Predicting the Impact of Glacier Loss on Fish, Birds, Floodplains, and Estuaries in the Arctic National Wildlife Refuge

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Abstract

In this paper we explore the impacts of shrinking glaciers on downstream ecosystems in the Arctic National Wildlife Refuge. Glaciers here are losing mass at an accelerating rate and will largely disappear in the next 50–100 years if current trends continue. We believe this will have a measureable and possibly important impact on the terrestrial and estuarine ecosystems and the associated bird and fish species within these glaciated watersheds.

Keywords: glaciers, birds, fish, shrubs, arctic, climate

Climate-Driven Change of Glaciers and Its Potential Impact on Physical Hydrology

Glaciers throughout the Brooks Range are losing mass at a rate that is accelerating with time, and most will likely disappear in the next 50 years. Research on McCall Glacier in the eastern Brooks Range documents this accelerated ice loss over the past 50 years (Nolan et al. 2005). It is clear that glacial retreat began in the late 1800s in this region, following the strongest advance since the last glacial maximum. From at least the 1500s to the 1800s CE, these glaciers expanded by storing water from the annual precipitation cycle, but now they are losing this mass, discharging more water than current annual precipitation levels. A variety of modeling predicts disappearance of glaciers in the near future (Delcourt et al. 2008), largely driven by a rise in the late-summer snowline, such that in many recent years there is no remaining accumulation of the past winter's snow. On inland valley glaciers like these, the position of this snowline is likely to be 10 times more sensitive to air temperature than to precipitation (Oerlemans 2001), and our local records show greater changes in air temperature than in precipitation over the past 50 years. McCall Glacier is one of the five largest of the over 400 glaciers in the Arctic Refuge, with an area of about 6 km^2 and an average thickness of about 75 m (Pattyn et al. 2009). Average size of glaciers in the region is about 1 km^2 and likely less than 20 m thick. Our measurements here and at many other glaciers in the area indicate area-averaged ablation rates from 0.5 to 1.0 m/a. Thus, even without sophisticated modeling, it is clear the bulk of the glacial ice here will disappear soon, and our photo comparisons indicate that many glaciers already have disappeared in the past 50 years.

Table 1. Glacierized area as of 1956

	Glacier area (km^2)	Watershed area (km^2)	Percent
Jago	126	2,208	5.7
Okpilak	139	1,011	13.8
Hulahula	116	1,841	6.3
Sadlerochit	38	1,698	2.2

Table 1 summarizes glacierization (percentage of land covered by glacier ice) characteristics of the four most heavily glaciated watersheds in Arctic Alaska, all located within the Arctic National Wildlife Refuge. The average glacierization is 6.2 percent over the entire area, about the same as that in the Hulahula River. These percentages have been decreasing over time as glaciers shrink; we recently acquired new digital elevation models and air photos of nearly all of these glaciers, but as yet we do not yet have updated measurements. While these glaciated watersheds are

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not huge by Alaskan standards, they are still large and located within an ecologically-sensitive area that is expected to be especially vulnerable to the effects of climate change, as we hope to demonstrate in this paper.

Stream discharge here in summer is dominated by glacier meltwater, in contrast to the rest of Arctic Alaska. Nonglaciated watersheds in Arctic Alaska such as the Colville, Sagavanirktok, and Kuparuk Rivers (which collectively drain about 80,400 km^2 of the North Slope) typically issue an average of 61, 44, and 52 percent, respectively, of their annual discharge to the Beaufort Sea during two weeks of snowmelt in the spring (McClelland et al., in press). We installed a discharge gauge on the Hulahula River in fall 2010, but do not yet have a full year of measurements. In the meantime, we have compared rates of river contribution averaged over watershed area to determine relative contributions of precipitation versus glacial melt. Annual precipitation in Arctic Alaska is usually less than 30 cm/a, with roughly half falling as snow and melting in early June. Current glacier ablation rates are usually over 80 cm/a averaged over the glacier area, or roughly 5 cm/a averaged over the watershed areas (assuming 6.2 percent glacierization). So, the glacier contribution is in the same order of magnitude as rain and snow contributions, and after the spring freshet glaciers dominate flow compared to the infrequent rains, much of which gets intercepted during overland flow. As glacier ablation rates continue to rise because of increased warming, the fraction of water contributed by glaciers may initially increase. When glacier reserves are depleted, however, their contribution will plummet.

This paper represents the initial attempt by the authors to integrate our individual research projects to contribute to a multidisciplinary understanding of how climate-driven changes in glaciers may affect ecological trajectories over the next 50 years.

Potential Impacts on Riparian Ecosystems

We have some evidence that indicates that the spread of vegetation within the floodplains of these glaciated watersheds is limited by the geomorphological instability related to increasing glacial discharge. We attempted to assess the effect of glaciers on floodplain stability by comparing time series of vertical air photos at locations along a river fed primarily by glaciers (Jago River) to a river fed by nonglacial sources (Kongakut River). Old and new imagery was opportunistically acquired, and comparisons between images were made where spatial overlap occurred. None of the imagery was acquired when water levels were high so that no vegetation would lie undetected under water. In each area where repeat imagery was overlain, we created a single (virtual) transect zig-zagging from one side of the river to the other and placed points every 50 m along the transect. Transects ranged in length from 5,850 m to 22,850 m, totaling 70,650 m and consisting of 1,413 sample points. The placement of the transects was constrained by the available imagery but otherwise could be considered random within the floodplain; points not within the floodplain were excluded from this analysis.

Three of the five Kongakut River transects showed an increase in vegetation in the floodplain since acquisition of the old imagery (old images acquired between 1948 and 1982). Of the two remaining transects, one showed equal number of vegetated points in old and new imagery, and another contained no vegetation in the floodplain in old or new imagery (Ø). Overall, floodplain vegetation along the Kongakut River increased over time ($p < 0.05$). There was an insignificant positive downstream trend in percent change in vegetated floodplain points, which was 0 percent, Ø, +30 percent, +48 percent, and +33 percent. The single long reach of the Jago River assessed using this technique contained equal number of vegetated points in old and new imagery (0 percent change).

