AN ABSTRACT OF THE THESIS OF

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William K. Jaeger

The goal of this thesis is to identify the factors which have most significantly contributed to historical dam removals in the United States. The trend of increased dam removals over time is specifically analyzed for evidence that increased scarcity of environmental goods and services is motivating dam removals. A theoretical model is presented to explain how dam removal is consistent with maximization of social welfare and to hypothesize the direction of the effects for variables which are believed to contribute to changes in the relative price of environmental goods. The empirical estimation is conducted using a time series dataset of characteristics of dams both removed and not removed between 1969 and 2016. The dataset is an aggregation of the American River's Dam Removal Database and the U.S. Army Corps of Engineers National Inventory of Dams, with additional explanatory variables added using geospatial identifiers. Using a logit regression, the effect of explanatory variables are estimated to identify which factors have most motivated past dam removals. The results of this analysis provide evidence that dam-specific characteristics and federal regulations are most significantly influencing dam removal decisions. Evidence that increases in the relative value of environmental goods and services have contributed to dam removals was inconclusive. Overall, this analysis suggests that removals are decided on an individual basis depending on the specific attributes of the dam under consideration.

Drivers of Deconstruction:
An Analysis of Dam Removal in the United States

by
Laura W. Marshall

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Laura W. Marshall, Author

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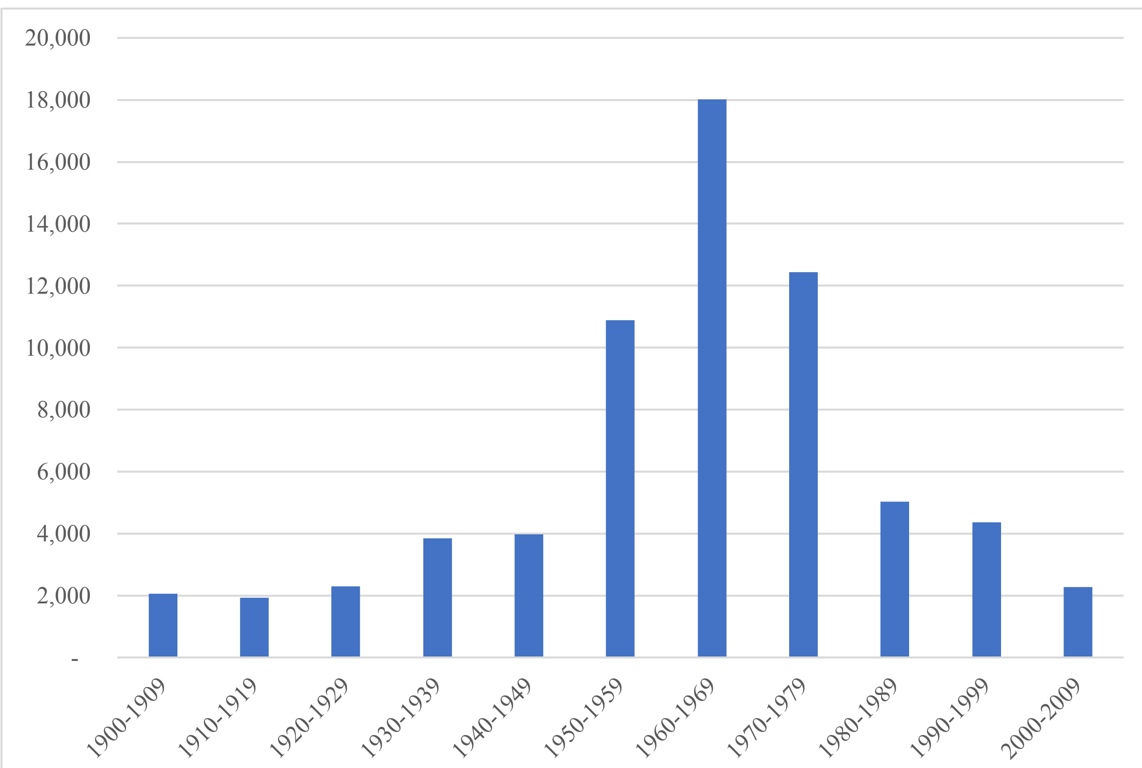
Introduction

1.1 Background

Dam building in the U.S. increased beginning in the 1900s, with the highest number of dams being built between 1950 and 1980 (Figure 1). During this period and since, the primary reasons for building dams include flood control, water storage (for agricultural, municipal, industrial, and recreational purposes), hydroelectricity, and transportation. Dams are heterogenous goods, being constructed for a variety of purposes, by a variety of interests, at both large and small scales, from materials ranging from earthen to concrete, and across all types of landscapes.

Figure 1: Number of Dams Built by Decade in the United States (1900 – 2010)



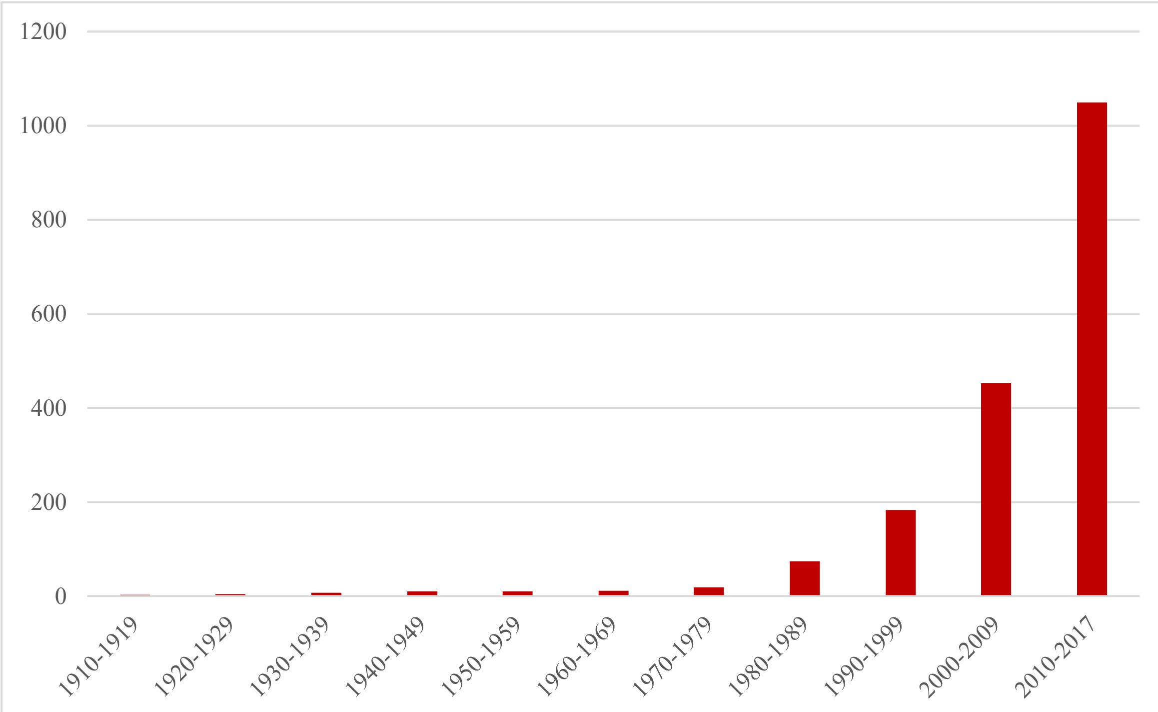
Source: Created with data from the National Inventory of Dams (USACE 2010)

The impacts of dams can affect entire communities because of the drastic way in which dams alter landscapes. Some of the impacts from dams are generally considered benefits, such as flood control, while others are considered costs, such as losses in ecosystem functionality. The magnitude and distribution of these impacts creates incentives for collective action to regulate dams. These can occur at the local, state, and federal levels.

According to the National Inventory of Dams (NID) maintained by the U.S. Army Corps of Engineers (USACE) there are at least 80,000 dams in the United States, which does not include low-hazard, small dams due to the priorities of data collection. Of the dams in the NID database, 51 percent have heights less than 25 feet and 92 percent have heights less than 50 feet (USACE 2013). The NID is the most comprehensive inventory of U.S. dams with more than 80,000, but it is estimated that there are approximately 2 to 2.5 million total dams in the U.S. (NRC 1992). Of these larger dams in the NID, only approximately 4 percent are federally owned. The majority of the dams in the NID are privately owned (65 percent), with an additional 18 percent owned by local government, 7 percent owned by states, and 2 percent owned by public utilities (USACE 2013). While the NID contains primarily larger dams, most dams in the United States are small, storing less than 100 acre-feet of water (The Heinz Center 2002). While non-federal dams are built for many of the same reasons as federal dams (e.g. flood control and water storage), some private dams were built for industrial purposes, such as providing power for mill activities like wheat grinding (The Heinz Center 2002). In addition to flood control, navigation, and milling, other reasons for non-federal dam building include recreation, stock watering, fire ponds, private water supplies, irrigation, waste disposal (especially for mining and farming byproducts), and hydroelectricity electricity production (The Heinz Center 2002).

Although dam building is continuing to occur in the U.S. it is being done at a decreasing rate since the 1970s. During that same period, the rate at which dams have been removed in the U.S. has exponentially increased. Over 1,000 dams were removed between 2010 and 2017 alone (Figure 2). The reasons why dam removals have occurred is the topic of this thesis and will be discussed in detail in subsequent sections.

Figure 2: Dam Removals by Decade in the United States (1910 – 2017)



Source: American Rivers (2017)

1.2 Economics of Dam Removal

Dams create many positive externalities reflected in the variety of purposes they are built for, such as flood control, recreation opportunities, navigation, water supply, and hydroelectricity. These positive externalities can create a market failure through free-riding, where people can utilize a benefit without paying for it directly. For example, public benefits of downstream flood control can result from a privately-built dam. This externalization of benefits can lead to an underproduction of the public good in the absence of government involvement (Samuelson 1954). Although dams provide positive externalities, they also create negative externalities such as risk of dam failure, aquatic habitat inundation, restricted access to upstream habitats for migratory species, reduced water quality, changes in the aquatic food web, and sediment accumulation, among others. These negative externalities represent market failure because the external costs are imposed on segments of society who do not own and/or benefit from the dam. For example, a dam that reduces salmon populations can result in reduced access to First Foods for Native Americans and loss of jobs for commercial fishermen during the closure of salmon fisheries, which imposes negative externalities on a population that is not directly benefiting from the dam.

Another type of market failure arises from the high fixed costs of building a dam. Natural monopolies occur when the market equilibrium is for only one firm to produce the good or service, creating a monopoly. This type of structure can occur due to high start-up costs and economies of scale. For some dams, natural monopolies arise because access to the resource, the river, is restricted to one firm for a particular river segment. This monopolistic structure encourages government intervention to prevent underproduction, which occurs with monopoly power. In response to those high start-up costs, government intervention also can provide financial assistance for construction costs of dams. The involvement of the U.S. Bureau of Reclamation and U.S. Army Corps of Engineers in dam building is an example of how the U.S. government has chosen to handle market failure for dams in the past. Note that the majority of dams, especially small dams, do not involve any government intervention.

Government also affects dams through implementation of regulations. The most relevant federal regulations for dams include the Federal Power Act, Endangered Species Act, the Flood Control Act of 1927, and the National Dam Safety Program. State and local regulations on dams vary by location. These regulations could be viewed within the public interest theory of regulation, which suggests that economic regulation arises when the public demands a change to unfair or inequitable market practices and regulation increases efficiency. In contrast to the public interest theory, the competing theory of agency capture asserts that regulations are in response to demand of interest groups in order to maximize rent extraction for those organized interests (Posner 1974). Both producers and private interest groups have incentive to organize and leverage regulations to promote their interests (Peltzman 1976; Becker 1976; McChesney 1987).

A decision to remove a dam may arise for a variety of reasons. Like any durable good, dams have a limited life expectancy. They can wear out, become unsafe, and/or fill with sediment. These changes can reduce the value of the dam to the point where benefit of removing the dam exceeds the benefit of retaining it. In addition to the expected depreciation of the dam, other changes can occur during the lifetime of the dam that may change the benefit-cost calculation of the dam owner in favor of dam removal. Conditions that have changed in the last few decades for dams include increased costs imposed by regulations. For example, in 1986, changes to the Federal Power Act have resulted in increased relicensing costs for certain dams (Amos 2014). Additionally, technological changes can alter the opportunity costs for dams by changing the price of alternatives. Examples of these technological changes include groundwater pumping making alternative water supplies cheaper than stored water or hydraulic fracturing making natural gas a cheaper source of energy than hydroelectricity. It should be noted that some structural changes to a society could also increase the value of a standing dam, such as a larger downstream population which increases the value of recreation, flood risk reduction, and electricity provided by the dam.

Over time, the tradeoffs between environmental goods and produced goods has also changed due to the decrease in available environmental resources.[1] When the majority of dams were initially built between 1950 and 1980 environmental resources were relatively abundant, so the costs of losing a free-flowing river, salmon habitat, and free-flowing water recreation were relatively low due to the availability of substitutes. Now, dams are numerous across the United States and undammed rivers are relatively scarce. Because the resource of a free-flowing river, the environmental good, is relatively scarce compared with produced goods, such as those measured by the consumer price index, the relative "price" of rivers (i.e. value or willingness to pay) is likely to be higher than in the past. What is driving this change in relative scarcity is that increases in income allow for increased consumption of the aforementioned consumed goods. Because produced goods become relatively more abundant, their relative price decreases and the relative price of the environmental good increases. If large enough, this change in valuation of the environmental goods may change the outcome of the benefit-cost analysis, leading to consideration of dam removal. Note that because many of the goods and services provided by a river are non-market, such as species habitat, the relative value of a non-dammed river can often not be directly measured.

[1] The term "environmental goods" refers to all goods and services provided by the natural environment and includes ecosystem services, recreational opportunities, species, habitats, and other environmental amenities. The term "produced goods" refers to all goods and services produced by firms and sold in markets, such as those measured by the Consumer Price Index.

1.3 Statement of Research Question

The goal of this thesis is to identify the factors that have contributed to dam removal decisions. While there are multiple reasons why dams are removed, this thesis will examine whether there is evidence that changes in the relative scarcity of environmental goods relative to other consumer goods may be motivating some dam removals. Evidence to support this theory will be measured by the effect of changes in real per capita income on the probability a dam will be removed. Increases in income are strong indicators that the levels of consumption of consumer goods are increasing. As more consumption occurs, environmental goods become scarcer, since they are available in fixed quantities and more cannot be produced. This change in scarcity is believed to increase the relative value of the environment, motivating dam removal. One of the ways that increased relative value of the environment are expressed is through regulations, such as the Endangered Species Act, so those types of institutions will also be evaluated to determine how they influence the probability of dam removal. Other explanations from the literature suggest that age and purpose of a dam will likely be factors that directly influence the probability of removal. Support for these theories and others will be evaluated in this analysis to determine which factors have most influenced historical dam removals decisions in the United States.

This thesis attempts to answer the research question by comparing dams that have been removed with the dams that have not. The U.S. Army Corps of Engineers records characteristics of high hazard and/or large dams in the United States through the National Inventory of Dams database. These non-removed dams are compared against removed dams, documented by the non-profit American Rivers, using a subset of comparatively-large dams. These datasets contain basic information about the dams and are georeferenced, which allows for the addition of regional economic indicators over a time series from 1969 to 2016.

1.4 Organization of Thesis

The organization of this thesis proceeds in six additional sections. Chapter 2 provides a review of the economic literature most relevant to dam removal as well as the non-economic research on dam removal. Chapter 3 presents the theoretical model used to identify the specific economic factors influencing dam removal decisions, as well as the empirical model used for the regression. Chapter 4 describes the data sources and provides summary statistics of the data. Chapter 5 presents the results of the regression analysis and robustness checks. Chapter 6 discusses the findings. Chapter 7 summarizes the conclusions of the research and opportunities for future study.

2 Literature Review

2.1 Economic Theory

While benefit-cost analyses have been conducted for individual dams, the phenomenon of dam removal has not been systematically evaluated from an economic perspective. Dams generally have not been the focus of economic study, but economic theory has been applied to water resources. The economic literature on water has often focused on the challenges related to economic valuation of the resource. In 1985, Young & Haveman authored a chapter in the "Handbook of Natural Resource and Energy Economics", which provides a general history of water resources in the United States and discusses strategies for valuing water (Young & Haveman 1985). Twenty years later, Hanemann published an explanation on the "Economic Conception of Water" in 2006, describing how the value of water varies depending on time, place, use, and quality of the resource (Hanemann 2006). Furthermore, Hanemann explains how water differs from other commodities because it functions as both a private and public good, depending on use. Additionally, water differs in its pricing mechanism, which is generally based on the infrastructure supply costs, rather than supply and demand (Hanemann 2006). In 2015, the "Handbook on Water Economics" was published, which provides an anthology of the current and past work on water economics (Dinar & Schwabe 2015). In addition to these economic studies of water, many of the more general theories from environmental economics can be applied to dam removal to inform what the potential motivators for removal might be.

2.1.1 Environmental Kuznets Curve

The Environmental Kuznets Curve (EKC) theory emerged in the early 1990s as part of the debate surrounding the North American Free Trade Agreement (NAFTA). The concern about NAFTA was that economic growth from trade would lead to further environmental degradation. On the contrary, economists found evidence that economic growth could actually lead to lower levels of pollution and less environmental degradation over time. Grossman and Krueger (1991) estimated an inverted-U shaped relationship between air pollution and per capita income. At lower income levels pollution is increasing up to a tipping point after which increases in income result in less pollution. Evidence for an EKC relationship was tested by Grossman & Krueger (1995) for water quality and urban air pollution, who estimated the turning point when improvements in environmental quality occur to be at a per capita income of approximately

$8000. If and when a turning point occurs depends on factors such as scale, preferences, technologies, income distribution, and institutions (Grossman & Krueger 1995; Jaeger & Kolpin 2001). Since these original papers, evidence for an EKC has been found for forests, soil erosion, and many other environmental goods and services.[2]

Environmental quality is affected by dams by the introduction of a physical barrier, the conversion of free-flowing water to slack water habitat, changes to the sediment and nutrient cycling which affects food supplies, and changes in flow regimes which can affect water temperature (Tullos et al. 2016).[3] Whether or not dam removal does represent an EKC is debatable, because although dams are being removed and altered to increase the level of environmental quantity (such as with added fish passage, spilling, sedimentation considerations), dams are also still being built in the United States at approximately twice the rate at which they are being removed. The purpose of this thesis is not to directly determine if there is an EKC relationship between economic growth and dams, but rather to determine if there is evidence that the mechanisms which can result in an EKC exist for dams and might be contributing to an increase in the instances of dam removal.

