.” *OregonLive.com*. http://www.oregonlive.com/earthquakes/index.ssf/2015/07/the_really_big_one_and_portlan.html

Kaika, Maria. 2002. "Dams as Symbols of Modernization: The Urbanization of Nature Between Geographical Imagination and Materiality." *Annals of the Association of American Geographers* 96, no. 2; 276-301.

Knight, Ben, and Travis Rummel. 2014. *DamNation*. Documentary. Felt Soul Media. http://www.imdb.com/title/tt3345206/.

Levin, P. S., & Tolimieri, N. 2001. “Differences in the impacts of dams on the dynamics of salmon populations”. *Animal Conservation*, *4*(4);. 291–299. http://doi.org/10.1017/S1367943001001342

Ladd, Chris. 2009. “Dam It All.” *Good Magazine*. http://www.good.is/post/dam-it-all/

Loomis, J. 2002. “Quantifying recreation use values from removing dams and restoring free-flowing rivers: A contingent behavior travel cost demand model for the Lower Snake River.” *Water Resources Research*, *38*(6); 2–1–2–8. http://doi.org/10.1029/2000WR000136

Manning, Rob. 2015. “Seismic Reviews Of Many Oregon Dams Way Behind Schedule.” *Oregon Public Broadcasting.* March 15, 2016. http://www.opb.org/news/article/seismic-reviews-many-oregon-dams-way-behind-schedule/.

Oregon Water Resources Department. “Dam Inventory.” 2016. Accessed April 20. http://apps.wrd.state.or.us/apps/misc/dam_inventory/.

Oregon Seismic Safety Policy Advisory Commission. 2013. “The Oregon Resilience Plan: Reducing Risk and Improving Recovery for the Next Cascadia Earthquake and Tsunami.” Salem, Oregon: 77th Legislative Assembly.

Poff, LeRoy N. and David D. Hart. 2002. “Why Dams Vary and Why is Matters for the Emerging Science of Dam Removal” *BioScience,* Vol. 52. No. 2.

Pierson, Thomas C. 2009. “InSAR Detection of Renewed Movement of a Large Ancient Landslide Int the Columbia River Gorge, Washington.” presented at the Geologic Society of America, Portland, OR, October 18. https://gsa.confex.com/gsa/2009AM/finalprogram/abstract_162891.htm.

Pierson, Thomas C. 2014.“Finding New and Complex Landslides in Forested Terrain: Mapping Using LiDAR in the Western Columbia River Gorge.” presented at the Geological Society of America Annual Meeting, Vancouver, BC. https://gsa.confex.com/gsa/2014AM/finalprogram/abstract_243459.htm.

Pradel, Daniel, Joseph Wartman, and Binod Tiwari. 2012. “Failure of Fujinuma Dam during the 2011 Tohuku Earthquake.” In *Joint Proc., 9th International Conference on Urban Earthquake Engineering/4th Asia Conference on Earthquake Engineering*. https://groupdelta.com/Papers/Failure-of-Fujinuma-Dam-During-the-2011-Tohoku-Earthquake.pdf.

Oliver, John. 2015. *Last Week Tonight with John Oliver: Infrastructure (HBO).* Last Week Tonight.https://www.youtube.com/watch?v=Wpzvaqypav8&nohtml5=False.

Pringle, Patrick. 2009. “Bonneville Landslide,” *Columbia Gorge Interpretive Center for Exploration*. http://www.geology.cwu.edu/facstaff/nick/g351/2009_Pringle_BonnevilleLandslide.pdf.

Rom, William N. 2011. *Environmental Policy and Public Health: Air Pollution, Global Climate Change, and Wilderness*. John Wiley & Sons.

Saleth, Maria R. 1992. “Big Dams Controversy Economics, Ecology, and Equity” *Economic and Political Weekly,* Vol. 27, No. 30.

“Statewide Geohazards Viewer.” Oregon HazVu. Oregon Department of Geology and Mineral Industries. Accessed April 19, 2016. http://www.oregongeology.org/hazvu/.

Strauth, David. 2015. “Study Outlines Impact of Tsunami on the Columbia River.” *Oregon State University, News and Research Communications*. http://oregonstate.edu/ua/ncs/archives/2015/feb/study-outlines-impact-tsunami-columbia-river.

“To Save the Salmon.” 1997. US Army Corps of Engineers.

U.S. Department of Interior. “Hazard & Risk Assessment.” Accessed March 11, 2016. http://earthquake.usgs.gov/research/hazrisk/.

Wang, Yumei, Steven Bartlett, and Scott Miles. 2012. “Earthquake Risk Study for Oregon’s Critical Energy Infrastructure Hub.pdf.” *Oregon Department of Geology and Mineral Industries*. http://www.oregongeology.org/sub/earthquakes/cei-hub-report.pdf

Wrobel, David. 2016. “The Legacy of Colonial Rule.” *University of Nevada, Las Vegas*. Accessed April 19. http://www.unlv.edu/news/article/legacy-colonial-rule.