The increase in floodplain vegetation along the Kongakut River is similar to the trend observed in North Slope floodplains west of the Canning River (Tape et al. 2006). Possibly, a decrease in discharge or decrease in aufeis volume is causing the increase in vegetated bars along the Kongakut River. The absence of trend in the Jago River floodplain suggests that glaciated watersheds are not following the same trajectories, but our observations thus far are too limited to make conclusive generalizations. Work is currently in progress to acquire high-resolution air photos of both glaciated and nonglaciated rivers in this area to further assess the role of enhanced glacial discharge on vegetative-growth dynamics.

Potential Impact on Fish Ecology

The loss of glaciers and their meltwater may reduce instream connectivity and cause fish habitats to become fragmented, especially in late summer when anadromous Dolly Varden (*Salvelinus malma*) are returning from estuarine/marine areas to reach spawning and overwintering areas in these glaciated watersheds. As an integral part of the aquatic ecology of Alaska's North Slope, these fish are particularly vulnerable to the effects of climate change (Martin et al. 2009) and also support a number of subsistence fisheries (Pedersen and Linn 2005). Anadromous Dolly Varden occur in most of the larger drainages north of the Brooks Range (Viavant 2009), and like other fish in the region, these populations have adapted to habitats and physical conditions that include a short growing season, extensive ice cover, summer water temperatures <10°C, and long periods of darkness (Reist et al. 2006). During the spring freshet, the mature individuals migrate from overwintering areas in rivers to estuarine and marine waters for summer feeding (Viavant 2005). In glacial streams, these fish primarily return to freshwater in August when glacial meltwater provides adequate discharge to allow migration (Martin et al. 2009). Juvenile fish overwinter in their natal streams for 2–3 years before making their initial journey to saltwater (Fechhelm et al. 1997).

The population of anadromous Dolly Varden in the Hulahula River has been the focus of several studies from the 1970s through the 1990s (Viavant 2009), with more recent, complementary work providing detailed information about Dolly Varden abundance and behavior. Helicopter surveys of index areas in the river estimated relative abundance at 9,575 and 3,653 Dolly Varden in mid-September of 2007 and 2008, respectively (Viavant 2009). Another study used sonar to estimate number of Dolly Varden returning to the Hulahula River in fall: 10,412 fish in 2005; 7,471 in 2006 (Osborne and Melegari 2008); 23,158 in 2007; and 12,340 in 2008 (U.S. Fish and Wildlife Service, unpublished data). Subsequently, a radio telemetry study in 2007–08 identified overwintering at four sites (U.S. Fish and Wildlife Service, unpublished data). The telemetry study also showed that a small fraction of the fish overwintering in the Hulahula River in one year overwintered the following year in nearby streams. Genetic studies distinguished the Hulahula River population from other stocks and provided a basis for understanding stock-specific ecology (Crane et al. 2005). Thus, we have some evidence that these fish can explore alternatives when faced with changing river conditions and perhaps have a means to track that.

Several harvest assessments have noted the importance of Dolly Varden from the Hulahula River to the Kaktovik subsistence fishery (Pedersen and Linn 2005). From October 2000 to September 2002, all fishing efforts by village residents in early winter occurred in the Hulahula River, with Dolly Varden being the only species captured (Pedersen and Linn 2005). Users reported that three sites in the river are traditionally used, but two sites were noted as the most productive for winter Dolly Varden fishing. No summer fishing took place in the Hulahula River.

Although the information about Dolly Varden from the Hulahula River is not complete, the existing data provide the most focused and comprehensive set of information available about this species on the North Slope. More information of this kind that could be used to evaluate the importance of seasonal meltwater and the effects that the loss of glacier may have on these fish would guide future management of this resource and provide a foundation for modeling climate change effects on migratory species in other aquatic systems. An integrated, multidisciplinary approach that links Dolly Varden ecology with concurrent assessments of glacier characteristics and stream attributes will be critical for assessing the sustainability of this resource for future users on the North Slope.

Potential Impacts on Shorebird Ecology

In 2010 we investigated shorebird and invertebrate abundance on three deltas, two of which were associated with rivers that received significant inputs of glacial meltwater (Jago and Hulahula Rivers) and one that has little glacier influence (Canning River). Our preliminary analyses suggest the differences between deltas fed by glacial versus nonglacial rivers may influence patterns of shorebird use. Glacially influenced deltas had siltier substrates, and the lagoons around the deltas were less salty during the period when shorebirds used them. Freshwater occurred along two-thirds of the waters' edge of glacial-influenced deltas, but much less freshwater occurred in the delta not glacially influenced. Characteristic conditions found on the glacial deltas and in adjacent waters were likely caused by inputs of silt, clay, and freshwater from melting glaciers in the Brooks Range. The delta with little glacial influence is a branch of the Canning River, which appears to have very little freshwater output during the late summer. Conditions here may illustrate what could happen on some glacially influenced deltas once late-summer meltwater from glaciers is no longer present.

Tens of thousands of shorebirds migrate to coastal habitats of the Arctic National Wildlife Refuge after breeding on the Arctic Coastal Plain of northern Alaska and Canada, and habitat differences apparently affect availability of shorebird food resources. The greatest concentrations of shorebirds are found on mudflats associated with river deltas, which provide important foraging habitat for post-breeding shorebirds (Taylor et al. 2010). Shorebirds likely depend on these delta mudflats for food resources to begin migration. For some species, food requirements are further increased during this period because of the molting of new flight feathers.