Multiple rationales for why the EKC is observed have been presented. They include the pollution havens hypothesis (Cole 2004) which suggests environmental quality improvements are offset by exporting environmental degradation to countries with lower per capita GDP levels. Given the long-term and localized nature of dams and their products (i.e. electricity, navigation, recreation, flood regulation). The pollution havens hypothesis is unlikely to be relevant for changes in riverine environmental quality. Another theory attributes the change to the structure of the economy, which is likely to be resource intensive at low levels of per capita GDP and then transition to service-based at higher levels of income (Dinda 2004). Additionally, preferences, technological change, and environmental quality as a luxury good have been put forward as potential hypotheses for why an EKC might exist (Roca 2002; Dinda 2004).

Focusing on technology as a mechanism to reduce pollution, Andreoni and Levinson (2001) provide evidence that an EKC relationship can emerge if there are increasing returns to scale of production for abatement technology because of the negative effects that pollution has

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[2] For further review of the current status and development of the EKC see Carson 2010 as well as Levinson 2002.

[3] It should be noted that increases in environmental goods can also occur with dams, such as increase in food availability for other species like pinnipeds and birds. For simplicity, those phenomenon are not considered here.

on consumption. Their work supported an earlier theory by Stokey (1998) who also believed that abatement technology becomes more affordable at higher levels of production and will be implemented because pollution and consumption are substitutes for each other, assuming an elastic marginal utility of consumption (i.e. that it is relatively easy to substitute pollution for consumption). Institutions have also been credited with contributing to the EKC relationship. Jones and Manuelli (1995) represent institutions as a fixed cost to show how collective decision making will influence the EKC. Lopez (1994) finds that an EKC can occur if producers internalize the externalities, and this internalization is often forced with government actions that occur to counter market failures.

2.1.2 Relative Prices of Environmental Goods

A related theory to the emergence of the EKC at higher levels of income is based on the relative price of environmental goods compared to consumer goods. The relative price theory incorporates the role of consumption and environmental quality as substitutes discussed by Andreoni & Levinson (2001) and Stokey (1998). Hoel and Sterner (2006, 2007) put forward the relative price theory within the debate about discount rates being used to quantify environmental actions.[4] The authors show that the relative price or "relative value" of environmental goods can be expected to increase when the environmental good (e.g. level of habitat or air quality) is scarce compared to the consumer good. Sterner & Persson (2007) provide a simple example of this phenomenon:

> "As the rate of growth is uneven across the sectors of the economy - the composition of economic output will inevitably change over time. Output of mobile telephones may grow fast while glaciers and coral reefs decline and therefore relative prices will change." (p.1)

In the presentation of their theory, Hoel and Sterner (2007) model the increased scarcity that results in higher relative prices for environmental goods as emerging from growth rate of the economy, characteristics of technology, and on properties of the social preference function. Lower elasticities of substitution values between consumer goods and environmental goods (i.e. consumers being less willing to substitute away from environmental goods) will also lead to

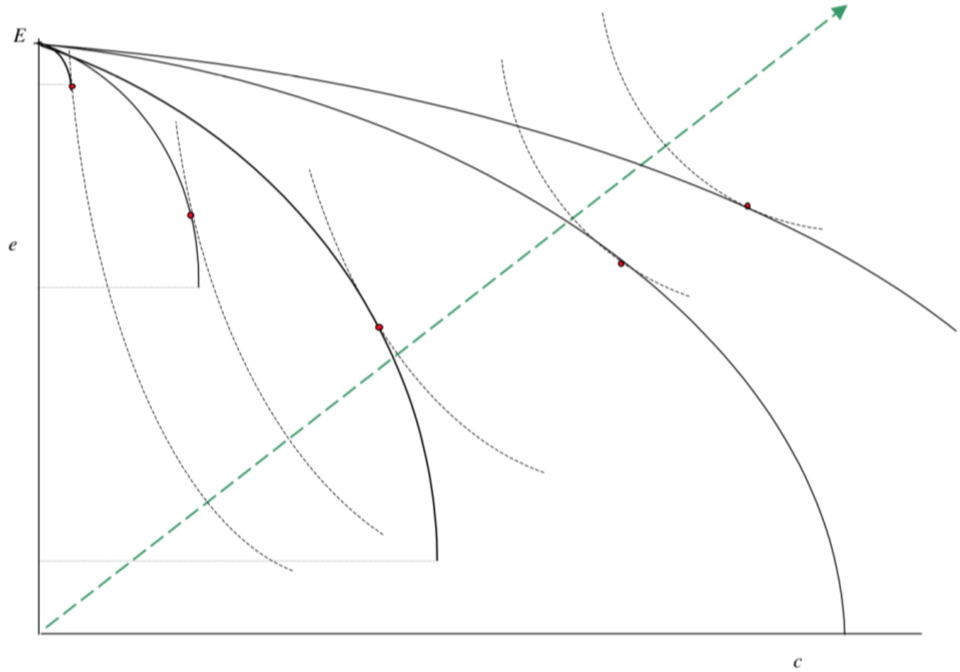
[4] The discount rate is used to deflate future dollars to reflect the fact that a dollar tomorrow is worth less than a dollar today.

increased relative prices (Hoel & Sterner 2007). The authors believe that the change in the relative price has the potential to counteract the effects of discounting. This relation to the discount rate was echoed by Jaeger and Kolpin (2001) who say that "the assumption that environmental values will be unchanged relative to goods prices could introduce large errors in these [benefit-cost analyses] calculations" (p.27). A possible explanation of dam removal could therefore be that changes in relative prices caused the economic value of dam to diminish to the point that the benefit-cost analysis no longer supports keeping a dam.

Jaeger and Kolpin (2001) directly relate the relative price theory to the EKC by presenting a model of how changes in relative prices can lead to increased environmental quality at higher levels of income. Their argument begins with the assertion that environmental resources, like natural riverine environments, are endowments which an economy has only a fixed amount of and cannot produce more of, in accordance with relative price theory. Due to human influences through either resource extraction or by imposing externalities, environmental resources decline over time during the initial growth of an economy. In contrast, commodity goods, such as those measured by the consumer price index are able to be produced at higher quantities at higher levels of income.

Figure 3 presents a graphical explanation of the theory which demonstrates how the production possibility frontier (PPF) increases at higher levels of income but can only extend on the axis for commodity production (c), since the maximum amount of environmental resources (E) is fixed. Due to these expansions of the PPF, there is a turning point (between the third and fourth points on the graph) where the marginal social value of environmental improvement (increased E) will outweigh the marginal value of additional commodity consumption. Outward shifts of the PPF can occur due to increases in income levels, increased population, and technological change, all of which can increase the potential production of consumer goods. This shifting out of the PPF changes the relative prices – at the optimum - as endowed environmental goods become relatively scarcer and consumption goods become relatively more abundant.

Figure 3: Production Possibility Frontier for Environmental Quality and Commodity Consumption



Source: Jaeger & Kolpin (2001)

Note: E represents the initial amount of an environmental resource, e is the amount of environmental quality produced/consumed, c is the amount of commodity produced/consumed, the convex line is the production possibility frontier (maximum possible output of bundles of e and c), and the concave dotted lines are indifference curves where the point of tangency represents the efficient production/consumption of e and c.

As economic growth occurs due to capital accumulation, the PPF expands to reflect the increased ability to produce goods. Society can allocate its productive capacity to produce private goods and public goods (through investment in abatement or restoration of environmental resources). Dam removal may be one of the ways society attempts to produce environmental goods and services. The efficient or optimal allocation of resources will be a balance between production of consumer goods and environmental goods. As growth occurs over time, the optimal allocation will reflect the new point of tangency between the marginal rate of substitution (MRS), the slope of the indifference curves, and the marginal rate of transformation (MRT), the slope of the PPF. The change in the slopes is driven by the change in the MRT brought about by productivity increases from technology but could also occur from changes in population or preferences. The slope of the MRS and MRT at the tangency point will reflect the relative marginal value or price of consumer goods and services relative to environmental goods and services. The value of the environmental good has also changed to reflect the increased relative scarcity of the environmental good compared to the consumer good.

The theory of relative prices can be applied to dam removal as a potential explanation for why dams are now being removed at an increasing rate. In the past 100 years in the U.S. there has been economic growth and development, rising incomes, and increases in population. Due to this economic growth, society has been able to accumulate capital and thus has increased productivity (e.g. technology, workforce development, etc.). With this increase in productivity, goods are produced at lower average costs and a greater variety of goods are being produced. At the same time, the income of consumers has increased as a result of economic growth, allowing them to purchase more consumer goods. As a result of the increased quantity of consumer goods, the marginal utility of consumption declines for consumer goods, but not for the endowed natural resources provided by the environment. To the extent that these consumer goods are associated with the presence of dam and the endowed environmental goods are associated with not having a dam these underlying forces could explain, or contribute, to a trend in dam removals. When many of the dams that are being removed were originally built it was for a specific purpose with a set of benefits and costs, as well as opportunity costs and available substitutes. Overtime, these conditions may have changed as a result of changes in relative prices, which may be why dams are now being removed.

2.1.3 Institutions

As society sees higher income and relatively less environmental quality, society can create institutions and regulations to protect the environment, just as society creates institutions to improve public safety and welfare. The economic concept of institutions is defined as anthropocentric organizational structures that "consists of both informal constraints (sanctions, taboos, customs, traditions, and codes of conduct) and formal rules (constitutions, laws, property rights)" (North 1991). Institutions evolve in response to market failure and instances where rent extraction is possible by institutionalizing the rules of the game and assigning property rights (Posner 1974; Olson 1986; Stiglitz 1989). As the mechanisms that society uses to achieve its goals, institutions address market failures such as freeriding, the undersupply of built public goods, and natural monopolies. Institutions are related to relative prices because, in representative political structures, regulations reflect the changes in relative values among members of society. If relative prices of environmental goods increase, regulations might arise which lead to increased environmental protection. Examples in the United States are the Endangered Species Act, the Clean Water Act, and other federal legislation, but also state regulations and membership to environmental organizations like the Sierra Club.

Formal institutions for dams have been created by government entities through both regulation as well as direct involvement of federal and state governments in dam ownership. Government sponsored dam building is believed to be due to the free-riding and natural monopoly potential of dams as public goods.[5] The laws and regulations that have been enacted represent policy choices corresponding to each institutional arrangement (Bromley 1989), which explains some of the state-specific variations in dam removal rates. Regulations affecting dam removal also reflect the various vested interests which either directly (e.g. American Rivers) or indirectly (e.g. increased transaction costs due to regulation) contribute to dam removal.[6] Section 2.2 of this thesis will provide details on the specific institutions and regulations which may be influencing dam removal decision-making.

2.1.4 Benefit-Cost Analysis

There have been a number of empirical economic studies that have evaluated the benefits and costs of specific dams. However, most dams have not had benefit-costs analysis (BCA) conducted for their continued existence, proposed maintenance, or potential removal. While a BCA for dam removal can capture market values like cost of removal it has difficulty reflecting non-market values such as ecosystem services. In accordance with relative price theory, the outcome and input factors to the BCA can change over time. Even without a formal BCA being conducted the inputs to the BCA may change enough to lead to a dam being removed.

One of the most recent and comprehensive benefit-costs analyses completed for dam removal was conducted in 2002 for four dams on the Lower Snake River in Washington operated by the U.S. Army Corps of Engineers. The benefit-cost analysis evaluated the scenarios presented in the Environmental Impact Statement (EIS) for the dams, one of which included dam

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[5] A natural monopoly occurs when a firm has decreasing average costs and leads to underproduction relative to competitive conditions (Nicholson & Snyder 2012).

[6] See Posner (1974) and Becker (1983) for economic theories of how regulations emerge, and Singleton (2000) for a discussion of when natural resource management is most influenced by collaboration versus agency capture.

removal (USACE 2002). Although the analysis considered the effects to the region's energy, loss of barge transportation, and irrigation benefits, it was criticized by economists as excluding important tribal benefits and non-use values (Whitelaw & MacMullan 2002). The U.S. General Accountability Office (GAO) also criticized how transportation costs were calculated and the omission of air quality effects in the EIS (GAO 2000). There is a great deal of uncertainty associated with pre-dam removal projections of future effects. For example, exact geomorphic changes and future fish population numbers are difficult to predict.

In addition to the Lower Snake River dams, there have been several case studies applying benefit-cost analysis to dam removals and evaluating dam removal outcomes. Gowan et al. (2006) performed a retrospective analysis of the influence of ecosystem valuation on the removal of the Elwha River dams. Their research determined that the monetization of ecosystem services played a minimal role in the decision to remove the dams.

As demonstrated by these limited examples of economic studies of dam removal, economic research is often only conducted for large, hydroelectricity dams, which ignores the majority of dam removals. While dam removal has not been systematically researched by economists, many other disciplines have scrutinized the ecological, engineering, and political factors that influence dam removals.

2.2 Institutions

2.2.1 State Policies

Both the physical and political geography of a dam are believed to influence the probability of dam removal. States like California and Wisconsin that have the largest number of dams correspondingly have the largest number of removed dams (Pohl 2002; American Rivers 2018). The number of dams in a state is not correlated with the percent which are removed, likely due to factors such as state economics, history, and dam functions (Foley et al. 2017). Pohl (2002) suggests that the high number of dam removals in the Great Lakes and northeastern states of Wisconsin, Minnesota, Pennsylvania, and Connecticut are partly due to the high number of old mill and water storage dams that once powered the Industrial Revolution but are now often abandoned, hazardous, or of low utility.

State institutional regulations are also believed to explain some differences in removal. Some states, including Wisconsin, Pennsylvania, Ohio, and Connecticut, have implemented processes to expedite dam removal permitting, and some scholars believe that these practices have resulted in a larger number of dam removals in those states (Doyle et al. 2003; Lowry 2005; Ashley 2004). Pohl (2002) similarly posits that programs like California's CalFed Bay Delta Program (CalFed) and Pennsylvania's "Growing Greener" program, both of which provide funding for dam removals, are a primary reason why California and Pennsylvania have some of the highest dam removal rates. Other states have directly financed dam removal by contributing funds or assuming ownership of a dam (Lowry 2005). Bellmore et al. (2017) attribute dam removal rate variations between adjacent states as being due to differences in state histories. For example, in the past New York removed a dam that released water contaminants, and now the state has a lower removal rate. Neighboring Pennsylvania experienced a catastrophic dam failure in the past, which resulted in deaths and monetary damages. Pennsylvania now has one of the highest dam removal rates, presumably to mitigate against future dam failures (Bellmore et al. 2017). Lowry (2005) suggests that dam removal policies may diffuse regionally among nearby state, leading to similar policies within regional pockets.

The variability in adjacent state dam removals supports the theory that removals are determined by politics and local institutions which either increase or decrease benefits of removal. There have been only a few instances of federal involvement in dam removal. The 1992 Elwha River Ecosystem and Fisheries Restoration Act was signed by President George H.W. Bush and provided funds for removal of the Elwha and Glines Canyon dams, although they were privately owned. The fact that the dams were in an area with a declining timber industry, close to Olympic National Park, and had strong tribal and environmental advocates is believed to be why the Elwha River dams not only had the political support for removal, but also obtained the needed congressional intervention (Gowan et al. 2006).

2.2.2 FPA and FERC

Depending on the characteristics of a dam it is subject to different regulatory requirements. Amos (2014) separates dams into three categories that determine the legal structure that applies to the dam: 1) federally owned and operated facilities, 2) federal and/or state licensed privately owned dams, and 3) privately owned unlicensed facilities. The first category, federally owned and operated facilities, are most influenced by the Endangered Species Act (ESA). Federal hydroelectric dams provide approximately half of the hydroelectric power in the United States (FERC 2017). To date, no federally owned and operated dams have been removed, and to take such action would require authorization from congress. The four Lower Snake River dams would be in this category if they are removed. The second category, federal and/or state licensed privately owned dams, are most influenced by the Federal Power Act and required licensing, as well as the ESA. Decommissioning of these dams requires "approval of a host of federal, state, and, potentially, local regulatory agencies before a dam can be removed" (Becker 2006). Dams removals that fall into this category include the Edwards Dam, Elwha and Glines Canyon Dams, Condit Dam, and the planned Klamath River dam removals. The third category, privately owned unlicensed facilities, are subject to the least regulatory requirements, often only impacted by state regulations.

For the second category, federal and/or state licensed privately owned dams, the Federal Energy Regulatory Commission (FERC) is the federal licensor as authorized by the Federal Power Act (FPA). There are approximately 2500 dams that are subject to FERC licensing in the United States. (FERC 2017). With few exceptions, FERC has jurisdiction over all non-federal hydroelectricity permits in the U.S (FERC 2017). These licenses are for 30 to 50-year terms and are required to be renewed once expired, although temporary authorizations are common during the renewal process. It is these FERC authorizations that have led Amos (2014) to suggest that "the Federal Power Act might be one of the keys to restoring western rivers " (p.2).

There are multiple reasons why the FPA and FERC relicensing are such a powerful lever for dam removal. In 1986, amendments to Section 10 the FPA required that "equal consideration be given to power development, energy conservation, fish and wildlife, recreational opportunities, and the preservation of other aspects of environmental quality" (p.12, Amos 2014). Although discretionary and only from other federal entities, these 10(a) recommendations are included in the relicensing process (Amos 2014). If a project is located at least partially on federal land, then federal agencies can submit mandatory permitting requirements in accordance with Section 4(e) of the FPA (Amos 2014). Similarly, Section 18 of the FPA allows for mandatory fishway prescriptions to be imposed on the license renewal by the U.S. Fish and Wildlife Service and/or the national Marine Fisheries Service (Amos 2014). Unlike Section 4(3), Section 18 does not require any federal land to be involved in the project, just an existence of a fishery resource that is managed by one of the agencies. Lastly and described as the most powerful of all is Section 10(j) which allows nonfederal entities (state fish and game agencies, state environmental quality agencies, state parks, etc.) to impose fishway prescriptions (Amos 2014). Although not mandatory, FERC is required to provide agency deference, which results in many of the 10(j) prescriptions being upheld in the final conditions of the relicense (Amos 2014). An ongoing lawsuit over the Hells Canyon Dam Complex between Oregon and Idaho is testing a new construct of Section 10(j), because the Oregon and Idaho laws regarding fish passage requirements for relicensing are in conflict. Thus far, FERC has not decided how the issue will be resolved (Ridler 2018).

In addition to these sections of the FPA, two additional FPA components are important for FERC relicensing. First, a 1994 policy statement by FERC entitled "Project Decommissioning at Relicensing" states that any project that is not relicensed must be decommissioned and that the licensee is responsible for the decommissioning costs (Amos 2014). FERC relicensing can be a very expensive process; if a license is approved the approval requirements can be very costly (such as installing fish passage or mitigation measures), and if approval is not sought or the licensee declines to accept the new license then there are decommissioning costs (Bonham 2008). The suite of options that FERC has for relicensing are: "(a) issue a new license to the existing licensee; (b) accept surrender of the license, (c) issue a non-power license; (d) require decommissioning; or, (e) authorize federal takeover of the project" (p.5, Bonham 2008). As of 2008, FERC had "issued a non-power license once, never ordered federal takeover, and rarely pursued decommissioning" (p.5, Bonham 2008).