Two groups of freshwater invertebrates, Oligochaeta and Chironomidae, were more abundant in the silty habitats of glacial-fed deltas. The nonglacial delta had low invertebrate abundance, presumably due to the absence of freshwater invertebrates in the sandier and saltier habitats found there. Invertebrate abundance remained low on this delta until a storm surge deposited saltwater invertebrates (Amphipoda) on the mudflat. The life histories of freshwater versus saltwater invertebrates differ, with implications for shorebirds. For example, freshwater species spend multiple years in mudflat habitats (Butler 1982, Danks et al. 1994), while occurrence of saltwater invertebrates is unpredictable. Chironomid larvae spend at least three years in mudflats before pupating and turning into adults. Larvae that are present in mudflats for multiple years provide a more predictable and stationary food resource than those of species with a yearly life cycle or species that are mobile. For example, saltwater invertebrates like Amphipoda retreat from mudflats each winter (Evans 1976, Craig et al. 1984) when the mud freezes. In the summer amphipods are generally unavailable to foraging shorebirds until they are washed onto mudflats by storm surges and become stranded in puddles. Because storm surges are unpredictable events, we consider saltwater invertebrates to be a less dependable resource for shorebirds.

In 2010, we sampled triglyceride levels in semipalmated sandpipers (*Calidris pusilla*) early in the post-breeding season before the occurrence of any storm surges. Triglyceride levels provide a measure of fattening rates (Williams et al. 1999, Guglielmo et al. 2002). We found triglyceride levels were higher for birds feeding on the glacially influenced deltas compared to mudflats without glacial influence. We assume the difference was due to the low abundance of invertebrates on the delta without glacial influence. Soon after our sampling a storm surge occurred, coinciding with a pulse in shorebird migration. After the water levels dropped we observed thousands of shorebirds feeding on both saltwater and freshwater invertebrates on all three deltas. It appears that shorebirds utilize saltwater food resources opportunistically, but they rely on freshwater invertebrates as a more consistent resource.

There had been little previous research on the relationships between shorebirds, invertebrates, and delta mudflats along the coast of the Arctic Refuge. Our work suggests that glacially influenced deltas in particular provide an important resource for post-breeding shorebirds. Loss of Brooks Range glaciers will likely lead to decreases in sediment transport and freshwater inflow in rivers that are currently influenced by glaciers. These decreases in turn are likely to result in sandier delta mudflats and saltier lagoons, with potential implications for invertebrates and the birds that feed on them. Our observation that deltas with no glacial influence lack freshwater invertebrate species suggests that these species will disappear in currently glaciated watersheds as their mudflats become sandier and saltier with the loss of glacial meltwater and silt. Therefore, we hypothesize that loss of glaciers will have a negative impact on shorebirds as they prepare for migration, and we plan to investigate this further.

Potential Impacts on Marine Foodwebs

Glacier loss could impact estuarine ecosystems within the Arctic National Wildlife Refuge by altering the quantity, quality, and seasonality of river inputs. For example, differences between river inputs with and without significant glacier influence may be important in determining amounts and pathways of terrestrial carbon and nitrogen movement through coastal food webs. A comparison of stream and river water chemistry among catchments with different percentages of glacier coverage in southeastern Alaska demonstrated that concentrations of dissolved inorganic nitrogen are negatively correlated with glacier coverage whereas concentrations of soluble reactive phosphorus are positively correlated with glacier coverage (Hood and Berner 2009). Bioavailability of dissolved organic matter is also positively correlated with glacier coverage (Hood et al. 2009). If the correlations described above hold true for glacier-fed streams and rivers within the Arctic Refuge, then the glaciers may be a particularly important source of soluble reactive phosphorus and labile dissolved organic matter in mid to late summer that is not available in rivers without significant glacier inputs.

Although concentrations of dissolved inorganic nitrogen were negatively correlated with glacier coverage in the Hood and Berner (2009) study, it should be noted that high nitrate concentrations have been linked to glaciers and (or) proglacial features in some other studies (Apollonio 1973, Hood and Scott 2008). Thus, robust conclusions about the importance of glacier-fed streams and rivers as sources of nutrients and organic matter to coastal waters of northern Alaska will ultimately require focused studies in this region. We can expect glacier loss to be accompanied by a general decrease in mid to late summer export, including a decrease in relatively labile dissolved organic matter associated with microbial activity within and beneath glaciers (Hodson et al. 2005), but specific trajectories of individual waterborne constituents remain uncertain.

While we now recognize that terrestrial organic matter inputs to the Arctic Ocean are larger and more labile than previously thought, many questions remain about the influence of these inputs on food webs. Is terrestrial organic matter a major energy source supporting metazoan consumers, or is most of the energy from terrestrial organic matter lost during microbial processing? Does decomposition of terrestrial organic matter serve as a source of or a sink for inorganic nitrogen in coastal waters? Most of the labile river-supplied organic matter delivered to coastal waters probably enters the microbial food web. Yet, a recent study by Dunton et al. (2006) provides evidence of significant carbon and nitrogen from terrestrial organic matter making it into Arctic cod collected from lagoons along the northern Alaska coast. This finding suggests that either there is a strong link between the microbial and metazoan food webs or there is a direct pathway for terrestrial organic matter into the metazoan food web. In order to effectively predict how productivity in arctic coastal waters may be influenced by future climate change, we need to gain a better understanding of how terrestrial inputs contribute to coastal food webs under current conditions. Present contributions and future losses of glacier inputs may be particularly important within the Arctic National Wildlife Refuge.

Discussion

There are many uncertainties regarding climate change and its impact on Arctic landscapes and ecosystems, but we believe we have identified a straightforward and testable hypothesis linking these together. Glaciers here exist solely at the mercy of climate, unlike tidewater glaciers that have strong nonclimatic influences and major ice sheets that can influence their own climate; a 1–2ºC warming has caused them to enter a trajectory where they will likely disappear in the near future. Even if climate remains constant from this time forward, most glacier ice here will disappear because the late-summer snowline is higher than the elevation of most of the mountains. While direct effects of current climate change on fish and birds may be subtle and difficult to detect, the indirect effects on downstream ecosystems caused by the loss of glacial meltwater and silt may be enormous and predictable. Thus we hypothesize that loss of glaciers in the Arctic National Wildlife Refuge will exert strong influence on downstream ecosystems, affecting fish, birds, shrubs, and marine ecology. In this paper we have attempted to share what we know of these influences and predict future trajectories. We are just beginning to investigate relationships between climate, glaciers, and ecology in this region, and we welcome input from the broader scientific community as we pursue this work.