The second relevant FPA component emerged from amendments to the FPA included in the Energy Policy Act of 2005. This change put additional burdens on fish management agencies prescribing fish passage as part of FERC licenses and creates a mechanism for additional administrative hearings (Amos 2014; Becker 2006). Some legal scholars believe that these changes have the potential to make it easier for FERC applicants to avoid fishway prescriptions (Becker 2006), although empirical evidence that less fishway prescriptions have occurred since 2005 is limited.

2.2.3 Other Federal Legislation & Agencies

In addition to the FPA, additional legislation affects dams across all ownership categories and dam purposes (i.e. not only hydroelectricity dams like FERC). The Endangered Species Act (ESA) intersects with the FPA due to the ESA Section 7 consultation requirements to avoid jeopardy for listed species (Amos 2014). The Section 7 consultations apply to any actions authorized, funded, or carried out by a federal agency (ESA §7(a)(2)), which includes actions for both federal and non-federal dams. For only federal dams, the National Environmental Policy Act (NEPA) requires that an environmental impact statement (EIS) be issued for "major Federal actions significantly affecting the quality of the human environment" (EPA 2019). Dam safety is administered primarily through the Federal Emergency Management Agency (FEMA), which convenes the Association of State Dam Safety Officials (ASDSO) for monitoring of potentially hazardous dams.

In addition to FEMA and ASDSO, the "U.S. Army Corps of Engineers, Bureau of Reclamation, Tennessee Valley Authority, Bureau of Land Management, Fish and Wildlife Service, National Resource Conservation Service, and Bureau of Indian Affairs all administer dam safety programs at the federal level" (p.64, The Heinz Center 2002). For all types of dams, the Clean Water Act (CWA) may also require permits are obtained for the discharge of sediment, temperature changes, and required dredging and filling operations associated with removal (The Heinz Center 2002). A barrier to dam removal is listing of the dam under the National Register of Historic Places, which does not prohibit removal but does create regulatory hurdles to removal if a structure is listed (The Heinz Center 2002). When a dam is removed, the now free-flowing portion of the river may be eligible for federal and/or state protections through the Wild and Scenic Rivers Act or similar state legislation, which could restrict future building of dams in the same locations (The Heinz Center 2002).

2.3 Non-Economic Studies of Dam Removal

2.3.1 General Overview

Non-economic studies of dam removal have been done that can inform the factors which might be leading to the trend of increased dam removal in the United States. The non-profit American Rivers estimates that over 1,450 dams have been removed since 1912 in the United

States. Of these, the majority of removed dams are small run-of-river dams, although there have been some larger storage dams that have been removed as well (The Heinz Center 2002). Based upon current trends, it is estimated that by 2050 between 4,000 and 36,000 additional dams will be removed (Grabowski et al. 2017). Rationales for dam removal include safety concerns, legal and financial liability, restoration, recreation, water quantity, and water quality (The Heinz Center 2002).

Approximately 214 studies of dam removal have been produced, the majority of which are case studies of specific dam removal instances or comparisons among removals (Duda et al. 2018). There was a sharp increase in scholarly discussion regarding the quality of dam removal information produced in the early 2000s, potentially in response to the EIS process in consideration of removal of the four federal dams on the Lower Snake River in Washington. During this period, there was a consistent call for additional research to be conducted both before dams are removed and monitoring after dam removal (Heinz 2002; Grant 2001; Bellmore et al. 2004). These calls for additional monitoring have persisted since the early 2000s, echoed by O'Conner et al. (2015) and empirically evaluated by Bellmore et al. (2017) who found that only approximately 10 percent of dam removals had any scientific evaluation. Of the 10 percent of dam removals which had some form of scientific evaluation, 35 percent included post-removal monitoring for more than two years and only 5 percent were monitored for more than five years (Bellmore et al. 2017). Past dam removal research has characterized the study of dam removal as focused on environmental aspects, with a lack of consideration of socioeconomic dimensions (Born 1998).

2.3.2 Engineering Aspects of Dam Removals

The majority of dam removals are believed to occur for safety reasons, stemming from aging infrastructure without corresponding maintenance (Pohl 2002; Babbitt 2002; Bellmore et al. 2004; Foley 2017). Catastrophic dam failures have occurred throughout the history of the United States and preventing future accidents is believed to be a motivating factor for dam removal. In 1889, the South Fork Dam in Johnstown, Pennsylvania failed and resulted in the deaths of over 2,200 people (Bellmore et al. 2017). The Saint Francis Dam near Los Angeles failed in 1928, resulting in over 600 casualties (Harrison 2016). As recently as 2017, Oroville Dam in California experienced a spillway failure that threatened the capitol of California. Hazard potential for dams is related to the size of the dam (how much water could be released if spilled), the age of the dam, as well as the durability of the construction material and design (The Heinz Center 2002).

As dams age, they not only become more hazardous, but also accumulate repair costs. An analysis of dams in Wisconsin found that the primary motivator for removal was the large costs of repair, which were often higher than the cost of removal (Born 1998). The cost of overdue dam maintenance in the United States is estimated as $64.9 billion (ASDSO 2016). Part of the reason for this high cost of repair is that many dams built in the 1900s are reaching the end of their functional lifespan, estimated as 60 to 120 years, and have either deteriorated or accumulated large amounts of sediment (Doyle & Harbor 2003; Poff & Hart 2002).

In addition to age and structure of dam, which influence hazard potential and cost of removal, the purpose of a dam is also believed to influence the probability of removal. Some purposes are believed to become obsolete over time, such as some mill and water storage dams (Pohl 2002). Reasons a dam may become obsolete are attributed to "the efficiency of competing regional power grids, changing transportation needs that eliminated water transport on small and medium sized streams, and the economic decline of water-powered industries" (The Heinz Center 2002). This theory is supported by a review by Grabowski et al. (2017), who found that small, privately-owned mill dams were overrepresented in dam removals. Their research also determined that hydroelectric dams and large irrigation dams are disproportionately removed compared with flood control, fishponds, farm and fire ponds, and recreation dams.

American Rivers' Dam Removal Database (DRD) remains the only data source for historic dam removals and much of the literature on dam removals relies on their data. Even the USGS relies on the American River's data for their Dam Removal Information Portal (DRIP).[7] The USGS "Dam Removal Science Database" is another documentation effort that records not only dam removal literature but also the dams that have been studied (Duda et al. 2018). An uncertainty in dam removal research is that the number of standing dams is unknown. The National Inventory of Dams, maintained by USACE, is estimated to be missing approximately 2 million small dams in the United States (NRC 1992).

[7] https://www.sciencebase.gov/drip/

2.3.3 Environmental Aspects of Dam Removals

Ecological restoration is increasing becoming a reason for dam removal in recent years as the ecological costs have become better understood (Pejchar & Warner 2001). However, the literature has been mixed, with other studies suggesting that ecological factors do not have a significant effect on the decision to remove a dam (Born 1998). While there have been numerous studies on the ecological effects of dam removal, there are only a few instances which specifically cite ecological restoration as the primary motivator for removal. A meta-analysis by Foley et al. (2017) found that only 130 out of 1,100 dam removal instances had ecological or geomorphic analysis conducted before or after removal, indicating that it was not considered in the majority of dam removals. Ecological effects which are generally desired for river restoration include increased riverine habitat, sediment exchange, and minimized barriers for fish (Bednarek 2001). Dam removal can also produce unwanted ecological effects; concerns following dam removal include "degree and rate of reservoir sediment erosion, excessive channel incision upstream of reservoirs, downstream sediment aggradation, elevated downstream turbidity, drawdown impacts on local water infrastructure, colonization of reservoir sediments by nonnative plants, and expansion of invasive fish" (Tullos et al. 2016). The increased sedimentation following dam removal is generally viewed as a short-term, although releases of contaminated sediment can be harmful to downstream environments (Bednarek 2001).

Hoenke et al. (2013) used a GIS analysis to prioritize dams for removal based on ecological factors. The criteria used to rank dams as high priority for removal include close proximity to anadromous fish spawning areas, high habitat quality, longer connected river miles, and few downstream dams. The creation of this prioritization tool was done by working with a representative from American Rivers, an organization which has been highly involved in dam removals over the years. Three of the top-twenty dams prioritized for removal were also identified by water resource managers as candidates for removal, indicating that the tool does represent decision making, but that other site-specific factors are relevant as well.

3 Theoretical & Empirical Models of Dam Removal

3.1 Theoretical Model

The hypothesis of this thesis is that economic growth and rising incomes, and the resulting change in relative scarcity of consumer goods versus environmental goods, has contributed to the rise in dam removals in the United States. This section presents a theoretical model to examine the hypothesis. For the model we assume an economy with a fixed number of n identical individuals whose preferences over the consumption of consumer goods (C) and environmental public goods and services (E) are described by a strictly concave utility function (U). The utility function represents the ordering of a choice set of an individual, where desirable situations yield higher utility than undesirable ones. The level of consumption is determined by income, which is constrained to be less than or equal to the average wage (w) multiplied by the individual's labor hours (l). Wages are determined by the production function equal to the per capita level of capital (k), inputs which are created by a dam (X_1) (e.g. stored water or electricity supplied by a dam), and inputs which are available without a dam (X_2) (e.g. river recreation or salmon habitat). For modeling purposes, the prices of k, X_1, and X_2 are assumed to equal one.

$$U = U(C, E) \tag{1}$$

$$C \ \leq wl \ \equiv Y \tag{2}$$

$$w = F(k, X_1, X_2) \tag{3}$$

The second derivatives of U and F with respect to all arguments are negative, indicating that there are diminishing returns to capital and inputs in production, and diminishing marginal utility of C, and E.

Environmental goods and services (E), are a function of riverine habitat (R), as well as other environmental amenities (S), such as clean air, forest stocks, etc. Riverine habitat is the difference between the historical amount or length of pristine, free-flowing rivers (R_o), minus the number of dams that are built, which is a function of X_1. The variables E, R, and S should be considered per capita levels for comparison.

$$E = E(R, S) \tag{4}$$

$$R = R_o - g(X_1) \tag{5}$$

Environmental goods and services are therefore a function of riverine habitat, the level of inputs available with a dam, and other environmental amenities, represented as follows:

$$E = E(R_o - g(X_1), S) \tag{6}$$

Additionally, X_2, inputs available without a dam, is itself a function of per capita riverine habitat (R). This relationship reflects the fact that consumption of X_1 results in a lower quantity available of X_2.

$$X_2 = f(R_o - h(X_1)) \tag{7}$$

Aggregating the individual utility functions (Equation 1) by the number of individuals in society (n) we can calculate the social welfare function equal to:

$$W = nU \tag{8}$$

Society's maximization problem for social welfare, subject to constraints on consumption, environmental quality and dams, is therefore:

$$\begin{aligned} \text{max:} \quad & W = n\,U(C, E) \\ \text{subject to:} \quad & C \leq f(k, X_1, X_2) * l \\ & E = E(R_0 - g(X_1), S) \\ & X_2 = R_0 - h(X_1) \end{aligned} \tag{9}$$

Substituting the constraints into the social welfare function allows the societal demand for dams, represented by X_1, to be represented within the utility function as:

$$W = n * U(f\big(k, X_1, R_0 - h(X_1)\big) * l,\ E(R_0 - g(X_1), S)) \tag{10}$$

By deriving an expression for the welfare change from adding a dam (X_1), we can take the total derivative of W with respect to X_1 to represent the marginal change in net social welfare. Denoting the marginal utilities as U_C and U_E and the partial derivatives for the first argument of the function as f_1, the total derivative of W with respect to X_1 would be:

$$\frac{dW}{dX_1} = nU_C \frac{dC}{dX_1} + nU_E \frac{dE}{dX_1} \tag{11}$$

$$= nU_C[lf_2 - lf_3 h'(X_1)] + nU_E E_1(-g'(X_1)) \tag{12}$$

$$= nU_C lf_2 - nU_C lf_3 h'(X_1) + nU_E E_1(-g'(X_1)) \tag{13}$$

If $\frac{dW}{dX_1}$ is positive it indicates that an additional dam is increasing social welfare, if it is negative it is decreasing social welfare. If dams are leading to losses in social welfare, that would indicate that there is an increased probability that a dam will not be built or would be removed. We can model changes in the inputs to the function to determine which changes would result in marginal social welfare becoming negative.

By inspection we can determine that the first term in (13) is positive and the second and third terms are negative. The first two terms represent the marginal utility of consumption. Term one is positive, representing the increase in marginal utility associated with higher levels of consumption. Term two is negative, represent the loss in marginal utility due to the lost consumption of X_2at higher levels of X_1. The third term is negative, representing the change in utility from a loss of environmental goods and services due to an increase in the number of dams.

The marginal rate of substitution (MRS) can be represented by the negative of the ratio of the marginal utility from consumption and marginal utility from environmental goods and services. The MRS is also equivalent to the slope of the indifference curves in Figure 3.

$$\text{MRS} = -\frac{U_C}{U_E} \tag{14}$$

The second derivates of $U_C$and $U_E$are negative, (U_{C2}<0 and U_{E2}<0), indicating that marginal utility is decreasing. For example, when consumption is high, the marginal utility of consumption is low because an additional unit of consumption does not add to utility as much as it would if consumption was low. That is, additional consumption at already high levels of consumption is valued less. When $U_C$is higher than $U_E$it indicates that additional consumption yields more utility than additional environmental goods and services.

Levels of capital (k) raise income and thus influence the marginal social welfare through term one of Equation 13. This additional capital allows for increased levels of consumption, which decreases the marginal utility of consumption (U_C). As more dams were built environmental goods and services were diminished,[8] reducing the level of E and increasing the marginal utility (U_E). Taken together, these changes are reflected in Equation 13 by declines in term one (which is positive) due to a reduction in U_C, and increases in terms two and three

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[8] In the historical example of the U.S. environmental goods and services also declined due to resource extraction and pollution, separately from dams, which would also decrease the level of E.

(which are negative) due to increases in X_1 and increases in U_E. This change can result in the marginal social welfare of a dam ($\frac{dW}{dX_1}$) being negative, which could increase the probability that a dam might be removed. As demonstrated by the historical example, the increase in dam removals in U.S. in the last few decades have followed a period of economic growth, suggesting that the marginal social welfare is negative for some dams.

This theoretical framework can also inform how other societal changes might influence the marginal social welfare from dams. Some dams have become obsolete over time because the purpose they were built for is no longer needed. The production function in Equation 13 can be considered a composite of all production functions in a society, including manufacturing, agriculture, recreation, etc. If we consider a flour milling dam that was used for manufacturing becoming obsolete, that individual production function would effectively go to zero. The dam may also become a liability and incur costs for the owner. Although separate from our model of social welfare, those increased costs and loss of benefits from the dam would lead to dam removal. Dams that have become hazardous and incurred maintenance costs would also experience these individual increases in costs, which could also lead to dam removal.

The production function for agricultural water users can also be considered within the aggregate production function F. In regions where agricultural water users represent a high portion of that region's production function the reduction in marginal utility of consumption caused by additional capital and dams might decrease less quickly than in regions without this use of storage water. This regional difference would be due to the differences in regional production functions (F). Similarly, regions with high hydroelectricity production might also experience less of a reduction of U_C compared with regions that produce electricity from other sources. Lower cost electricity would support more intensive use of electricity, which would then increase the marginal product of capital and labor, resulting in higher levels of consumption. Although there would be increased consumption, the marginal utility of consumption may remain relatively high because more intensive use of electricity is occurring at lower prices. We would expect dam removals to then be less common in regions obtaining high value from dams from irrigation water, hydroelectricity, or barge transportation.

We consider X_2, non-dam inputs (e.g. free flowing rivers and riparian habitat) as a public good. As a public good it is non-rival and non-excludable, meaning that the consumption by one person does not decrease the potential for consumption by another person. For this reason, at higher population levels or population densities, total consumption of X_2 would increases by the number of people and the social value of E goes up proportionally with population. Dams also provide benefits such as reduced flood risk and reservoir recreation that could be considered public goods, reflected in X_1. To the extent that X_1represents public goods, the increase in population would increase the social value of consumption of those inputs. However, $X_1$is also comprised of many private goods which likely experience an increase in total consumption at higher population levels, but a decrease in per capital consumption given scarce resources. More total consumption of X_1 would decrease the levels of X_2 and E available, increasing U_E in addition to the loss of per capita E caused by the population increase. Depending on how U_C changes, the marginal social welfare could become negative due to a potential reduction in term one and increases in terms two and three of Equation 13.

Increases in other environmental amenities (S) could increase the total amount of E available (depending on how much R is substituted for S), which could decrease U_E, reducing the probability of dam removal. Additionally, dam operations could change to allow for more riverine functionality up to a limit, which would lead to increases in E. In Equation 13 this change would be represented by a change in function g of term three that results in less loss of E with increases in X_1. At higher levels of E, the marginal utility (U_E) would be lower, reducing the probability that a dam would be removed. However, if S is decreasing, perhaps from overfishing, degraded water quality, or deforestation, then the level of E decreases through S, independent of changes in the number of dams, which increases U_E. With increases in U_E term 3 might become negative enough to cause the marginal social welfare from additional dams to become negative, suggesting that dams would be removed.

Regulations and social institutions are not represented as independent parts of this theoretical analysis, rather they are considered the mechanisms through which society allocates resources where there are spillovers across individuals (due to externalities or public goods). In these instances of market failure there is a need for collective action – because the market economy cannot be expected to achieve efficiency. To maximize social welfare, public action including regulations and public expenditures are necessary (see Samuelson 1954 for a discussion of why public goods are underproduced in the absence of government involvement). While not explicit in the theoretical model presented here, the impact of regulations and social institutions are recognized as either directly or indirectly impacting the decision to build or remove dams.

3.2 Empirical Model

Based upon the theoretical model for demand for an environmental good, specifically a free-flowing river, an empirical model can be developed to reveal how the theoretical demand is expressed via measurable outcomes. The goal of this research is to identify which factors influence dam removal decisions, in which direction, and to what magnitude. Given the goals of the study, the dependent variable of interest is defined as a removed dam.

Historical dam removal can be evaluated through as a discrete time duration model, since not all dams receive the treatment effect (removal) and dams that are removed vary in the number of years between construction and removal. The distribution of the duration of time before treatment can be modeled as the probability that removal will occur for each time period of analysis (Jenkins 1995). Given that the dependent variable of interest in this analysis (dam removal) is binary, it has been demonstrated that standard binary choice models, such as logit and probit, can be used to estimate discrete time duration models (Jenkins 1995; Beaudin & Huang 2014). Beaudin & Huang (2014) use a logit method in their estimation of the probability of closure for ski resorts in New England. Their research estimated the probably that an individual ski resort would close in each year from 1970 to 1996, and the independent variables included both fixed effects (e.g. location, height of mountain, number of lifts) as well as variable effects (e.g. amount of snowfall in that year, annual GDP growth), similar to the dam removal analysis proposed in this paper.

To describe the status of a dam over time, during the studied period, the following construction of the binary dependent variable Y_{it} is applied.

$$Y_{it} \quad = 1 \text{ if the dam is removed in year t} \qquad (15)$$

$$= 0 \text{ if the dam is not removed in year t}$$

To describe the probability of removal of a dam, let P_i be the probability that a dam *i* is removed as a (nonlinear) function of a set of explanatory variables X.

$$P_i(Y = 1 \mid X) = G(\beta_0 + \beta_1 x_{1i} + \ldots + \beta_k x_{ki}) \qquad (16)$$

where $G(.) \geq 0$, is a function taking on either the value zero or one, and β is a set of parameters. The structure of G(.) is consistent with the logistic function, where for all real numbers *z*:

$$G(z) = \exp(z)/(1 + \exp1(z)) = \Lambda(z) \qquad (17)$$

Maximum likelihood estimation is then used to estimate the logit model. The density of Y_i, given xi is further defined, absorbing the intercept into the variable X, as:

$$f(y \mid x_i; \beta) = G(\beta_0 + \beta_1 x_{1i} + \ldots + \beta_k x_{ki})^y + (1 - G(\beta_0 + \beta_1 x_{1i} + \ldots + \beta_k x_{ki}))^{1-y},\ \ y = 0,1 \qquad (18)$$

When y=1, equation 16 is equal to $G(\beta_0 + \beta_1 x_{1i} + \ldots + \beta_k x_{ki})$. When y=0, equation 16 is equal to $1- G(\beta_0 + \beta_1 x_{1i} + \ldots + \beta_k x_{ki})$. The log-likelihood for a sample size of *n* is obtained by taking the log of equation 16 and summing it across all observations.

Because G(.) is defined as the standard logit cumulative density function, the corresponding logit estimator is therefore $\hat{\beta}$.

$$l_i(\beta) = y_i \log[G(\beta_0 + \beta_1 x_{1i} + \ldots + \beta_k x_{ki})] + (1-y_i)\log[(1 - G(\beta_0 + \beta_1 x_{1i} + \ldots + \beta_k x_{ki}))] \qquad (19)$$

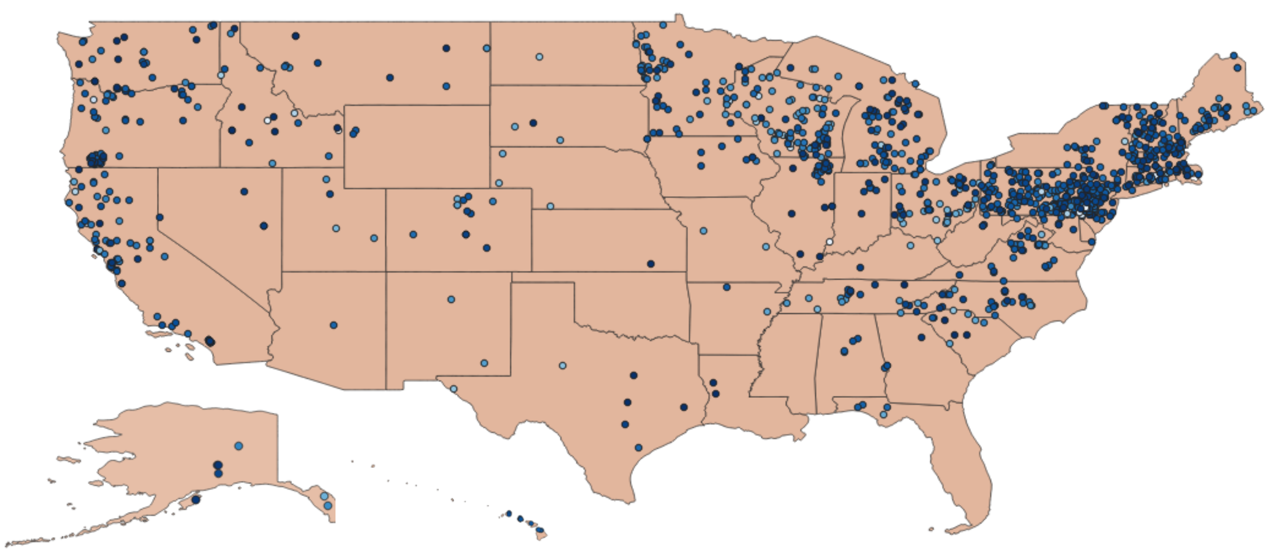
4 Data

4.1 Dependent Variables

4.1.1 American Rivers Dam Removal Database

The non-profit American Rivers has collected information on dams that have been removed in the United States and complied the data in their Dam Removal Database (DRD). This data source represents the most comprehensive documentation of historic dam removals.[9] The DRD documents 1,478 dam removals from 1912 to 2017 as of January 2018. Although the dates of dam removals extend as far back as the year 1916, the database itself was begun in the 1990s (Grabowski et al. 2018; Bellmore et al. 2017). Data on removed dams is collected annually for each state by contacting state offices, non-profits, or other stakeholders (J. Thomas-Blate of American Rivers, personal communication, October 8, 2018). In order to be added to the DRD as a removed dam, the full height of the dam must be removed such that ecological function, natural river flow, and fish passage can be restored at the site. Figure 5 provides a spatial reference for where the American Rivers database shows dam removals have occurred in the United States.

Figure 4: Dams Removed in the United States (1916 – 2016)



Source: Created with data from American Rivers Dam Removal Database

[9] The data source and metadata can be viewed and downloaded at www.americanrivers.org/DamRemovalDatabase.

Note: Each point represents a dam, with lighter points dams that were removed longer ago and darker points removed more recently.

It was noted by J. Thomas-Blate of American Rivers that some states have more comprehensive tracking and/or responsiveness than others, so there may be systematic bias for some states missing entries or missing data fields (personal communication, October 8, 2018). Variance in state data collection and dam removal policies has been documented by other research as well (Lowry 2005; Fox et a. 2016). Table 1 provides the fields in the American Rivers dam removal database and the percent of entries that have complete information. Note that although all entries have corresponding information about which state the removal occurred in, not all states are represented, with no dam removals being recorded in Oklahoma or Mississippi. The variables to note with high levels of missing data in the Dam Removal Database include NID_ID (due to all removed dams not being in the NID), *Dam_Height_ft*, *Dam_Length_ft*, *Year_Built*, *Owner*, *Original Use*, *Type_Material*, *River_Miles_Reported*. Of these, *Year_Built* and *Dam_Height_ft* are the variable of most concern due to missing data, since they will be used for the analysis to represent the age and size of removed dams.

Table 1: Data Summary American Rivers Dam Removal Database (2018)

Field	Description	Number of Blank Entries	Percent with Complete Data
AR_ID	Dam identifier for American Rivers	1477	99.9%
NID_ID	Dam identifier from the National Inventory of Dams	267	18.1%
Dam_Name	Name of Dam	1478	100.0%
Description	Qualitative information about removal	496	33.6%
Year_Removed	Year dam was removed, as provided by stakeholder	1372	92.8%
Latitude	Decimal degrees of dam location prior to removal	1292	87.4%
Longitude	Decimal degrees of dam location prior to removal	1292	87.4%
City_County	Closest city or county to the dam removal site	1321	89.4%
River	River in which removed dam was located	1404	95.0%

Field	Description	Number of Blank Entries	Percent with Complete Data
HUC8	Hydrologic unit (8 digit) from the USGS Watershed Boundary Dataset.	1310	88.6%
State	State abbreviation as defined by USPS	1478	100.0%
Dam_Height_ft	Dam height, prior to removal, as provided by stakeholder	1087	73.5%
Dam_Length_ft	Dam length, prior to removal, as provided by stakeholder	730	49.4%
Year_Built	Year removed dam was built, as provided by stakeholder	554	37.5%
Owner	Designated owner of dam prior to removal, as provided by stakeholder	532	36.0%
Original Use	Designated use of dam prior to removal, as provided by stakeholder	586	39.6%
Type_Material	Type of dam and/or material that comprised the removed dam	640	43.3%
River_Miles_Reported	River miles opened for fish passage as reported by stakeholder	493	33.4%

4.1.2 National Inventory of Dams

Data on dams that have not been removed was obtained from the National Inventory of Dams (NID) Database maintained by the U.S. Army Corps of Engineers (USACE). The version of the dataset being used for this analysis was updated as of 2010 and includes approximately 84,000 dams. Relevant fields from the NID database include the following: NID identification number, longitude, latitude, county, river, city, owner type, dam type, purposes, year completed, dam length, dam height, maximum discharge, maximum storage, downstream hazard potential, congressional district. The goal of the NID is not to collect data on all dams in the United States. Dams are included in the NID if they meet at least one of the following criteria:[10]

1) High hazard potential classification - loss of human life is likely if the dam fails,

[10] See U.S. Army Corps website for the National Inventory of Dams for more information: http://nid.usace.army.mil/cm_apex/f?p=838:12

2) Significant hazard potential classification - no probable loss of human life but can cause economic loss, environmental damage, disruption of lifeline facilities, or impact other concerns,
3) Equal or exceed 25 feet in height and exceed 15 acre-feet in storage,
4) Equal or exceed 50 acre-feet storage and exceed 6 feet in height.

4.1.3 Aggregation of Removed and Not-Removed Dams

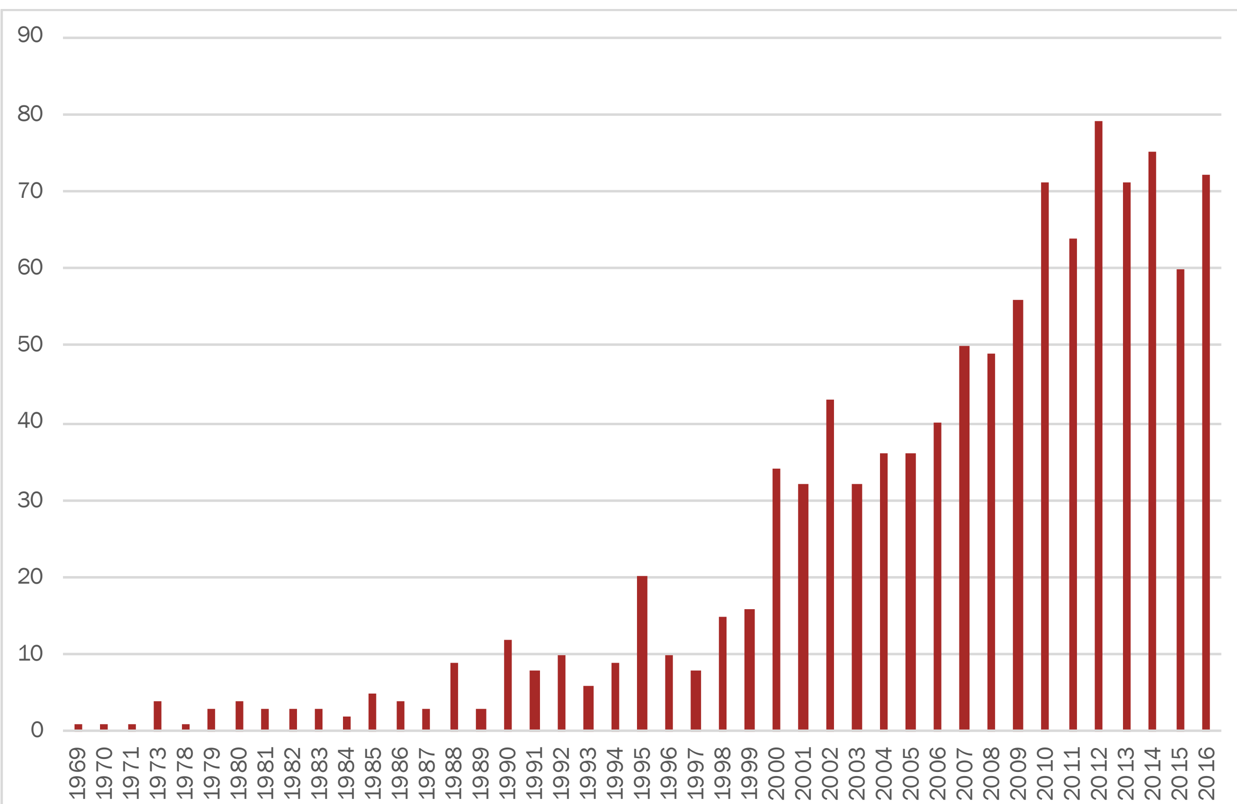
The first step in the analysis was to create a database of both removed and not-removed dams. This aggregation was done by combining the American Rivers DRD and the NID data. When dams are removed their entries are not always removed from the NID; as a result, 164 duplicate data points were identified between the DRD and NID datasets and marked as removed. Additionally, due to the differences in database purposes, the sizes of dams in the American Rivers DRD is significantly smaller than the dams in the NID (median height of 7.5 feet in DRD and 25 in NID). To correct for this discrepancy, 362 dams were removed from the analysis from the American Rivers DRD dataset that met one of the following criteria: were not in the NID database, were less than 10 feet in height, or were less than 40 feet in length. The 10-foot height and 40-foot length thresholds were chosen after an analysis of the NID data, which contained 15 dams which were either lower in height or length and therefore appeared to represent the minimum size of dams in the NID. Another significant difference is the year built between the dams in the DRD and NID, with the DRD having significantly earlier years of construction. To correct for this difference dam removals prior to 1969 were excluded from the analysis. In addition, the following actions were taken on the dataset to remove unusable data entries, correct possible data collection errors, and make decisions in cases of multiple or conflicting data:

1) Removed all entries missing either latitude or longitude;
2) If year built or year removed was represented by range of years, the median was selected;
3) If dam was rebuilt or modified the original construction date was used;
4) Removed DRD data where missing the year the dam was removed;

5) Removed entries where latitude or longitude was obviously wrong (i.e. latitude exceed 90 degrees or longitude exceeded 180 degrees);
6) Removed Guam entries in NID because no corresponding removals in DRD;
7) If DRD and NID height conflicted, the maximum value was used.
8) The NID dataset had multiple purposes ("Original Use" in DRD) and owner-types listed. The DRD data only had one entry to reflect the primary purpose and primary ownership. In order to make the data comparable only the primary purpose and primary owner was used from the NID.

After the data cleaning was completed, there were 1,037 removed dams from the NRD and 81,337 not removed dams from the NID that made up the individual dam observations for each year between 1969 and 2016. Figure 5 shows the distribution by year of removal for the removed dams being considered in this analysis.

Figure 5: Number of Dams Removed (1969 - 2016)



Source: American Rivers Dam Removal Database

4.1.4 Data Discrepancies

Research comparing the DRD and NID, as well as other dam removal data sources, has been conducted by Grabowski et al. (2018), who found similar discrepancies in the age and heights of dams between the two datasets. This discrepancy is believed to be due to the fact that the NID is specifically not set up to collect data on all dams, while the DRD is designed to report all types of dam removals. To illustrate how the NID is structured, Poff & Hart (2002) compared the NID to state databases of dams in Utah and Wisconsin; the authors found that the NID is missing many dams that are in the state record, small dams are overrepresented, and that purposes of fire protection, stock, and small farm ponds are underrepresented.

Improved data collection on dam characteristics and better tracking of dam removals have been consistently called for in the literature. In 2002 The Heinz Center made several recommendations to improve data on dam removal, including creating a geospatial database, ensuring entries in National Inventory of Dams reflect dam statuses if removed, and conducting monitoring and evaluation protocols following dam removal (The Heinz Center 2002). Since 2002, the only recommendation which clearly has been fulfilled is the creation of the geospatial database since both the NID and DRD contain latitude and longitude information.

4.2 Independent Variables

4.2.1 Description of Variables

Table 2 provides the names and descriptions of the independent variables used for the analysis. The DRD and NID provide eight of the variables of interest that were used in the regression modeling: *removed*, *age*, *height*, *max_discha*, *max_storag*, *owner*, *purpose*, and *hazard*. An additional two variables were constructed using ArcGIS based upon the latitude and longitude provided by the DRD and NID: *near_dist* which measures the distance to the nearest other dam and *dam_count* which is a count of the number of dams in the county.