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Land Use and Salmon Habitat: A Comparison of North Pacific Watershed Parameters

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Abstract

Links between land use and freshwater habitat have been demonstrated in diverse studies, most focusing on one area, one time period, or comparisons among small drainages. This meta-analysis combined varied data sources to examine linkages between land use and the status of salmonid stocks on the North American coast from San Francisco Bay, California, to Bristol Bay, Alaska. To focus on land use only, the sample consisted of 61 midsized, coastal watersheds (approximately 500–60,000 km^2) and excluded basins where manmade dams blocked more than 20 percent of the drainage area. To quantify human influence on the landscape, the parameters percentage of forest cover, road density, percentage of total impervious area, human population density, and the composite Human Footprint Index (from Columbia University's Socioeconomic Data and Applications Center) were used as indicator metrics. To quantify salmon stock health, fisheries assessments of stock status for *Oncorhynchus* populations were evaluated and combined to create an index of salmonid status for each sample watershed. Linear regression showed that the human development metrics correlated. Comparison between the development parameters and the index of salmonid status showed a significant inverse relationship. Because the underlying data lack rigor and the systems are so complex, the relationship is suggestive rather than definitive. Developing better data for such parameters and monitoring them over time could provide useful information for science, fisheries management, and land use planning in the region.

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Evaluating Biodiversity Response to Forecasted Land Use Change: A Case Study in the South Platte River Basin, Colorado

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Abstract

Effects of future land use change on watersheds have important management implications. Seamless, national-scale land-use-change scenarios for developed land were acquired from the U.S. Environmental Protection Agency Integrated Climate and Land Use Scenarios (lCLUS) project and extracted to fit the South Platte River Basin, Colorado, relative to projections of housing density for the period 2000 through 2100. Habitat models developed from the Southwest Regional Gap Analysis Project were invoked to examine changes in wildlife habitat and biodiversity metrics using five ICLUS scenarios. The scenarios represent a U.S. Census base-case and four modifications that were consistent with the different assumptions underlying the A1, A2, B1, B2 Intergovernmental Panel on Climate Change global greenhouse gas emission storylines. Habitat models for terrestrial vertebrate species were used to derive metrics reflecting ecosystem services or biodiversity aspects valued by humans that could be quantified and mapped. Example metrics included richness of species of greatest conservation need, threatened and endangered species, harvestable species (e.g., upland game, big game), and total vertebrate species. Overall, the defined scenarios indicated that housing density and extent of developed lands will increase throughout the century with a resultant decrease in area for all species richness categories. The A2 Scenario in general showed greatest effect on area by species richness category. Areas with low or high species richness were projected to experience the greatest declines. The integration of the land use scenarios with biodiversity metrics derived from deductive habitat models may prove to be an important tool for decisionmakers involved in impact assessments and adaptive planning processes.

Keywords: deductive habitat models, wildlife habitat, biodiversity metrics, ecosystem services, land use scenarios, South Platte River Basin

Introduction

While many direct and indirect stressors can affect biodiversity, land use change is considered to be the most significant (Sala et al. 2000, Mattison and Norris 2005, Swetnam et al. 2010). Land use and land cover change are two processes that have consequences on a global scale and are driven by population trends and urban growth (Bierwagen et al. 2010). The United States population is projected to be between 402 and 616 million in 2090, an increase of 31–55 percent from 2000 (U.S. Environmental Protection Agency 2010).

The U.S. Environmental Protection Agency (EPA) has investigated the future impacts of population growth and urban development in depth. The Integrated

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Climate and Land Use Scenarios (ICLUS) dataset was created by the EPA to address the potential scenarios of population growth and housing development from 2000 to 2100 (U.S. Environmental Protection Agency, Bierwagen et. al 2010).

The U.S. Geological Survey Gap Analysis Program (GAP) has developed datasets for biodiversity conservation purposes in the continental United States (Prior-Magee et al. 2007). The GAP process provides landscape-level assessment for the conservation of biological diversity. GAP maps the distribution of plant communities and predicts the distribution of suitable habitat for terrestrial vertebrate species and compares these distributions with land stewardship to identify biotic elements at potential risk of endangerment. The baseline datasets GAP provides are uniquely suited for use with biodiversity assessments at broad multiple scales. The Southwest Regional Gap Analysis Project (SWReGAP) provides these datasets for the American Southwest states of Arizona, Colorado, Nevada, New Mexico, and Utah (Prior-Magee et al. 2007).

Evaluating the effect of urban encroachment and development on biodiversity is becoming increasingly important. Synthesis and analysis of future land use scenarios using datasets such as the ICLUS and SWReGAP habitat models are valuable to science and the future of conserving biodiversity, especially for informing land managers and decisionmakers about potential consequences and benefits of environmental management choices.

Study Area

The South Platte River Basin ranges from the plains of western Nebraska, eastern Colorado, and Wyoming to the mountains of the Front Range in Colorado (Figure 1). Within the South Platte River Basin are many rapidly growing cities, such as Denver and Fort Collins, Colorado, each with increasing pressures on terrestrial and aquatic environments caused by land use change and water development. This area has a projected population growth exceeding 50 percent by 2050 (U.S. Census Bureau 2005), suggesting continued growth and land use change in the future.

Overall, the South Platte River Basin spans 62,580 km^2 with vegetation ranging from grasslands in the plains to mixed conifer forests in the mountains. The study area comprised the portion of the basin within Colorado due to the availability of spatial data and habitat models from SWReGAP (Figure 1). Of the 49,030 km^2 within Colorado, approximately 28 percent is classified as agriculture, 22 percent as Rocky Mountain Ponderosa Pine, and 7 percent as Western Great Plains Sandhill Shrubland (Prior-Magee et al. 2007).