The dataset used for the analysis was constructed for the years 1969 to 2016, with each dam having corresponding independent variables for each of the years after 1969 (or after construction if built after 1969) and prior to removal (or all years if not removed). For example, if a dam was removed in 1973, it would have data for periods 1969 to 1973 and the variable *removed* would be zero in all years except 1973. If a dam was not removed, then the variable *removed* would be zero for all periods and the dam would have time-series data for all periods from 1969 to 2016. Of the 34 total variables, 22 are fixed variables which are constant for each individual dam, *i*, for each year, *t*. The other 12 variables vary by time period, either annually, biannually (party due to the congressional elections every two years), or every 5 years (variables whose source is the USDA agricultural census). Variables denominated in dollars were adjusted to real 2016 dollars using the Bureau of Labor Statistics CPI Inflation Calculator.[11]

Table 2: Independent Variables Used and Source of Data

Variable	Description	Frequency of Variation (Years)	Geography	Source
removed	Indicator if dam was removed in that period or not (1 if removed, 0 if not removed)	Varies (1)	N/A	American Rivers
age	Year built subtracted from reference year (if built after 1969 then observations prior to year completed are dropped)	Varies (1)	N/A	USACE NID & American Rivers
height	Dam height (feet)	Fixed	N/A	USACE NID & American Rivers
state	State where dam is located	Fixed	N/A	USACE NID & American Rivers
neardist	Distance to nearest other dam (meters)	Fixed	N/A	Created with ArcGIS
damcount	Number of other dams within the county	Fixed	County	Created with ArcGIS
party	Political representation for congressional district (1 if republican, 0 if democrat)	Varies (2)	Congressional District	US House of Representatives
population	Number of residents of the county per year	Varies (1)	County	BEA
real_income	Nominal per capita personal income for county converted to 2016 dollars ($)	Varies (1)	County	BEA
pop_density	Population divided by land area at the county level generated as population/area_land	Varies (1)	County	BEA
area_land	Land area of county (sq. miles)	Fixed	County	US Census
area_water	Area of water in county (sq. miles)	Fixed	County	US Census
hydrogen	Total hydroelectricity generation in state (kWh)	Varies (1)	State	EIA

[11] The BLS CPI Inflation Calculation is available at: https://www.bls.gov/data/inflation_calculator.htm

Variable	Description	Frequency of Variation (Years)	Geography	Source
real_elect	Electricity average price in the state, all sectors, in 2016 dollars (cents per kWh)	Varies (1)	State	EIA
hydro_prices	Interaction of real_elect*purposes5 to represent price effect for hydroelectricity dams	Varies (1)	State	N/A
realfmlandval	Per acre value of agricultural land and buildings in 2016 dollars ($)	Varies (5)	County	USDA - Agricultural Census
realcropval	County total market value of agricultural products sold in 2016 dollars ($)	Varies (5)	County	USDA - Agricultural Census
cropval_pctinc	County agricultural sales as a percent of total county income generated as realcropval/(real_income*population)	Varies (5)	County	See realcropval, real_income, and population
esa_amphib	Distance to critical habitat for listed amphibians (meters)	Fixed	N/A	US Fish & Wildlife
esa_birds	Distance to critical habitat for listed birds (meters)	Fixed	N/A	US Fish & Wildlife
esa_clams	Distance to critical habitat for listed clams (meters)	Fixed	N/A	US Fish & Wildlife
esa_fish	Distance to critical habitat for listed fish (meters)	Fixed	N/A	US Fish & Wildlife
esa_mammal	Distance to critical habitat for listed mammals (meters)	Fixed	N/A	US Fish & Wildlife
esa_reptiles	Distance to critical habitat for listed reptiles (meters)	Fixed	N/A	US Fish & Wildlife
esa_snails	Distance to critical habitat for listed snails (meters)	Fixed	N/A	US Fish & Wildlife
owner (categorical)	Type of Owner (F=Federal, S=State, L=Local, U=Public Utility, P=Private). Note that some dams reflected multiple owners, but only the primary owner is included.	Fixed	N/A	USACE NID & American Rivers
purpose (categorical)	Primary purpose of dam (I=Irrigation, H=Hydroelectric, C=Flood Control, N=Navigation, S=Water Supply, R=Recreation, P=Fire Protection or Stock, F=Fish & Wildlife, D=Debris Control, T=Tailings, G=Grade Stabilization, O=Other). Note that many dams are multipurpose, but only primary purpose was included.	Fixed	N/A	USACE NID & American Rivers
hazard (categorical)	Potential hazard to the downstream area resulting from failure or mis-operation of the dam (L=Low, S=Significant, H=High, U=Undetermined)	Fixed	N/A	USACE NID & American Rivers

Variable	Description	Frequency of Variation (Years)	Geography	Source
dam_type (dummy variables)	Material the dam is constructed from (RE=Earth, ER=Rockfill, PG=Gravity, CB=Buttress, VA=Arch, MV=Multi-Arch, RC=Roller-Compacted Concrete, CN=Concrete, MS=Masonry, ST=Stone, TC=Timber Crib, OT=Other)	Fixed	N/A	USACE NID & American Rivers

4.2.2 Rationale for Variables

The variables included in this analysis can be grouped into four categories representing various hypotheses surrounding contributing factors for why dams are removed. The first category is related to general economic indicators for the county. The second category includes variables which might increase the costs of existing dams, which would lead to a change in the benefit-cost analysis to keep a dam and may lead to removal. The third category represents benefits from dams, which may decrease the probability of removal. The fourth category represents dam specific characteristics that are not representative of larger macroeconomic forces, such as the height and age of the dam.

Economic & Demographic Variables

As presented in the theoretical model and the literature review on the Environmental Kuznets Curve and relative price effects, economic growth in the United States is believed to have resulted in increased consumption of consumer goods and decreased quantity of environmental goods and services. To test if the relative scarcity of environmental goods has contributed to dam removal, the effect of real per capita incomes on willingness to pay has changed over time and if this effect has contributed to dam removals. To capture these effects, the average annual per capita income in the county is included (*real_income*), converted to 2016 dollars. Population may also affect environmental quality; higher populations levels may be associated with marginal improvements in environmental quality at high income levels (Jaeger & Kolpin 2001). Because counties are of varying sizes, population density (*pop_density*) is the variable that is used for the analysis.

Institutional & Environmental Variables Related to Costs of Keeping Dam

Regulations can increase the cost of maintaining an existing dam. As discussed in the literature review section on the FPA and FERC, ownership of the dam, as well as size, purpose, and hazard level, determine which regulations the dam is subject to and if FERC licensing is needed. Because hydroelectricity dams specifically are subject to FERC regulation, that purpose is included as the reference purpose as a dummy variable. Only non-federal dams are subject to FERC, so the *owner* category of federal is used as the reference variable.

The variables reflecting the Endangered Species Act (ESA) critical habitat are included to capture any effects from ESA regulations on dam removal. Distance from a dam to critical habitat was performed for the following species types: amphibians, birds, clams, fish, reptiles, snails, and mammals. An additional variable *esa_min* reflects the minimum distance to critical for all of the aforementioned species types. Note that the species type crustaceans and corals were not included, although they have water-based habitats, due to the small amount of critical habitat that has been designated. Additionally, insects and plant species were not included because they do not have water-based habitats.

Direct political status is reflected by the variable *party,* which indicates the political representation of the congressional district the dam is located in. This variable captures any political effects present due to the two-party political system in the U.S. Generally during the period of study of 1969 to 2016 used for this analysis, both republicans and democrats supported environmental policies in the early years of the study period (1969 – 2016) and large dam removals have been approved by both administrations. Dummy variables for states are also utilized to capture state-specific variation.

Economic Variables Related to Benefits from Dams

Dams provide goods and services used as inputs for other industries. This added value from dams will reduce the probability of removal if they provide significant benefits. There may be political opposition to removing dams in areas with high portions of the population who derive income from dams. Examples of industries which are likely to support keeping dams due to the benefits they receive from them include agricultural irrigators, hydroelectricity producers, and barge transporters. The value of local agriculture is measured both in terms of the dollar value of the industry from real farmland value and real crop sales as a portion of total county income. The category of irrigation as one of the selections for the *purposes* variable also incorporates the agricultural interests for a particular dam. For hydroelectricity, the variable *hydrogen* reflects the annual amount of hydroelectricity generated in the state. Additionally, the variable *real_elect* accounts for the cost of electricity in the state, to capture any price effects that may be influencing the probability that a dam is removed. For example, if electricity is relatively expensive it may decrease the probability that a hydroelectric dam is removed because that electricity is providing significant value to the county. The real electricity price is interacted with dam purpose of hydroelectricity since only hydroelectric dams are believed to be influenced by electricity prices. For barge transportation, the variable *purpose* includes navigation, which can measure if that purpose specifically influences probability of removal.

Dam Characteristics

The majority of the variables reflect characteristics about the dam. These include the dam age (*age*), height (*height*), state dam is located in (*state*), number of other dams in the county (*damcount*), distance to nearest other dam (*near_dist*), amount of land and water in county dam is located in (*area_land* and *area_water*), owner of dam, (*owner*) primary purpose of dam (*purpose*), dam hazard level (*hazard*), and dam construction material (*dam_type*). These variables were included to account for the structural and environmental effects of the dam on the probability of removal.

4.2.3 Variables Not Included

Although efforts were made to include all potentially relevant variables in this analysis, it is acknowledged that some variables of significant interest were not included. Probably the most important omitted variable is transportation services provided by a dam, which could be represented by the number of locks present in the dam. The *purpose* variable does include a category for navigation, but since only the primary purpose was considered it is possible that some dams used for navigation would not reflect that fact if their primary purpose is something else. The number of locks would be a more precise measure of the value of river transportation for a particular dam. While the NID does include field for number of locks, the American Rivers DRD does not. Other variables of interest which were not included in this analysis include a measure of stored water use in industries other than agriculture, such as manufacturing. Again, the *purposes* variable does include water supply, but it is unclear if this represents only municipal water supply or water supplied for other purposes (non-municipal, industrial, primary municipal, secondary municipal, etc.). To understand the potential for productive agriculture in the area near the dam, variables such as aridity of the climate, vegetation coverage, and agro-climatic zone characteristics (soil type, average annual rainfall, and temperature) could also be used. These variables were deemed beyond the scope of this analysis and reflected in the economic decision making by the other agricultural indicators, primarily the variable for real farmland value .

Although the amount of hydroelectricity generation was included as a variable, another valuable information point would be the amount of hydroelectricity generation relative to hydroelectricity demand for a county, essentially the excess hydroelectricity production, which is presumable exported outside the county or state. To understand the relative importance of hydroelectricity as an electricity source the portion of hydroelectricity relative to all other electricity sources would have also been a useful variable, but data was not available.

Direct engineering costs of dam removals is also a variable of interest that was not available in the DRD. Cost obviously influences probability of removal because it factors in to the benefit-cost decision of whether to remove a dam or not (USACE 2002; Babbitt 2002). Cost is partially a function of the size of a dam, with larger dams having higher costs of removal, so it is partially accounted for by that variable. In addition to cost of removal, the maintenance and repair costs avoided by removing the dam are also unknown but would have been useful for this analysis. Graber et al. (2010) found regional differences in costs of dam removal based on a comparison of Pennsylvania and mid-west removals, with Pennsylvania having lower costs.

Other variables of interest that were not included in this analysis is the strength of local dam removal activists and quality of state dam removal institutions. As discussed by Ashley (2004), states with regulations that support dam removal experience more instances of it. Additionally, the presence of tribal, non-profit, and environmental stakeholders is believed to increase probability of removal (Chaffin & Gosnell 2017), while political polarization is believed decrease probability of removal (Dorning 2018). A measure of political polarization, number of river-restoration focused environmental advocacy and/or non-profit groups, and strength of local tribal institutions would be potential measures for these effects – but were not used in this analysis due to lack of data availability for the timeframe of interest.

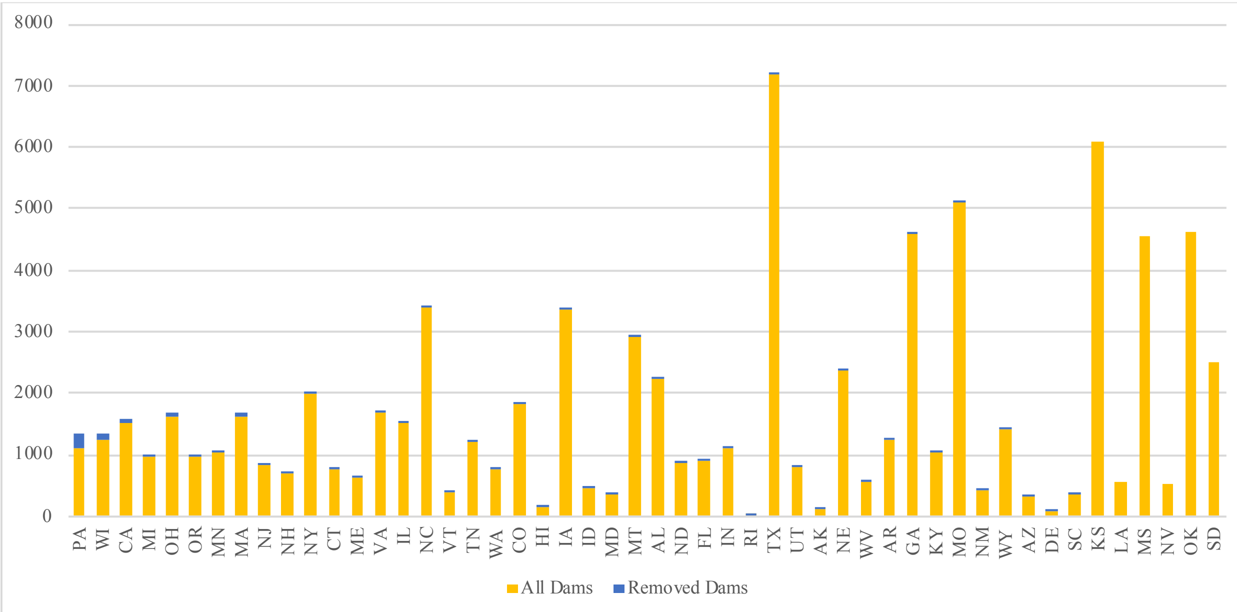
4.3 Summary Statistics

This section describes the characteristics of the data used for the regression analysis. As a reminder, because only dams in the DRD and NID databases were included in this analysis, when the phrase "total dams" is used it represents only those dams which were used for the regression analysis from these datasets (see Section 4.1.3. for a description of what data points were excluded from the analysis from these original datasets).

State institutions, in the form of regulations and reporting of dam removal, are believed to influence dam removal probabilities. There are significant differences in removal rates for states. Figure 6 provides a summary of the magnitude of dams removed compared with the total number of dams in a state. The states are organized by highest number of dams removed. Pennsylvania has the highest total number of removals with 264 dams removed, approximately 24.5 percent of total dams in the state. Texas stands out as having the highest number of total dams, but a relatively small portion of dams removed with only 4 documented removals. The states of Kansas, Louisiana, Mississippi, Nevada, and Oklahoma did not have any dams removed in this dataset. An additional point of interest is Rhode Island, which had four dams removed, representing all total dams for the state (indicating a 100 percent removal rate for dams in Rhode Island).[12] Figure 7 displays the total number of dam removals in each state.

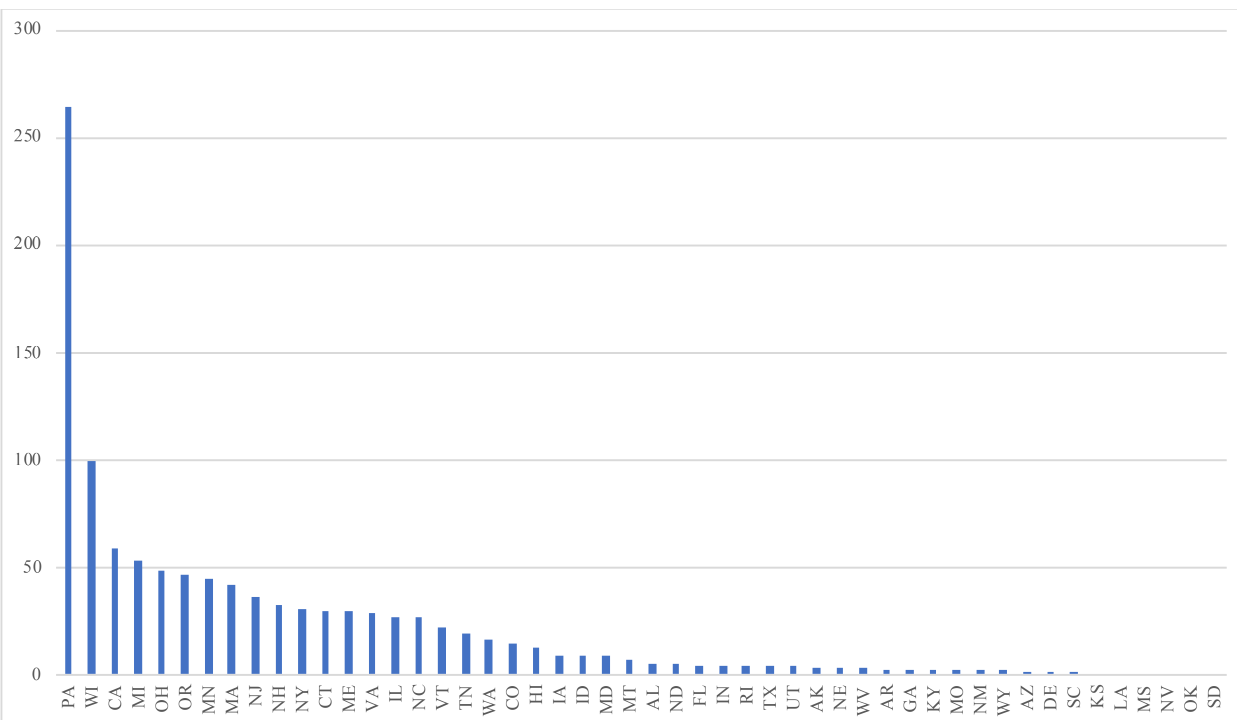
[12] Please note that the author is not indicating that there are no dams in Rhode Island, but simply that based on the adjusted DRD and NID data there are not dams that have not been removed in Rhode Island used for this analysis.

Figure 6: Number of Dams Removed and Not Removed by State



Source: DRD and NID

Figure 7: Number of Dams Removed by State



Source: DRD and NID

Table **3** displays the summary statistics for all numerical variables used in any of the regression iterations. Since each dam had an entry from 1969 to either 2016 or the year it was removed, the total number of observations used for the preferred regression specification is 1,887,601, which includes 2,844 observations for 114 removed dams and 1,884,757 observations for 65,843 not removed dams.

Table 3: Summary Statistics of Variables Used for Regression (removed and not removed)

Variable	Obs.	Mean	Std. Dev	Min	Max	Mean Removed	Mean Not Removed	Units
Economic & Demographic Variables								
Per capita real income.	1,887,601	33,027	9,074	7,798	193,473	34,907	33,024	Dollars (2016)
County pop. density	1,887,601	164	427	0.2	67,743	255	163	People per sq mile
Institutional & Environmental Variables Related to Costs of Keeping Dam								
ESA distance to critical habitat (amphibian)	1,887,601	700,383	435,761	0	3,899,140	1,094,143	699,789	Miles
ESA distance to critical habitat (birds)	1,887,601	242,783	147,106	0	1,314,855	253,060	242,768	Miles
ESA distance to critical habitat (clams)	1,887,601	533,534	597,863	0	6,312,191	653,165	533,354	Miles
ESA distance to critical habitat (fish)	1,887,601	421,488	295,561	0.1	3,895,689	511,013	421,353	Miles
ESA distance to critical habitat (mammal)	1,887,601	1,087,097	731,325	0	3,867,764	1,955,763	1,085,786	Miles
ESA distance to critical habitat (reptile)	1,887,601	794,154	436,602	0	3,984,429	719,132	794,268	Miles
ESA distance to critical habitat (snail)	1,887,601	674,575	421,047	213.6833	3,737,347	1,098,104	673,936	Miles
Congressional representation (See Table 2)	1,887,601	0.57	0.49	0	1	0.58	0.57	N/A
Type of ownership (categorical)	1,887,601							N/A

Variable	Obs.	Mean	Std. Dev	Min	Max	Mean Removed	Mean Not Removed	Units
Dam purpose (categorical)	1,887,601							N/A
Economic Variables Related to Benefits from Dams								
Hydro-electricity generation	1,887,601	5,189	11,062	-309	104,171	7,336	5,186	Million kilowatt hours
Electricity price for hydropower dams	1,887,601	20.51	6.04	7.35	99.96	23.18	20.51	Dollars (2016) per million Btu
Farmland value	1,887,601	2,979	5,193	100.335	828,321	4,218	2,977	Dollars (2016) per acre
Market value of agricultural commodities sold	1,887,601	1.01E+08	1.87E+08	4180.8	5.20E+09	9.34E+07	1.01E+08	Dollars (2016) for county
Ag. sales as portion of county income	1,887,601	0.18	0.30	1.80E-06	6.02	0.08	0.18	Percent of ag. sales (2016 dollars)
Dam Characteristics								
Age of dam	1,887,601	41.0	26.7	0	211	78.5	40.9	Years
Height	1,887,601	30.3	28.6	0.5	770	22.9	30.4	Feet
Nearest other dam	1,887,601	3,002	3,825	0	287,295	3,066	3,002	Miles
Number of dams in county	1,887,601	72	69	0	484	46	72	Number of dams
Area of land	1,887,601	1,257	1,552	22.96	20,053	1,083	1,257	Square miles
Area of water	1,887,601	40.89063	132.6961	0.01	8,741	136.07836	40.746964	Square miles
Type of hazard (categorical)	1,887,477							N/A
Construction material of dam (categorial)	1,874,811							N/A

Note: Detailed descriptions of the data sources for the variables are in Table 2

The variables for dam length, maximum discharge, and maximum storage are missing a significant number of observations for removed dams (data exists for 63.7 percent, 7.9 percent, and 13 percent of all removed observations, respectively), a result of missing data in the DRD dataset. Due to this lack of data, these variables were not included in the regression and instead height was relied upon as the primary size variable (data is available for 76.7 percent of removed dams). Similarly, the variable for dam age, which is the difference between the reference year and year constructed up until the point of removal, only has observations for 47.6 percent of observations due to year constructed missing from the DRD dataset. In contrast, approximately 85 percent of NID dams have a record of year completed. American Rivers indicated that a potential systematic reason why this variable would be missing is due to states not collecting the information or it not being known for older dams (J. Thomas-Blate of American Rivers, personal communication, October 8, 2018). Table 4 indicates that removed dams (DRD) are most likely to be older, with the highest percent removed being built between 1900 and 1950. This difference in age categories is not necessarily indicative of sample selection bias because it is expected that removed dams might be generally older (Ashley 2004).

Table 4: Year Dam was Constructed (Removed and Not Removed)

Year Constructed	Total Dams	Total Removed	Percent Not Removed	Percent Removed
1800 - 1849	344	20	0.42%	1.88%
1850 - 1899	1,764	74	2.14%	6.95%
1900 - 1950	14,087	294	17.10%	27.63%
1950 - 1999	50,724	86	61.56%	8.08%
2000 - 2016	2,281	0	2.77%	0.00%
Unknown	13,201	590	16.02%	55.45%
Total	**82,401**	**1064**	**100.00%**	**100.00%**

The data for variables from the USDA Agricultural Census were only available from 1982 to 2012 census years (*farm_employment* and *real_cropval*) due to differences in data collection and/or data availability prior to 1982 and the 2017 Agricultural Census not having been released. Each county with data available has observations from 1982 to 2012.

There are five categorical variables used in the analysis state the dam is located in, purpose of dam, owner type, hazard level, and construction material of the dam. Table 5 provides summary statistics for purpose of the dam and demonstrates how removed dams are underrepresented by more than half for recreation, flood control, fire protection, tailings, and underrepresented to a lesser extent for irrigation and other. Removed dams are overrepresented in purpose type for water supply, unknown, and hydroelectric. The unknown field is attributable to missing data points, indicating that just under half of removed dams had unknown purposes. Of the removed dams which have data, the most underrepresented purposes are recreation, flood control, and fire protection, while the most overrepresented purposes are irrigation, water supply, hydroelectricity, and fish and wildlife.

Table 5: Primary Purpose of Dam (Removed and Not Removed)

Purpose	Total Dams	Removed	Not Removed	Percent Removed	Percent Removed with Data	Percent Not Removed
Recreation	26,976	133	26,843	12.5%	24.7%	33.0%
Flood Control	13,566	23	13,543	2.2%	4.3%	16.7%
Fire Protection or Stock	12,427	10	12,417	0.9%	1.9%	15.3%
Irrigation	7,875	72	7,803	6.8%	13.4%	9.6%
Water Supply	7,089	130	6,959	12.2%	24.2%	8.6%
Other	4,879	33	4,846	3.1%	6.1%	6.0%
Hydroelectric	2,209	98	2,111	9.2%	18.2%	2.6%
Fish & Wildlife	1,854	24	1,830	2.3%	4.5%	2.2%
Tailings	793	0	793	0.0%	0.0%	1.0%
Grade Stabilization	431	6	425	0.6%	1.1%	0.5%
Debris Control	358	4	354	0.4%	0.7%	0.4%
Navigation	267	5	262	0.5%	0.9%	0.3%
Unknown	3677	526	3151	49.4%		3.9%
Total	**82,401**	**1,064**	**81,337**	**100.0%**		**100.0%**

Table 6 describes the differences in dam ownership for removed and not removed dams. Overall, there is extensive missing data for removed dams in this category, with only 13 percent of removed dams having a known owner. When accounting for only the dams with data, removed dams are underrepresented for private dams and overrepresented for all other ownership types. It is likely that the lack of private dams is a result of data collection, since American Rivers usually contacts state agencies to find out about dam removals, and if private dams are not subject to regulations they often do not make it in the DRD (J. Thomas-Blate of American Rivers, personal communication, October 8, 2018).

Table 6: Primary Dam Ownership (Removed and Not Removed)

Ownership	All Dams	Removed	Not Removed	Percent Removed	Percent Removed with Data	Percent Not Removed
Private	55,872	64	55,808	6.00%	48.48%	68.60%
Local	16,459	46	16,413	4.30%	34.85%	20.20%
State	4,090	15	4,075	1.40%	11.36%	5.00%
Federal	2,929	7	2,922	0.70%	5.30%	3.60%
Unknown	3,051	928	2,123	87.55%	-	2.61%
Total	**82,401**	**1,060**	**81,341**	**100.00%**		**100.00%**

Similar to ownership, hazard level only has data for 12.5 percent of removed dams, reflecting missing data from the DRD (Table 7). Of the removed dams with data, there is an underrepresentation in low hazard dams (51 percent removed but comprises 69 percent of dams) and an overrepresentation with high and significant hazard levels. This distribution is consistent with the literature, which suggests that the higher the hazard a dam presents the more likely it is to be removed (The Heinz Center 2002).

Table 7: Hazard Level (Removed and Not Removed)

Hazard Level	All Dams	Removed	Not Removed	Percent Removed	Percent Removed with Data	Percent Not Removed
High	13,411	29	13,382	2.7%	20.4%	16.5%
Low	56,044	73	55,971	6.9%	51.4%	68.8%
Significant	11,848	40	11,808	3.8%	28.2%	14.5%
Unknown	1098	922	176	86.70%	-	0.20%
Total	**82,401**	**1,064**	**81,337**	**100.0%**	**-**	**100.0%**

Although a slightly higher percentage of data points are complete for removed dams for the variable *dam_type*, which describes the construction material of the dam, 45 percent of removed dams do not have this variable (Table 8). There is a large discrepancy between removed and not removed dams for *dam_type*; almost 88 percent of not removed dams in the NID are Earthen, while only 26 percent of removed dams are this type. Removed dams are over-represented in concrete dams at 48 percent, while only 2 percent of not removed NID dams are concrete. These discrepancies are likely due to data recording differences, as well as concrete dams being less likely to be recorded in the NID and earthen dams being more likely to be in the NID due to the corresponding higher and lower hazard risks. Note that the NID dataset had “undetermined” as a hazard option, but since the DRD did not have this distinction those became unknown, essentially indicating missing data instead.

Table 8: Dam Construction Material (Removed and Not Removed)

Dam Type	Total Dams	Removed	Not Removed	Percent Removed	Percent Removed with Data	Percent Not Removed
Buttress (CB)	196	8	188	0.8%	1.4%	0.2%
Concrete (CN)	2,008	279	1,728	26.2%	47.9%	2.1%
Rockfill (ER)	637	3	634	0.3%	0.5%	0.8%
Masonry (MS)	393	13	380	1.2%	2.2%	0.5%
Multi-Arch (MV)	18	0	18	0.0%	0.0%	0.0%
Other (OT)	500	22	478	2.1%	3.8%	0.6%
Gravity (PG)	2,313	27	2,286	2.5%	4.6%	2.8%

Dam Type	Total Dams	Removed	Not Removed	Percent Removed	Percent Removed with Data	Percent Not Removed
Roller Compacted (RC)	1,451	2	1,449	0.2%	0.3%	1.8%
Earthen (RE)	71,207	152	71,055	14.3%	26.1%	87.4%
Stone (ST)	242	52	190	4.9%	8.9%	0.2%
Timber Crib (TC)	151	21	130	2.0%	3.6%	0.2%
Arch (VA)	169	4	165	0.4%	0.7%	0.2%
Unknown	3,117	481	2,636	45.2%	-	3.2%
Total	**82,401**	**1,064**	**81,337**	**100.0%**	**-**	**100.0%**

4.4 Potential for Sample Selection Bias

For the regression used in this research, observations are dropped from the dataset and not used in the regression if there are missing data, such as owner type or purpose of dam. By excluding observations due to missing data, it is possible that sample selection bias is being introduced if the observations are missing these variables in a non-random way. For example, private dams may be more likely to be missing owner type and purpose designations because there is no need to keep a record of those for most all private dams. More generally, there are an estimated 2 million dams that are not included in the NID dataset because of data collection methods, but these smaller dams would be included in the DRD if they are removed. The smallest dams from the DRD were excluded for this analysis (see Section 4.1.3), however, the threshold at which they were excluded (10-feet height or 40-foot length) may not have been sufficient to remove the bias caused by the different sample pools. Therefore, there is also potential for sample selection bias due to the merging of the two databases for this analysis. This potential sample selection bias could result in biased and inconsistent estimators, caused by the error term having zero mean and being correlated with one or more of the independent variables.

5 Results

5.1 Regression Results

As described previously in the empirical model (Section 3.3), a logit model is used to estimate the magnitude and direction of the independent variables on the probability of dam removal due to the binary nature of the dependent variable. Stata 14 was used for the regression analysis. The first regression iteration isolates the economic indicator variables, including variables that are most likely to reflect the impact of economic growth. Variables were selected if they measure the economic status of the county. Variables which are believed to be highly correlated with income are excluded because many of the variables in the data set might have confounding relationships that would compete for explanatory power. In addition to real per capita income, the interaction term of real electricity price with the dummy variable for hydroelectricity dam purposes is also included to capture the effect of higher electricity prices increasing the value of hydroelectric dams. Variables representing the value of agriculture in the county are also included in the model as real crop sales as a percent of county income and real farmland value. These variables measure the economic importance of agriculture in the county and had low correlation with income (-0.1020 for crop sales as percent of county income and 0.3895 for real farmland value). Age and height of the dam are included as characteristics of the dam which the literature suggests are strong predictors of dam removal and are also not correlated with income. This first model has the following functional form, as a logit model:

Model 1: $\text{Removed}_{it} = \beta 1\text{Per Capita Real County Income}_{it} + \beta 2\text{Real Electricity Price*Hydroelectricity Dam (dummy)}_{it} + \beta 3\text{Real Crop Sales as Percent of County Income}_{it} + \beta 4\text{Real Farmland Value}_{it} + \beta 5\text{Age Of Dam}_{it} + \beta 6\text{Height}_{i}$

The second model includes variables which are believed to have changed due to economic growth. These include the regulatory variables which reflect how society collectively governs dam removal. This model excludes per capita income and variables which are related to the economic benefits from dams to focus on the costs of dams reflected by the regulations. This regulatory model includes population density as an economic indicator and congressional representation as a political indicator. The dummy variables for ownership of the dam (federal) and purpose of dam (hydroelectric) are also included as indicators for if the dam is subject to

FERC regulations. Distance to Endangered Species Act listed critical habitat is included to measure the effect of regulations related to that legislation. Additionally, age and height of the dam are again included as characteristics of the dam. This second model has the following function form, as a logit model:

Model 2: Removed $_{it}$ = β1Population Density $_{it}$ + β2RPolitical Representation $_{it}$ + β3Ownership of Dam (dummy) $_{i}$ + β4Purpose of Dam (dummy) $_{i}$ + β5Distance to ESA Habitat $_{i}$ + β6Age Of Dam $_{i}$ + β7Height $_{i}$

The third model combines Model 1, which isolates income effects and benefits from dams, and Model 2, which isolates regulatory effects are believed to have arisen from economic growth. Model 3 includes all variables in the prior two models with the exception of the dummy variable for purpose of the dam from Model 2, which is included in the interaction term with real electricity price in Model 1. Additional variables were added to Model 3 that include a dummy variable for the hazard potential for the dam, hydroelectric generation in the state, the distance to the nearest other dam, the number of dams in the county, the material the dam is constructed from, and the number of square miles of water in the county. These variables are included to add explanatory power to the model, as there is some evidence in the literature that they may contribute to dam removal, but they are not believed to be the primary drivers for removal. Results do not differ substantially for Model 3 with or without inclusion of these additional variables. The results of all three models are presented in **Table 9**.

Table 9: Models 1 – 3 Regression Results

	Model 1		**Model 2**		**Model 3**	
	n	**1,910,655**	**n**	**2,839,672**	**n**	**1,887,601**
Dependent variable: Removed (1 if removed, 0 otherwise)						
Variable	**dy/dx**	**P>|z|**	**dy/dx**	**P>|z|**	**dy/dx**	**P>|z|**
Per capita real income	-4.62E-08	0			-9.34E-09	0.015
Real electricity price*Hydroelectricity dams	1.17E-04	0			0.0000828	0
Real crop sales as percent of county income	-0.0087171	0			-7.53E-04	0.00
Real farmland value	1.79E-08	0			**-2.29E-08**	0.002
Population density			1.04E-07	0	1.66E-07	0.036
Congressional political representation			-0.000012	0.8	**0.0001545**	**0.01**
Ownership (federal)			0.0008969	0	7.02E-04	0.00

	Model 1		Model 2		Model 3	
	n	**1,910,655**	**n**	**2,839,672**	**n**	**1,887,601**
Dependent variable: Removed (1 if removed, 0 otherwise)						
Variable	**dy/dx**	**P>|z|**	**dy/dx**	**P>|z|**	**dy/dx**	**P>|z|**
Dam Purpose (hydroelectricity)			0.0043547	0		
Distance to snail critical habitat			-1.21E-06	0	**5.34E-07**	0.006
Distance to reptile critical habitat			2.56E-06	0	4.44E-06	0
Distance to mammal critical habitat			2.06E-06	0	2.51E-06	0
Distance to fish critical habitat			-6.67E-06	0	-5.51E-06	0
Distance to clams critical habitat			6.48E-07	0	1.18E-06	0
Distance to bird critical habitat			-3.30E-06	0	-1.55E-06	0
Distance to amphibian critical habitat			4.55E-06	0	1.48E-06	0
Age of dam	0.0000815	0	0.0000166	0	2.15E-05	0
Height of dam	-0.0003003	0	-0.000027	0	-2.22E-05	0

Note: Model 3 included additional independent variables which are not included in this table (hazard type, hydroelectric generation, distance to nearest other dam, number of dams in the county, construction material of dam, and area of water). The bold numbers in Model 3 indicate where either the sign of the marginal effect or the statistical significance changed compared with Models 1 and 2.

The variable for real farmland value changes signs from positive in Model 1 to negative in Model 3. This change may be due to omitted variable bias in Model 1. There is a 0.6824 correlation between real farmland value and population density, so by including both in Model 3 it is also possible that bias has been introduced, influencing the marginal effects for the variables. Similarly, the variable for political representation changes from negative in Model 2 to positive in Model 3 and went from insignificant to statistically significant at the five percent level. It is possible that endogeneity (correlation of the variable with the error term) is occurring for political representation in Model 2 due to omitted variables. The marginal effect of real per capita income is consistent between Model 1 and 3, although the marginal effect decreases in Model 3. This consistency between the models suggests that real per capita income is not being biased by collinearity. The correlation between real per capita income is highest for population density (0.4216), but there is no evidence for any bias caused by the correlation.

These models are estimated using logit and the results and interpretations are presented in terms of marginal effects, which measures the effect of a one unit change in the independent variable on the probability of removal. In all four of the models there are very few variables with large marginal effects, interpreted as the change in probability of dam removal associated with the variable. Model 3 is the preferred specification of the model because inclusion of the additional variables does not appear to be causing multicollinearity bias, and there is evidence for potential omitted variable bias without all the variables in Models 1 and 2. Because the one-unit change reflected in the marginal effects reported in Table 10 is not necessarily meaningful for the magnitude of each variable, the interpretations are provided in terms of a one-standard deviation change using the values from the year 2016 (with the exception of real farmland value and real agricultural sales as a percent of county income which are from the year 2012 due to data availability from the USDA Agricultural Census). See Table 10 for the corresponding interpretations of the variables. Dummy variables were excluded because a one-unit change is a meaningful interpretation by design.

Table 10: Interpretation of Marginal Effects as Standard Deviation Changes

Variable	Standard Deviation	Marginal Effect	Std. Dev. Effect	Interpretation
Per capita real income	10,862	-9.34E-09	-1.01E-04	An increase of $10,862 in per capita real income reduces probability of dam removal by 1.01E-04 percent.
Real electricity price*Hydroelectricit y dams	5.99	0.0000828	4.96E-04	An increases of $0.599 in real electricity prices increases probability of removal by 4.96E-04 percent.
Real crop sales as percent of county income	0.32	-7.53E-04	-2.41E-04	An increase of 32 percent of crop sales as percent of county income decreases probability of removal by 2.41E-04 percent.
Real farmland value	5595	-2.29E-08	-1.28E-04	An increase of $5595 in real farmland value decreases probability of removal by 1.28E-04 percent.
Population density	575	1.66E-07	9.54E-05	An increase of 575 people per sq mile increases the probability of removal by 9.54E-05 percent.
Distance to snail critical habitat	258.3	5.34E-07	1.38E-04	Being 258 miles further from snail critical habitat increases probability of removal by 1.38E-04 percent.
Distance to reptile critical habitat	280.2	4.44E-06	0.0012	Being 280 miles further from reptile critical habitat increases probability of removal by 0.0012 percent.
Distance to mammal critical habitat	456.1	2.51E-06	0.0011	Being 456 miles further from mammal critical habitat increases probability of removal by 0.0011 percent.
Distance to fish critical habitat	189.5	-5.51E-06	-0.0010	Being 189.5 miles further from fish critical habitat decreases probability of removal by 0.0010 percent.

Variable	Standard Deviation	Marginal Effect	Std. Dev. Effect	Interpretation
Distance to clams critical habitat	379.5	1.18E-06	4.48E-04	Being 379.5 miles further from fish critical habitat decreases probability of removal by 4.48E-04 percent.
Distance to bird critical habitat	91.8	-1.55E-06	-1.42E-04	Being 91.8 miles further from fish critical habitat decreases probability of removal by 1.42E-04 percent.
Distance to amphibian critical habitat	271	1.48E-06	4.01E-04	Being 271 miles further from amphibian critical habitat increases probability of removal by 4.01E-04 percent.
Age of dam	26.75	2.15E-05	5.75E-04	An increase in dam age of 26.75 years increases probability of removal by 5.75E-04 percent.
Height of dam	29.46	-2.22E-05	-6.54E-04	An increase in dam height of 26.75 decreases probability of removal by 6.54E-04 percent.