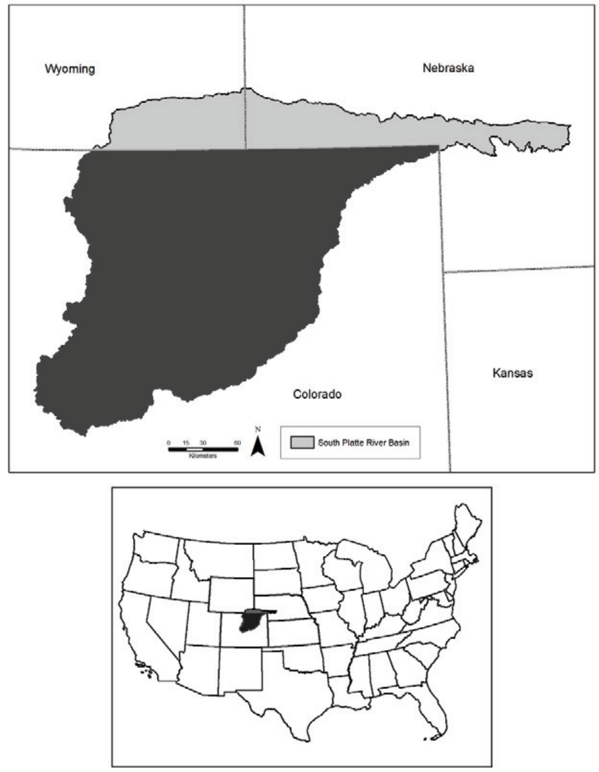


Figure 1. Location and extent of the study area (black) within the South Platte River Basin (black and grey).

Methods

The EPA-ICLUS (Version 1.3.1) dataset was used to assess habitat change and effects on biodiversity metrics. These seamless, national-scale land-use-change scenarios for developed land were acquired from EPA's Office of Research and Development (U.S. Environmental Protection Agency 2010). The data were extracted from the national coverages for the South Platte River Basin. This dataset allowed for analysis of projections of housing density for the period 2000 through 2100 for the five ICLUS scenarios, including a U.S. Census baseline and four modifications consistent with the different assumptions underlying the A1, A2, B1, and B2 Intergovernmental Panel on Climate Change (IPCC) global greenhouse gas emission storylines (Table 1; Bierwagen et al. 2010). The five ICLUS datasets were reclassified to identify urban (1) or nonurban areas (0).

For this analysis we characterized 4 biodiversity metrics of 17 available (Table 2). These were total vertebrate species richness (maximum=239), state designated Species of Greatest Conservation Need (SGCN) richness (maximum=98), federally Threatened and Endangered (T&E) species richness (maximum=12), and all harvestable species (e.g., upland game, big game) richness (maximum=50). The remaining 13 biodiversity metrics will be examined in subsequent study.

Table 1. EPA land-use-change scenarios for the conterminous United States (Bierwagen et al. 2010).

Scenario	Description
Baseline condition (BC)	Represents a level of medium fertility rates, medium domestic migration, and medium international migration.
A1	Represents fast economic growth, low population growth, and high global integration. Fertility is low with high domestic and international migration.
B1	Represents a globally integrated world but with more emphasis on environmentally sustainable economic development. Fertility and domestic migration are low while international migration is high.
A2	Represents continued economic development, with more regional focus and slower economic convergence between regions. Fertility and domestic migration are high and international migration is medium.
B2	Represents a regionally-oriented world of moderate population growth and local solutions to environmental and economic issues. Fertility rates are medium with low domestic migration and medium international migration.

The four biodiversity metrics were derived from 817 terrestrial vertebrate habitat models developed from SWReGAP (Boykin et al. 2007, 2010). We categorized each metric into four equal intervals of species richness (Appendix A).

Using ESRI ArcGIS 10, the current (year 2000) condition was characterized for the four biodiversity metrics. Current condition provides a baseline comparison for subsequent scenarios. The areas of each species richness category for each biodiversity metric were then quantified for nonurban land cover using the five ICLUS future development scenarios. ICLUS classified areas with housing density greater than 0.8 hectares per housing unit as nonurban (EPA 2010). The change in square kilometers and relative change of land classified as urban and nonurban were calculated and compared among the 5 future development scenarios for the year 2100. This change analysis allowed for examination of biodiversity metrics under each scenario.

Table 2. List of 17 available biodiversity metrics for species richness derived from the Southwest Regional Gap Analysis Project (Prior-Magee et al. 2007). Metrics in italics were used in the present study.

Biodiversity metrics
All vertebrate species
Reptiles
Amphibians
Birds
Mammals
Threatened and Endangered species
All Species of Greatest Conservation Need
Reptile Species of Greatest Conservation Need
Amphibian Species of Greatest Conservation Need
Bird Species of Greatest Conservation Need
Mammal Species of Greatest Conservation Need
All harvestable species
Harvestable upland game species
Harvestable big game species
Harvestable furbearer species
Harvestable waterfowl species
Bat Species of Greatest Conservation Need

Results

Ninety-seven percent of the South Platte River Basin study area was classified as nonurban using the Baseline 2000 Scenario (Table 3). This extent decreased by 2100 in all scenarios to 92–94 percent, with scenario A2 decreasing the greatest. The majority of area classified as nonurban within the study area was associated with species richness categories 2 and 3 (Figure 2).

Table 3. Nonurban and urban area (km^2) and percent (%) of total for baseline 2000 and five future land-use-change scenarios (A1, A2, B1, B2, and BC; see text)

	Nonurban		Urban	
	(km2)	(%)	(km2)	(%)
Baseline 2000	47,425	97	1,523	3
A1 2100	45,708	93	3,240	7
A2 2100	44,873	92	4,074	8
B1 2100	46,219	94	2,729	6
B2 2100	45,852	94	3,095	6
Baseline 2100	45,867	94	3,081	6

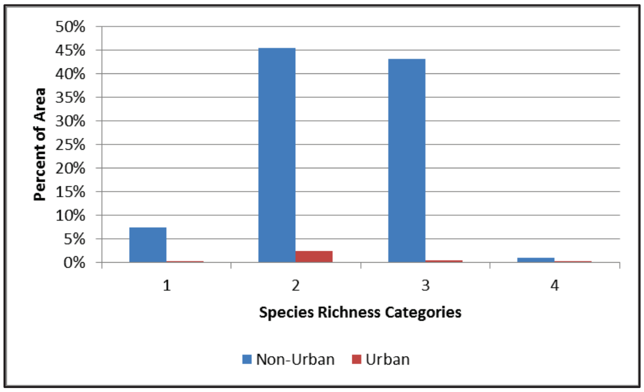


Figure 2. Percent of urban or nonurban area within the South Platte study area by total vertebrate species richness category for the baseline 2000 reference condition. Categories range from 1 (lowest richness) to 4 (highest richness; Appendix A).