5.2 Standardization Coefficients

To determine which of the independent variables have the largest effect on the dependent variable the variables are standardized using beta coefficients, also known as standardization coefficients. Standardization coefficients present the effect of a one standard deviation change in the independent variables. To obtain a standardization coefficient, each observation has the mean observation subtracted from it, and is then divided by the standard deviation. The result of this transformation converts the independent variables to unitless, allowing them to be compared to each other (Wooldridge 2012). Table 11 presents the results of the ranking of marginal effects based on standardization coefficients.

Table 11: Standardization Coefficients for Independent Variables

Rank	Variable	St.Coef	Prob(z)
1	Distance to reptile critical habitat	0.465	0
2	Distance to mammal critical habitat	0.4361	0
3	Distance to fish critical habitat	-0.3939	0
4	Number of dams in county	-0.2784	0
5	Height of dam	-0.2442	0
6	Age of dam	0.2228	0
7	Price of electricity for hydroelectricity dams	0.2116	0
8	Distance to clam critical habitat	0.169	0
9	Distance to amphibian critical habitat	0.1505	0
10	Hydroelectricity generation	-0.1243	0
11	High hazard dam (dummy)	0.1108	0
12	Agricultural sales as percent of county income	-0.0828	0

Rank	Variable	St.Coef	Prob(z)
13	Area of water in the county	0.0649	0
14	Distance to nearest other dam	-0.0607	0
15	Material dam is constructed from is earthen (dummy)	-0.0564	0
16	Distance to bird critical habitat	-0.0534	0
17	Distance to snail critical habitat	0.0521	0.006
18	Owner type is federal (dummy)	0.0496	0
19	Real farmland value	-0.0405	0.002
20	Real per capita income	-0.034	0.015
21	Population density	0.0336	0.036
22	Congressional political representation is republican	0.0287	0.01
23	Significant hazard dam (dummy)	0.0192	0.092

Note: Both the "lstand" and "listcoef" commands were used in Stata, which yielded similar rankings.

All variables in the beta coefficient model have the same sign as Model 3, the preferred specification. Based on the results of the standardization coefficients, the most influential variables are the ESA distance to critical habitat variables. The standardization coefficients for distance to critical habitats for fish and birds are negative, which indicates that increased distance from critical habitat reduces the probability of removal. This means that the closer a dam is to fish or bird critical habitat the more likely the dam is to be removed. However, the standardization coefficients for all other species types are positive and statistically significant, suggesting that the further a dam is from these habitats the higher the probability of removal. It is possible that regional variables are confounding the results of the critical habitat variables, since many listed species may be clustered in particular regions of the United States, causing endogeneity basis if the coefficient is reflecting some of that regional effect as well. Critical habitat designation is highly concentrated on the west coast, as well as in some parts of Florida and in Maine. Distance to critical habitat likely is not a linear variable. Any effect that does exist is probably only for dams closest to the critical habitat and the effect goes to zero at larger distances. For this reason, a robustness check for only dams within 5 miles of critical habitat is performed in Section 5.3.

Other economic variables which rank high as beta coefficients include the real price of electricity for hydroelectric dams. From Model 2 we know that hydroelectric dams are associated with a higher probability of removal than non-hydroelectric dams. For hydroelectric dams, increases in electricity prices are associated with increases in the probability of removal in Model 3. The theoretical model predicted that higher electricity prices would be associated with lower probability of removal because the value of electricity produced by hydroelectricity dams would be higher, but the reverse was found to be true. However, an explanation for the positive coefficient for electricity prices for hydroelectricity dams may be because private hydroelectricity dams are subject to FERC licensing, increasing their probability of removal regardless of electricity prices. A model with just real electricity prices, regardless of the dam's purpose being hydroelectricity, was also conducted and also had a positive coefficient. Because electricity prices are composites for the states based on imports and exports, it is not surprising that a relationship counter to the theory was found.

Increased hydroelectricity output for a state is associated with decreases in the probability of removal in Model 3. Hydroelectricity output was the 10th largest effect in the beta coefficients model. This result is likely because regions with high hydroelectricity production are reliant on power from dams, decreasing the probability of dam removal. This result may be because high production of hydroelectricity is a proxy for the topography and hydrology of the county. A high level of hydroelectricity production indicates that the dam is in a good location to produce hydroelectricity, and probably very profitable hydroelectricity, which means removing the dam has high costs.

Agricultural sales as a percent of county income, as well as real farmland value, have negative marginal effects, indicating that increases in these measures of the strength of the local agricultural economy decrease the probability of dam removal. These results could be due to the fact that the variables reflect irrigated agriculture, which is often more highly valued. If the dams make it possible to irrigate larger areas, the dependence on this source of irrigation water may be particularly valuable in a given region, thereby a factor lowering the probability of dam removal. However, neither of these variables have economic significance because their standardization coefficients were smaller than 0.1 and the marginal effects for a one-standard deviation change were smaller than 0.001 (Table 10).

The marginal effects for the variables for real per capita income, population density, and congressional political representation did not have economic significance on the probability of dam removal based on both the beta coefficients and marginal effects for a one-standard deviation change. Economic significance is being defined as having a standardization coefficients larger than 0.1 or a marginal effect for a one-standard deviation change larger than 0.001 (Table 10). Although not economically significant because the magnitude of effects was small, the coefficient for real per capita income is negative. This result indicates that increases in real per capita income are associated with decreased probability of removal, which is contrary to the expected result from the theoretical model. However, to the extent that higher per capita incomes generally have contributed to the expansion of regulations like ESA and FERC relicensing, these factors are influencing removals and these regulations may be created because of economic growth that increases income may be expressed indirectly through those regulatory actions. This model did not have a more direct empirical way to measure the relative value of riverine environments compared with consumer goods, and county income may not be an adequate proxy.

5.3 Fixed Effects Regression

An additional type of regression is used to capture the panel characteristics of the data. Model 4 estimates the effect of the dependent variables on the probability of removal using fixed effects at the county level, which removes all time-constant variables to only estimate the variables that change annually by comparing the variables in each observation period. A fixed effect model was not able to be run at the dam-level because there was not enough variation for the number of observations. The variables which change every year include real per capita income, population density, hydroelectricity generation for the state, real electricity prices for hydroelectric dams, farm employment, real farm income, and real crop value. Congressional political representation is time dependent, but does not change every period so it was not included due to lack of variation between periods. However, the variables for party and owner type were interacted with years since 1969 in order to include them in the fixed effects regression. The dam-level data was collapsed by county and year, resulting in 86,369 observations. When collapsing the data, the dependent variable *removed* is converted from binary to an average between zero and one, with higher values representing a higher percentage of dams removed in the county. The results of the fixed effect estimation at the county-level are presented in Table 13.

Table 12: Results from Fixed Effects Regression Compared with Model 3

	Model 3 - Logit Model		Model 4 - Fixed Effects	
	n	1,887,601	n	86,369
Dependent variable: Removed (1 if removed, 0 otherwise)				
Variable	**dy/dx**	**P>|z|**	**dy/dx**	**P>|z|**
Per capita real income	-9.34E-09	0.015	-1.29E-07	0
Real electricity price*Hydropower dams	8.28E-05	0	7.85E-04	0
Real crop sales as percent of county income	-7.53E-04	0	-6.05E-04	**0.35**
Real farmland value	-2.29E-08	0.002	-3.32E-08	0
Population density	1.66E-07	0.036	7.53E-06	0
Political representation	1.55E-04	0.01	1.52E-04	0
Federal Ownership (dummy)	7.02E-04	0	6.07E-04	0
Age of dam	2.15E-05	0	**-1.52E-04**	0
Height of dam	-2.22E-05	0.00	-6.92E-04	0
High hazard dams (dummy)	0.0001	0.092	0.0292	0
Significant hazard dams (dummy)	0.0008	0	-0.0080	0.001
Hydroelectric generation	-3.28E-08	0	-5.53E-08	0.037
Distance to nearest other dam	-4.18E-08	0	-2.75E-06	0
Number of other dams in county	-1.07E-05	0	-1.63E-05	**0.476**
Construction material of dam (dummy)	-0.0005	0	-0.2163	0
Sq. miles of water in county	4.49E-07	0	-1.05E-05	0.077

The primary change between the fixed effects and logit model is that the marginal effect/coefficient for age of dam becomes negative with fixed effects. The interpretation of this effect is that increases in age decrease the probability of dam removal. This result is contrary to the literature and all the other regressions, since age is believed to predict of dam removal. However, because fixed effects are aggregated at the county level this represents only the average age of dams in the county and is not dam specific. The previous regressions and the literature suggest that these factors, like age of dam, height of dam, and purpose of dam, are some of the largest effects for predicting dam removal. Because the fixed effect model averages these factors it loses the precision afforded by the other models. The other variables in the fixed effects model do not change significantly, which suggests that the logit model is appropriate to use even though it does not specifically account for the panel data like the fixed effect model does.

5.4 Robustness Checks

Six robustness checks were performed to test the consistency of the marginal effects estimates from Model 3. Results for robustness checks one through four are available in Appendix I.

The first check of the results changes the timeframe of the data. Instead of beginning in 1969, all observations prior to 1992 were removed. The model structure is based upon Model 3. The purpose of this check is to control for reporting bias in the DRD, since it was created in the 1990s. Additionally, this iteration isolates potential effects from policy changes, including the 1986 FPA amendments and the 1992 congressional approval to removal the Elwha River dams. For this robustness check, all directions of marginal effects and orders of magnitudes were consistent with Model 3. The statistical significance of per capita real income changed from the one percent level to no longer being statistically significant compared with the reference Model 3. This robustness check was also tested with the dummy variable for purpose of dam as hydroelectricity instead of the interaction of electricity price for hydroelectricity dams and there was no increase in marginal effect compared with Model 2 (which also had the dummy for purpose of dam as hydroelectric). This consistency suggests that the 1986 FPA amendments have not increased the probability that hydroelectricity dams will be removed. This result also suggests that there is no influential bias as a result of data collection for the DRD beginning in the 1990s.

The second robustness check isolates only large dams over 25 feet. Robustness Check 2 in Appendix I present the results of this analysis. The model structure is also based upon Model 3. This iteration of the model highlights the potential for endogeneity, since it is believed there is an inherent difference due to larger dams being in the NID and smaller dams being in the DRD based on the data collection methods of each database, causing correlation with the error term. The smallest dams were removed from the DRD when merging the two datasets, in order to reduce this known endogeneity, so these robustness checks confirm if that action had the intended result. After isolating only dams larger than 25 feet there were 4,133 removed observations with an average height of 43.0 feet and 1,771,208 not removed observations with an average height of 42.1 feet. There were significant changes in this robustness check, suggesting that large dams are removed for different reasons than small dams and there may be potential endogeneity. In this large-dam model, the marginal effects for the variable for congressional political representation went from positive to negative, while maintaining statistical significance, suggesting that large dams are more likely to be removed with more democratic representation. This opposite result could also be due to a bias caused be endogeneity. In Model 3, the full sample with all heights, the opposite was found, for dams of all sizes there is evidence that more are removed with republican congressional representation. However, the variable for congressional political representation does not have economic significance in Model 3, so this potential endogeneity does not appear to be affecting the variables that do have economic significance. The variables representing economic effects, including real per capita income, electricity prices for hydroelectric dams, and crop sales as a percent of county income did not change significantly. Other changes for this model are that statistical significance for the variables for population density and real farmland value both became insignificant at the 10 percent level.

The third robustness check (Robustness Check 3 in Appendix I) used OLS to estimate the results using the robust command to control for potential heteroskedasticity. Heteroskedasticity occurs when the error term has non-constant variance, which can cause the OLS standard errors to be biased due to violation of the zero conditional mean Gauss-Markov assumption. This iteration also uses the Model 3 structure. By using the heteroskedasticity-robust standard error for the dependent variables, Robustness Check 3 corrects for heteroskedasticity. If the p-values change it evidence that the preferred specification, Model 3, is reporting incorrect statistical significances. As presented in Appendix II, the only changes in statistical significance are for distance to amphibian critical habitat and hydroelectricity generation for the state, both of which became more significant. Based upon this robust correction heteroskedasticity does not appear to be a concern. It should be noted that the R-squared for the OLS regression was small at 0.014, indicating that the variables in the model explain only a small fraction of why dams are removed.

A VIF test was also conducted after this OLS Robustness Check 3 to test for multicollinearity caused by independent variables being correlated. Of most concern is multicollinearity in Model 3 between income and the other economic variables, such as population density and real crop sales as percent of county income. Multicollinearity can cause biased estimators because the effect is attributed to both of the correlated variables instead of independently. Multicollinearity also increases the variance of estimates. The variance inflation factor (VIF) was calculated for each of the variables using an OLS regression followed by the vif command in Stata. The VIF for a variable j is equal to $VIF_j = 1/(1 - R_j^2)$.[13] The highest VIF value was for the ESA critical habitat variables for amphibians (3.99) and fish (3.49). The VIF value for population density is 2.04 and for real per capita income it is 1.41. None of the VIF values are higher than ten, suggesting that multicollinearity is not affecting the estimation results (Wooldridge 2015).

A fourth robustness check (Robustness Check 4 in Appendix II) is conducted to test for the possibly that real income changes have not been significant enough in some parts of the country for relative price effects to manifest. A dummy variable was created for if the county had higher than the median real per capita county income ($29,060) and the real per capita income variable was removed from this robustness check. The marginal effect for the dummy variable for the highest income counties was negative, consistent with real per capita income in Model 3, but was a stronger magnitude of 0.006. The interpretation of this result is that being in a higher real per capita income county decreases probability of removal by 0.006 relative to being in a lower real per capita income county. The sign for electricity prices for hydroelectric dams went from positive to negative, suggesting that for high-income counties increases in electricity prices are associated with decreased probability of removal. This result for electricity prices for hydroelectric dams is more consistent with the theory, because as electricity prices increase the costs of dam removal also increase, suggesting fewer dams would be removed. Also in this robustness check the marginal effect for crop value as a percent of county income became much larger in magnitude (-0.16). A 100 percent increase in crop value as a percent of county income would therefore be associated with a 0.16 percent decrease in probability of removal. This finding provides some reinforcement for the theory that dams which contribute to high-value agriculture are less likely to be removed, but are not very robust given the direction change of the marginal effect at the higher income levels.

[13] See Wooldridge (2015) p. 86 for further discussion of VIF.

The fifth robustness check generates a dummy variable for distance to ESA critical habitat for each of the species if a dam is within 5 miles. The model specification has the same functional form as Model 3. Table 14 below presents the results of this analysis. When only considering dams within 5 miles of ESA critical habitat, the habitats for mammals, fish, and birds increase the probability of removal. Being within 5 miles of amphibian and clam critical habitat decreases the probability of removal. These results have economic significance because they are larger than 0.001 in marginal effects and have a larger than 0.1 beta coefficient. These findings are also consistent with Model 3 except for mammal critical habitat, which had a positive coefficient in Model 3 suggesting that decreases in distance decrease the probability of removal. However, because it is expected that the proximity to ESA critical habitat to only have an effect close to dams and not at all distances this robustness check is the preferred interpretation. This robustness check suggests that the Endangered Species Act is influencing dam removal for some species types in areas close to critical habitats. This result is consistent with the literature review, which has documented cases like the Elwha Dam which were removed partly to provide habitat for ESA listed salmon species.

Table 13: Marginal Effects of Being Within 5 Miles of ESA Critical Habitat

Within 5 mi of critical habitat for:	dy/dx	P>|z|	Number of Dams Removed within 5 Miles	Number of Dams Not Removed within 5 miles
fish	0.00111	0	2,860	70,292
mammal	0.00207	0	412	14,692
bird	0.00182	0	3,001	79,134
clam	-0.002494	0	749	80,851
amphibian	-0.003731	0	1,199	30,689
reptile	omitted		533	9,255
snail	omitted		133	4,517

The sixth and final robustness check attempted to isolate the state-specific effects that contribute to dam removal. The state dummies for the ten states with the most dam removals are included, which are Pennsylvania, Wisconsin, California, Michigan, Ohio, Oregon, Minnesota, Massachusetts, New Jersey, and New Hampshire. The dummy variable for California was dropped due to lack of variation. Marginal effects for each state and p-values are included in

Table 14. Pennsylvania, which has the highest number of dam removals, also has the largest marginal effect, suggesting that being in Pennsylvania, relative to other states, increases probability of removal by 0.004 percent. In contrast, Oregon, which has the 6th highest number of dam removals has negative marginal effects, suggesting a dam there is less likely to be removed relative to the average of all omitted states. The marginal effects for these state variables are some of the highest seen in the model iterations, suggesting that state specific policies are influencing the probability of dam removal.

Table 14: State Specific Marginal Effects

Variable	State	dy/dx	P>|z|
state_dum38	PA	0.0044	0
state_dum48	WI	0.0024	0
state_dum22	MI	0.0039	0
state_dum35	OH	0.0013	0
state_dum37	OR	-0.0016	0
state_dum23	MN	0.0007	0.035
state_dum19	MA	0.0013	0
state_dum31	NJ	0.0024	0
state_dum30	NH	0.0017	0

6 Discussion

Economic & Demographic Variables

The economic and demographic variables (per capita real income and population density) were statistically significant, but the magnitudes of effects did not generally support the relative prices hypothesis directly. Based on the theoretical model, we expect increases in per capita real income to increase the probability of dam removal. The direction of the variable representing real per capita income at the county level is consistently negative in all models, suggesting increases are associated with a decreased probability of removal. This result is not an outright rejection of theoretical model because real per capita income does not measure how the marginal utility from environmental goods and services compares to the marginal utility of consumption. Income growth is believed to increase consumption, decreasing the marginal utility of additional consumption. With more consumption, environmental quality declines, creating a relative scarcity that increases the marginal utility of environmental goods and services. Although these changes in marginal utility are initially caused by economic growth (i.e. higher incomes), it is unclear what the lag between income growth and dam removal is. Dam removals are believed to take years to manifest after the relative values have changed or after the costs exceed the benefits of keeping the dam, so it is possible that the timing of removal with income is not properly represented. It is also unclear if county income is the appropriate indicator. There is a spectrum between personal income and country gross domestic product, which vary significantly. For this reason, the variables representing institutions and regulations are likely better indicators of any change in the marginal rate of substitution between consumer goods and environmental goods.

Population density did have a positive marginal effect in all models and robustness checks. The magnitude of the effect is that one standard deviation increase of 575 people per square mile is associated with a 0.0001 percent increase in probability of removal, which did not meet the threshold for economic significance. This result may be attributing effects of urbanization, which has increased since 1969. If people move from rural areas, which might rely on dams for water storage or for agricultural or milling operations, to urban areas which rely less on dams, the net social welfare from the rural dams might become negative, increasing the probability of dam removal.