A reduction in area based on predicted suitable habitat was identified for all species richness categories for all biodiversity metrics in all scenarios (Figures 3A–D). The decrease in area ranged from 1 to 12 percent. The A2 Scenario resulted in the greatest decreases with 7 of the category-metric comparisons resulting in a 7 percent or greater change. The A2 Scenario represents continued economic growth, high population growth and high domestic and medium international migration.

Species richness categories 1 and 4 had the highest decreases in total species richness, SGCN richness and T&E richness (Figure 3A–D). Thus, the analysis suggests that the most species rich (category 4) and species poor (category 1) areas will be detrimentally affected by urbanization. Each species categories contained equal number of species; however the amount of area for these categories was quite different (Figure 2). Categories 1 and 4 had a very small extent in 2000 (Figure 2), and thus small changes in area lost can have large effects on the percentage of area lost for these categories.

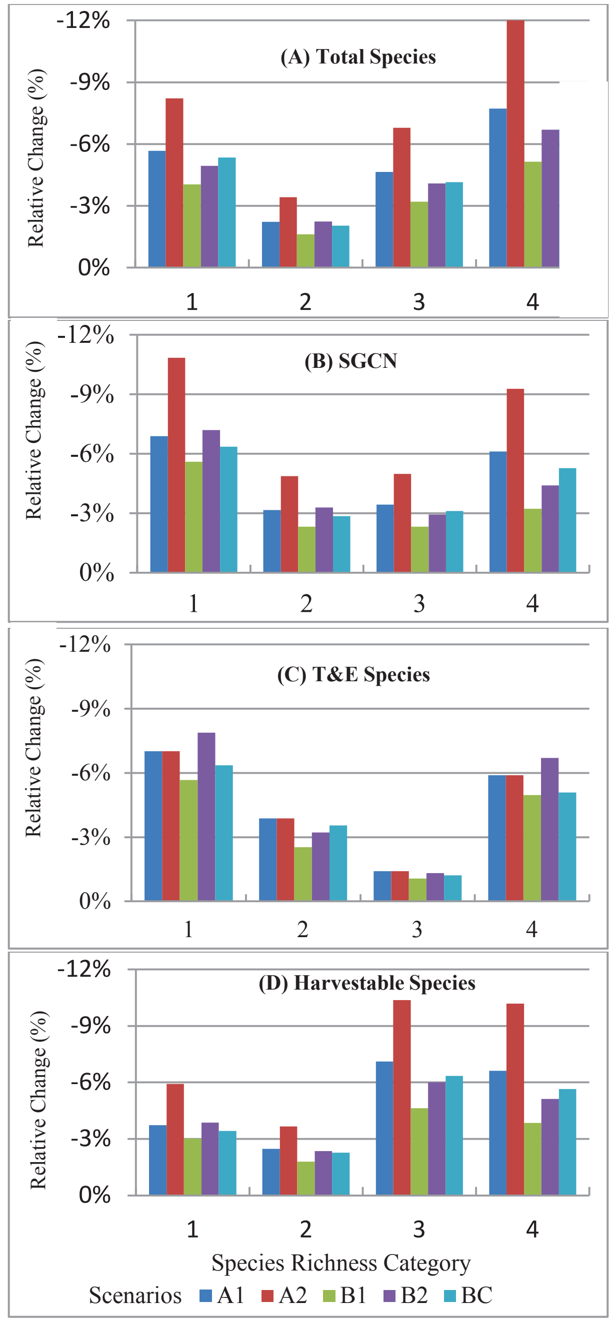
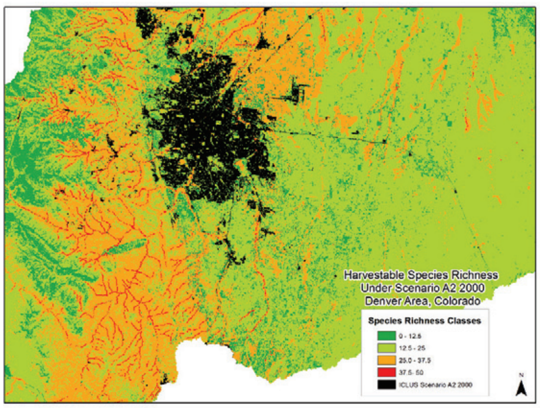


Figure 3. Relative change (%) in extent of nonurban land cover to 2100 across five future land use change scenarios within four species richness categories for (A) total vertebrate species (B) Species of Greatest Conservation Need (SGCN), (C) Threatened and Endangered species, and (D) harvestable species. Future change scenarios were A1, A2, B1, B2, and BC (see text). The four species richness categories range from 1 (lowest richness) to 4 (highest richness; Appendix A).

Harvestable species showed a different pattern for relative change by species richness categories under the 5 scenarios in comparison to the other three species richness metrics. Specifically, richness categories 3 and 4 showed the greatest extents of declines rather than categories 1 and 4 (Figure 3D). This resulted from categories 3 and 4 being well represented in areas of projected urban growth. The spatial pattern of harvestable species (Figure 4) identifies an abundance of categories 3 and 4 occurring near Denver and the cities of the Front Range. Urban growth also affects a large portion of Category 2 south of Denver; however, this is a smaller percentage of this category.

A



B

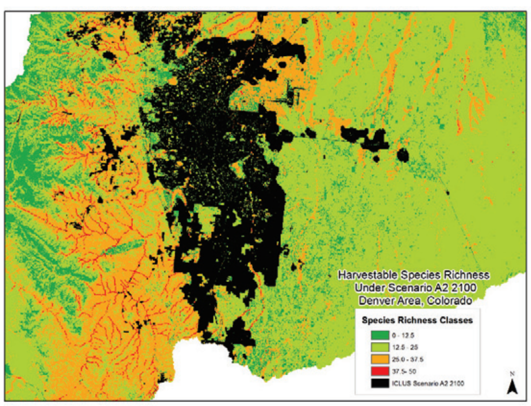


Figure 4. Distribution of harvestable species richness categories for current urban extent from Baseline 2000 (A) and future urban extent from A2 Scenario 2100 (B) surrounding Denver, Colorado within the South Platte River Basin study area.

Conclusions

The analysis indicated declines in nonurban extent over the next century. This change is projected to result in decreases in extent of area for all species richness categories for the four metrics examined: total vertebrate species, Species of Greatest Conservation Need, Threatened and Endangered species, and harvestable species. Among the five climate change scenarios, Scenario A2 presents the greatest increase in urban growth both in percent change and total area. Areas with low or high species richness are projected generally to experience the greatest declines. Areas with suitable habitat for high numbers of harvestable species will be affected by this urban growth.

Our purpose was to integrate available land use scenarios with deductive habitat models to provide an important tool for decisionmakers involved in impact assessments and adaptive planning processes across a variety of environmental management sectors. This initial analysis will be followed by future work on the remaining 13 biodiversity metrics (Table 2) and in different geographies to test transferability of the process.

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Appendix A

Extent and change in land cover types from the baseline scenario in 2000 for five climate change scenarios, four biodiversity metrics, and four categories of species richness (1, low; 4, high). Biodiversity metrics were species richness for total vertebrate species, Species of Greatest Conservation Need (SGCN), Threatened and Endangered (T&E) species, and harvestable species. For nonurban and urban "% of total" refers to percent of total land cover in study area. Relative change (%) refers to area of nonurban land cover in scenario relative to area of nonurban land cover in Baseline Scenario 2000.

	Total vertebrate species				SGCN species				T&E species				Harvestable species			
Species richness category (number of species)	1 (4–59)	2 (60–119)	3 (120–179)	4 (180–239)	1 (1–24)	2 (25–49)	3 (50–74)	4 (75–98)	1 (0–3)	2 (4–6)	3 (7–9)	4 (10–12)	1 (0–12)	2 (13–24)	3 (25–37)	4 (38–50)
Baseline Scenario 2000																
Nonurban (km^2)	3,590	22,229	21,105	501	3,010	12,214	31,555	646	6,276	27,959	13,090	100	5,800	31,405	9,694	526
Urban (km^2)	96	1,184	228	15	351	1,011	154	7	1,283	174	64	2	373	1,030	112	7
Nonurban (% of total)	7%	45%	43%	1%	6%	25%	64%	1%	13%	57%	27%	0%	12%	64%	20%	1%
Urban (% of total)	0%	2%	0%	0%	1%	2%	0%	0%	3%	0%	0%	0%	1%	2%	0%	0%
A1 Scenario 2100																
Nonurban (km^2)	3,387	21,734	20,125	462	2,802	11,829	30,471	607	5,836	26,874	12,904	94	5,584	30,629	9,005	492
Urban (km^2)	302	1,680	1,205	53	560	1,397	1,236	46	1,725	1,257	251	7	590	1,807	801	42
Nonurban (% of total)	7%	44%	41%	1%	6%	24%	62%	1%	12%	55%	26%	0%	11%	63%	18%	1%
Urban (% of total)	1%	3%	2%	0%	1%	3%	3%	0%	4%	3%	1%	0%	1%	4%	2%	0%
Relative change (%)	–6%	–2%	–5%	–8%	–7%	–3%	–3%	–6%	–7%	–4%	–1%	–6%	–4%	–2%	–7%	–7%
A2 Scenario 2100																
Nonurban (km^2)	3,295	21,468	19,670	440	2,683	11,620	29,985	586	5,836	26,874	12,904	94	5,457	30,256	8,688	473
Urban (km^2)	393	1,946	1,660	75	679	1,606	1,723	67	1,725	1,257	251	7	717	2,180	1,117	60
Nonurban (% of total)	7%	44%	40%	1%	5%	24%	61%	1%	12%	55%	26%	0%	11%	62%	18%	1%
Urban (% of total)	1%	4%	3%	0%	1%	3%	4%	0%	4%	3%	1%	0%	1%	4%	2%	0%
Relative change (%)	–8%	–3%	–7%	–12%	–11%	–5%	–5%	–9%	–7%	–4%	–1%	–6%	–6%	–4%	–10%	–10%
B1 Scenario 2100																
Nonurban (km^2)	3,445	21,869	20,430	475	2,841	11,930	30,822	625	5,921	27,253	12,951	95	5,625	30,842	9,245	506
Urban(km^2)	243	1,545	901	40	522	1,295	885	27	1,641	879	204	7	548	1,593	561	27
Nonurban (% of total)	7%	45%	42%	1%	6%	24%	63%	1%	12%	56%	26%	0%	11%	63%	19%	1%
Urban (% of total)	0%	3%	2%	0%	1%	3%	2%	0%	3%	2%	0%	0%	1%	3%	1%	0%
Relative change (%)	–4%	–2%	–3%	–5%	–6%	–2%	–2%	–3%	–6%	–3%	–1%	–5%	–3%	–2%	–5%	–4%
B2 Scenario 2100																
Nonurban (km^2)	3,413	21,730	20,242	467	2,793	11,812	30,630	618	5,782	27,060	12,917	93	5,576	30,666	9,112	499
Urban (km^2)	275	1,684	1,088	48	570	1,413	1,078	35	1,779	1,071	237	8	598	1,770	694	34
Nonurban (% of total)	7%	44%	41%	1%	6%	24%	63%	1%	12%	55%	26%	0%	11%	63%	19%	1%
Urban (% of total)	1%	3%	2%	0%	1%	3%	2%	0%	4%	2%	0%	0%	1%	4%	1%	0%
Relative change (%)	–5%	–2%	–4%	–7%	–7%	–3%	–3%	–4%	–8%	–3%	–1%	–7%	–4%	–2%	–6%	–5%
Baseline Scenario 2100																
Nonurban (km^2)	3,398	21,774	20,228	467	2,818	11,866	30,571	612	5,877	26,966	12,930	95	5,602	30,690	9,079	497
Urban (km^2)	290	1,640	1,103	48	544	1,359	1,136	41	1,684	1,166	225	7	572	1,746	727	37
Nonurban (% of total)	7%	44%	41%	1%	6%	24%	62%	1%	12%	55%	26%	0%	11%	63%	19%	1%
Urban (% of total)	1%	3%	2%	0%	1%	3%	2%	0%	3%	2%	0%	0%	1%	4%	1%	0%
Relative change (%)	–5%	–2%	–4%	–7%	–6%	–3%	–3%	–5%	–6%	–4%	–1%	–5%	–3%	–2%	–6%	–6%