Because many of the outputs from dams are non-market good and services, there is no direct way to estimate the non-market benefits and costs of dam removal. This non-market relative value of dams compared with consumer goods is believed to change due to increases in the production possibility frontier, which expands with economic growth. Changes to the production possibility frontier are also believed to be impacted by a variety of factors, such as technologies, institutions, and initial endowments of environmental goods (Jaeger & Kolpin 2001), which were not directly measured by this analysis. Dams are also unique among environmental variables because they do provide benefits to people (flood control, water storage, reservoir recreation) and dams do not affect human health like other environmental goods like clean air, which has been found to follow an EKC curve.

Institutional & Environmental Variables Related to Costs of Keeping Dam

This analysis found some evidence linking the Federal Power Act and FERC relicensing requirements to increased probabilities of dam removal, however the results were mixed. If a dam is subject to FERC relicensing was not explicitly a variable in this model, but proxies were used with the inclusion of variables that indicated ownership type, large dams, and purpose of hydroelectricity. Ownership type was lacking sufficient observations (88 percent of removed dams were missing data for ownership. Height of the dam is consistently negatively associated with probability with dam removal, consistent with the theory that larger dams have a lower probability of removal. This relationship likely occurs because larger dams are able to store more water and provide more benefits due to economies of scale, which increases the costs of removal.

The dummy variable for purpose of hydroelectricity had a marginal effect of 0.004 in Model 2, large enough to have economic significance, and was statistically significant at the one percent level, indicating that hydroelectricity dams are more likely to be removed relative to other dam purposes. Because most hydroelectricity dams are subject to FERC, this evidence supports the theory that dam removal is driven by the FERC relicensing process. This result is also consistent with the findings of Grabowski et al. (2018) who found hydroelectricity dams to be the most commonly removed type of dam removal.

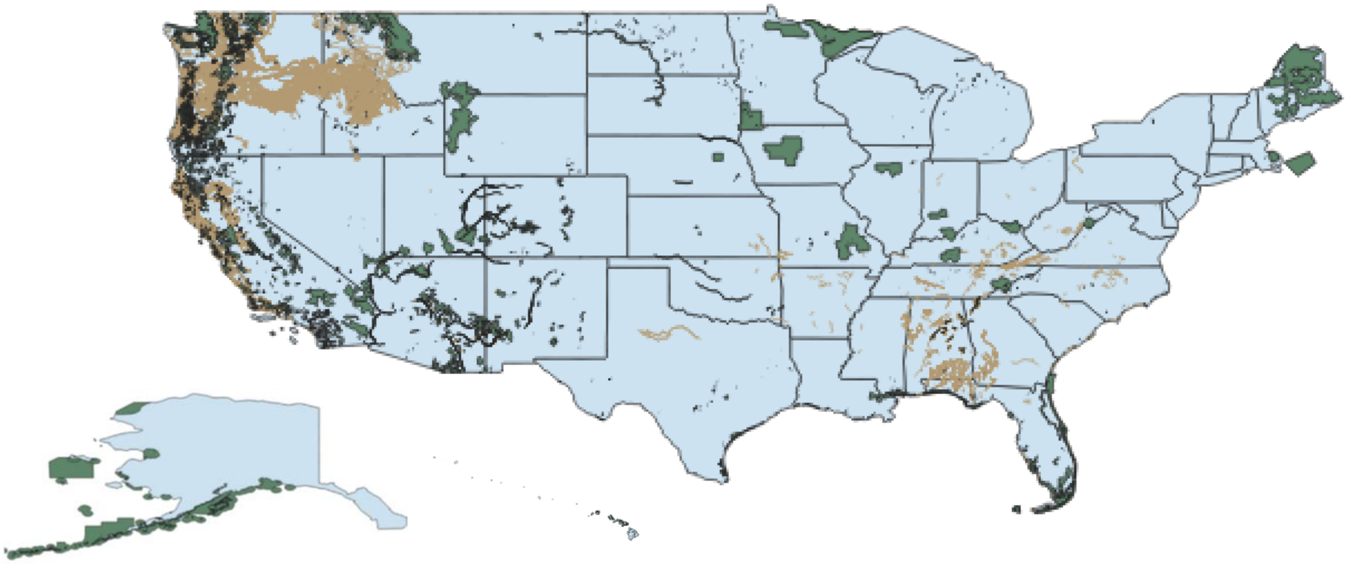
The results of the variable reflecting ownership type actually contradicted the FERC hypothesis, which suggests federal dams are least likely to be removed and non-federally owned dams are most likely to be removed due to FERC relicensing (Amos 2014; Bonham 2008; Lowry 2005; Doyle & Harbor 2003). The coefficient for federally owned dams (*owner1*) is positive across all model iterations, indicating that federally owned dams have a higher probability of removal relative to other ownership types. However, the results did not achieve economic significance due to the magnitude of the marginal effect and standardization coefficient. These results are also not believed to be reliable due to the large amount of missing data on ownership type for removed dams; 88 percent of removed dams were missing ownership data, but only 3 percent of not-removed dams were missing ownership information. It is possible that the way American Rivers collects dam removal data likely biases towards federal, state, and local utilities because the state and other data-reporting agencies would be more aware of those types of dams being removed, but are less likely to be aware of small, private dam removals. For these reason, the positive marginal effects of federal dam ownership are not significant enough to contradict the hypothesis that FERC relicensing is influencing dam removal.

The results of robustness check 5 suggest that being within 5 miles of critical habitat for fish, mammals, and birds increases the probability that a dam will be removed. These variables indicating distance to ESA critical habitat are also related to FERC relicensing requirements, because dams within critical habitat that are subject to FERC are more likely to require fish passage or other costly modifications mandated by U.S. Fish and Wildlife and the National Marine Fisheries Service (Amos 2014). It is possible that critical habitat is not an adequate proxy for indicating that either ESA Section 7 consultations or FERC relicensing will lead to dam removal due to the presence of ESA listed species. Under ESA§4(b)(2), critical habitat does not have to be designated if doing so has adverse impacts, so portions of habitat which might contain endangered species are not designated (Taylor et al. 2005). Additionally, not all ESA listed species have critical habitat designated; as of January 2015, critical habitat has only been designated for 704 of the more than 1,500 ESA listed species.[14] The lack of critical habitat designations and exclusion of data on species regulations at the state-level may be underrepresenting the magnitude of species requirements impacting removal. Figure 8 presents a spatial distribution of where critical habitat is in the United States, demonstrating the concentrations on the west coast and the state of Maine. For fish, many dams may have contributed to the reason for the species' ESA listing and critical habitat designation. Although dams are being removed near critical habitat, there are still many dams near critical habitat,

[14] https://www.fws.gov/endangered/what-we-do/critical-habitats-faq.html

especially in the Pacific Northwest where dams are generally larger and less likely to be removed.

Figure 8: Critical Habitat Designations in the United States



Source: Created with data from U.S. Fish and Wildlife Service available at: https://ecos.fws.gov/ecp/report/table/critical-habitat.html

Note: Green represents critical habitat on land, lakes or at sea, while brown represents critical habitat in rivers.

Previous research suggests dam removals are influenced by political jurisdictions due to spatial variability, attributed to strength of local institutions that support dam removal (Pohl 2002), histories of different states and/or regions (Bellmore et al. 2017), and other state policies that either hinder or support dam removal, such as permitting requirements (Doyle et al. 2003; Lowry 2005; Ashley 2004). The results of this analysis support the findings that regional differences influence probability of removal because the state variables in robustness check 6 had some of the largest marginal effects. This robustness check also found that Pennsylvania, New Jersey, and New Hampshire have the highest probabilities of dam removal. Congressional political representation did not meet the threshold for economic significance. Republican congressional representation was slightly (0.00015) associated with higher dam removal rates in that district, except for large dams (heights taller than 25 feet) where democratic congressional representation increased probability of removal (-0.0002 coefficient), suggesting the result is not robust. There does not appear to be a direct relationship between political ideology and probability of dam removal.

Economic Variables Related to Benefits from Dams

The variables which measure the effect of benefits from dams do not have magnitudes of effects that have economic significance. However, the direction of the variables did suggest that when there are larger benefits from the dam the costs of removal increase, decreasing the probability of removal. Agricultural sales as a percent of county income has a negative coefficient, indicating that increases in agricultural sales relative to county incomes decreases the probability of dam removal. This result may suggest that the benefits provided by the dam in the form of irrigated agriculture are responsible for higher levels of agricultural sales, making the cost of dam removal is higher. Similarly, hydroelectricity production for the state has a negative coefficient, suggesting that as more electricity is provided from hydroelectricity that the benefits from the dam increase and the costs of removal increase. Farmland value also had a negative coefficient, again suggesting that benefits from dams in the form of increased farmland value (potentially from irrigated agriculture) increase the costs of dam removal.

The marginal effect for the variable representing electricity prices for hydroelectric dams is positive in Model 3, suggesting that an increase in state electricity prices is associated with an increase in the probability of dam removal. This variable also met the threshold for economic significance. However, in Robustness Check 4 for high income counties the marginal effect was negative, suggesting this result is not very robust, likely due to the multitude of factors contributing to electricity prices. There is not a clear explanation for why there would be a positive marginal effect between electricity prices and the probability of dam removal. The marginal effect for hydroelectric dams, included in the interaction term, has a positive coefficient (see Model 2), which is might be the effect that is being picked up in this interaction term, resulting in a positive coefficient overall. Because state electricity prices depend on a larger regional grid that includes imports from out of state and not just a single dam’s electricity production, there are likely many confounding factors in these results.

Dam Characteristics

The variable for dam age had a positive coefficient in all the regression iterations, indicating that older dams were more likely to be removed than more recently built dams. This finding of an age effect is supported by the literature, which suggests that as dams age they become more hazardous, increasing the costs of keeping the dam (Pohl 2002; Babbitt 2002; Bellmore et al. 2004; Foley 2017). However, other literature has not found a strong age effect (Grabowski et al. 2018; Ashley 2004). The variable for age of dam did meet the threshold for economic significance. The hazard level of the dam may not be correlated with age if maintenance is occurring on some dams and not others, causing some older dams to be relatively safe and some without maintenance to be relatively dangerous. There was a measure of hazard included in the data for this analysis, but it did not produce reliable estimates due to the high amount of missing data in the DRD.

The variable for dam height had a negative marginal effects in all model iterations, suggesting that larger dams have a smaller probability of removal, which supports the theory that small dams are more likely to be removed because of the lower costs of removal. The marginal effects also met the threshold for economic significance. Height did meet the threshold for economic significance.

The variables for distance to nearest other dam and number of dams in the county reflects the proximity to other dams and have negative marginal effects, suggesting that the higher the density of dams in the county the lower the probability one of those dams will be removed. This result is the opposite of what was predicted by the theory, which suggests that the more dams there are in a concentrated area the marginal value of each dam is lower compared with areas with less dams, increasing the probability that one of the dams would be removed. However, a potential explanation for the effect might be that areas with high numbers of dams have more ideal conditions for dams and are extracting higher value, perhaps from nearby high-value agriculture or landscapes supportive of hydroelectricity production. Because these higher benefits from dams might be correlated with the density of dams in an area, it might explain why lower density areas have a higher probability of removal. Distance to nearest other dam has economic significance, but number of dams in the county does not.

The variable for square miles of water in the county has a positive marginal effect, indicating that the more area covered by water in the county the more likely a dam will be removed. Because lakes cover more area than rivers, and lakes are able to exist in flatter landscapes, this result could indicate that regions with higher elevation variation (i.e. mountainous counties) are less likely to remove dams because they are needed for flood control. However, this variable does not meet the threshold for economic significance.

The dummy variables for hazard type of the dam (high and significant hazard levels) both had positive marginal effects, but only high hazard dams met the threshold for economic significance. This result is consistent with expectations that the more hazardous a dam is the more likely it is to be removed. Lastly, the marginal effect for the dummy variable for dam construction material (earthen) was negative, suggesting earthen dams are less likely to be removed, on average, compared with other construction materials, but it did not meet the threshold for economic significance.

7 Conclusion

This thesis seeks to identify the factors that have contributed to historical dam removal decisions in the United States by performing the first empirical economic analysis of factors that may be influencing dam removals. Overall, this research did not conclude that a single factor or bundle of factors most influence dam removal, indicating that dam removals are largely determined on a case-by-case basis dependent on the specific environmental and socio-economic factors for an individual dam. Costs and benefits of dam removal vary for each location, dependent on environmental factors like stream geomorphology, sedimentation, and fish habitat, as well as socio-economic factors like permitting costs, alternatives, and public perceptions of the dam. This research also provided some evidence that social desires to restore riverine habitat may be influencing those benefit-cost calculations, leading to dam removals in areas with some threatened or endangered species.

Although all variables used for this analysis had small marginal effects, the signs of the effects were generally consistent with expectations. Dam age and height were found to be both statistically significant and some of the most influential explanatory variables. Additionally, this analysis provides evidence that being near Endangered Species Act listed critical habitat for fish, mammals, and birds increases the probability that a dam will be removed. There was also evidence that FERC relicensing is influencing dam removals, because hydroelectric dams are more likely to be removed than other types of dams. Consistent with prior studies, this analysis also found significant variation between individual U.S. states on the probability of dam removal. Results of this research can be used to inform the field dam removal research, because it was the first attempt to explain historical trends in dam removal based in economic theory and that estimated the probability of removal based on time-series data.

More dam specific variables are a way to potentially increase the explanatory power of future empirical analyses. Dams are highly heterogeneous, so there is a significant amount of variation between dams. Without having the specific data on the attributes of each dam, future empirical analysis will also be limited by the data. For example, owner type was missing for many of the removed dams, so the effects of this variable were inconclusive. Assuming that American Rivers will continue to maintain the Dam Removal Database (DRD), in the next few decades dam removal data will likely improve as it becomes more standardized and has a longer period for reference. Opportunities for improvement of the DRD are to match fields like owner-type and construction material type with the fields used in the NID to allow for improved comparison between the datasets. Methods to improve data collection on removed dams could be accomplished by expanding survey efforts to include stakeholders like soil and water conservation districts, as well as working with state agencies to improve dam removal tracking efforts. Costs of dam removal should also be defined and then tracked consistently based on which costs are included to provide an estimate of willingness to pay for dam removals. In addition, a federally-funded data collection effort on dam removal in conjunction with requirements that all dam removals be reported would likely increase the quality of the data and potential for more precise analysis.

The number of dams removed is likely to increase in the future due to the rising economic costs of maintaining dams and the continued imperilment of aquatic organisms. Assuming the FERC relicensing requirements stay at least as stringent as they are now, hydroelectric dams are likely to continue to be removed. Dams in the United States will also continue to age, becoming more hazardous and/or obsolete, which may further increase the rate of dam removal if they are not replaced. To the extent that society and interest groups value restoring natural riverine functionality, represented by the relative scarcity of undammed rivers and streams, dam removal will continue to occur.

However, there are also reasons why dam removal may not become more common in the future. As energy shifts to renewable resources, and carbon taxes become a possibility in the United States, dams may become more highly valued because they may emit lower greenhouse gas levels than alternatives like natural gas and coal. This change would increase the costs of removing dams, because the lost benefits from dams would be higher, decreasing the probability that they would be removed. Global trade has made transportation of goods relatively more expensive, and dams with locks may increase in value due to the transportation services they provide if trucking costs continue to increase and barging becomes a cost-effective substitute. Climate change may also increase demand for dams, decreasing the probability of removal, to the extent that water supplies for municipal and irrigation purposes become less secure and water storage and flood control are more highly valued.

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Appendix

Appendix A: Results from Robustness Checks

Variable	Model 3		RB 1 - After 1992		RB 2 - Larger than 25 ft		RB 3 - OLS		RB 4 - High Income	
	n	1,874,294	n	1,317,329	n	1,006,211	n	1,874,294	n	86,369
	dy/dx	P>|z|	dy/dx	P>|z|	dy/dx	P>|z|	dy/dx	P>|z|	dy/dx	P>|z|
real_income	-9.34E-09	0.015	-6.32E-09	0.131	-6.48E-08	0	-3.27E-08	0		
high_income									-0.0057744	0.009
hydro_prices	0.0000828	0	0.0000726	0	0.0000151	0	0.0005323	0	-0.0012532	0
cropval_pctinc	-7.53E-04	0.00	-0.0012945	0	-0.0021789	0	-0.0004418	0	-0.1623906	0
realfmlandval	-2.29E-08	0.002	-2.86E-08	0.001	3.95E-09	0.69	-7.80E-08	0	-1.18E-06	0
pop_density	1.66E-07	0.036	2.22E-07	0.01	-1.73E-07	0.182	8.32E-07	0.024	0.0000171	0
party	0.0001545	0.01	0.0002519	0	-0.0002102	0	0.0001515	0.013	0.0140708	0
owner1	7.02E-04	0.00	0.0006562	0	0.0011422	0	0.0007887	0	0.0317967	0
esa_snail_mi	5.34E-07	0.006	4.43E-07	0.039	1.19E-06	0	1.08E-06	0	0.0000175	0.023
esa_reptile_mi	4.44E-06	0	4.16E-06	0	1.58E-06	0	2.14E-06	0	-6.75E-06	0.343
esa_mammal_mi	2.51E-06	0	2.25E-06	0	1.27E-06	0	9.58E-07	0	0.0001468	0
esa_fish_mi	-5.51E-06	0	-4.78E-06	0	-1.57E-06	0	-2.02E-06	0	1.02E-07	0.993
esa_clams_mi	1.18E-06	0	9.83E-07	0	7.72E-07	0	-9.26E-07	0	0.0001696	0
esa_birds_mi	-1.55E-06	0	-8.63E-07	0.043	-1.13E-06	0.001	-1.03E-06	0.063	-0.0001406	0
esa_amphib_mi	1.48E-06	0	1.30E-06	0	5.12E-07	0.086	1.01E-06	0	0.0001474	0
age	2.15E-05	0	0.00002	0	0.0000125	0	0.0000413	0	0.001199	0
height	-2.22E-05	0.00	-0.0000201	0	-4.17E-06	0	-0.0000222	0	-0.0001579	0.003
hazardtype1	0.0001381	0.092	0.0001799	0.05	-0.000156	0.019	-0.0003799	0	0.0534678	0
hazardtype3	0.0008391	0	0.0007926	0	0.000165	0.018	0.0010539	0	0.0773997	0
hydrogen	-3.28E-08	0	-2.62E-08	0	1.26E-09	0.556	-1.76E-08	0.003	-1.12E-06	0
neardist	-4.18E-08	0	-4.76E-08	0	-9.71E-08	0	-3.06E-08	0	1.07E-06	0.109
damcount	-1.07E-05	0	-8.47E-06	0	-5.47E-06	0	-5.30E-06	0	-0.0003609	0
damtype8	-0.0005092	0	-0.000518	0	-0.0005555	0	-0.0012436	0	-0.0768201	0
area_water	4.49E-07	0	3.11E-07	0.005	1.78E-07	0.029	3.72E-06	0	0.000011	0.002
constant							0.0008005	0.001		