Modeling Impacts of Environmental Change on Ecosystem Services across the Conterminous United States

P. Caldwell, G. Sun, S. McNulty, E. Cohen, J. Moore Myers

Abstract

Climate model projections suggest that there will be considerable increases in temperature and variability in precipitation across the conterminous United States during the next 100 years. These changes in climate coupled with changes in land use and increases in human population will likely have a significant effect on water resources, carbon fluxes, biodiversity, and the services they provide. As society reacts to changing environmental conditions, the adaptation and mitigation strategies for one ecosystem service could come at the expense of another. It is critical that planning tools be developed to evaluate these tradeoffs between ecosystem services so that sound management decisions may be made in the face of climate, economic, and demographic change. This paper presents the Water Supply Stress Index–Carbon & Biodiversity model (WaSSI-CB) and demonstrates its potential for predicting changes in water supply and demand, carbon dynamics, and potential biodiversity under multiple stresses. The core of WaSSI-CB is a water balance model (WaSSI) that is sensitive to land cover and climate and operates on a monthly time step at the 8-digit hydrologic unit code (HUC) watershed scale across the conterminous United States. Annual U.S. Geological Survey water demand estimates are adjusted for population, disaggregated to the monthly scale, and compared to groundwater and surface water supply to assess water supply stress. Gross ecosystem productivity, ecosystem respiration, and net ecosystem carbon exchange are estimated using actual evapotranspiration. Similarly, potential biodiversity of reptiles, birds, amphibians, mammals, vertebrates, and tree distribution and abundance are estimated as a function of evapotranspiration. We show how the model may be used to predict the effects of climate, population, and land cover change on water resources and carbon fluxes in the next 50 years using downscaled monthly future scenarios, population projections, and hypothetical changes in land cover. Finally, the paper explores tradeoffs among management strategies for these ecosystem services.

Keywords: water supply, water demand, carbon sequestration, biodiversity, climate change

Introduction

Increasing water use in the United States has led to widespread hydrologic manipulation and consumptive off-stream water use, practices that alter river flows (Vörösmarty et al. 2004), threaten the sustainability of the resource (Alcamo et al. 2003), and degrade ecosystem function (Carlisle et al. 2010). Future changes in climate will place additional pressure on freshwater supplies (Bates et al. 2008). The effect of these stressors will be highly variable over both time and space, making it difficult to assess effects on water resources into the future.

Like water supply, carbon sequestration and biodiversity are valuable ecosystem services that are vulnerable to the effects of climate change and human activities (Nemani et al. 2003, Beer et al. 2010). Carbon sequestration, or net ecosystem exchange (NEE), is the difference between ecosystem respiration (Re) from autotrophs and heterotrophs and gross ecosystem productivity (GEP), or photosynthetic assimilation of carbon by foliage. When NEE for an ecosystem is negative, the ecosystem is a net carbon sink. When NEE is positive, the ecosystem is a net source of carbon. Ecosystem water use, or evapotranspiration (ET), is tightly coupled with ecosystem productivity (Law et al. 2002, Sun et al. 2011 a) and biodiversity (Currie and Paquin 1987, Currie 1991). As a result, NEE and biodiversity can be predicted based on ET, and the factors that affect ET

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(e.g. climate change, land use change) will also have an effect on NEE and biodiversity. Managing an ecosystem to enhance NEE or biodiversity will result in reduced residual water supply for human use because NEE and biodiversity increase with increasing ET.

Management tools are needed that can evaluate the tradeoffs between these ecosystem services at multiple spatial and temporal scales in the United States. Unfortunately, there are few integrated models of water supply and demand, carbon dynamics, and biodiversity with which to evaluate the effect of climate, land cover, and population change or the tradeoffs between management strategies for these ecosystem services. The U.S. Department of Agriculture Forest Service has developed the Water Supply Stress Index–Carbon & Biodiversity model (WaSSI-CB) that is intended to fill this need. The model can be used to project the effects of global change on water supply stress, carbon sequestration, and potential biodiversity across the conterminous United States at the 8-digit hydrologic unit code (HUC) watershed scale (Sun et al. 2008, Sun et al. 2011 a). In this paper, we apply the WaSSI-CB model to project the effects of population, land cover, and climate change on water supply, carbon sequestration, and potential biodiversity, and we explore tradeoffs among management strategies for these ecosystem services.

Methods

The core of WaSSI-CB is a monthly water balance model (WaSSI) that is sensitive to land cover and climate, computing the water balance for each of eight land cover classes independently in the approximately 2,100 8-digit HUC watershed scale across the conterminous United States. Evapotranspiration (ET), infiltration, soil storage, snow accumulation and melt, surface runoff, and baseflow processes are accounted for within each basin based on spatially explicit 2001 MODIS land cover (Figure 1), and discharge (Q) is conservatively routed through the stream network from upstream to downstream watersheds. ET is estimated with an empirical equation based on multisite eddy covariance ET measurements using MODIS derived monthly leaf area index (LAI), potential ET (PET_{hamon}), and precipitation (PPT) as independent variables (Sun et al. 2011 a, b). Estimation of infiltration, soil storage, and runoff are accomplished through the integration of algorithms from the Sacramento Soil Moisture Accounting Model and STATSGO-based soil parameters (Koren et al. 2003).

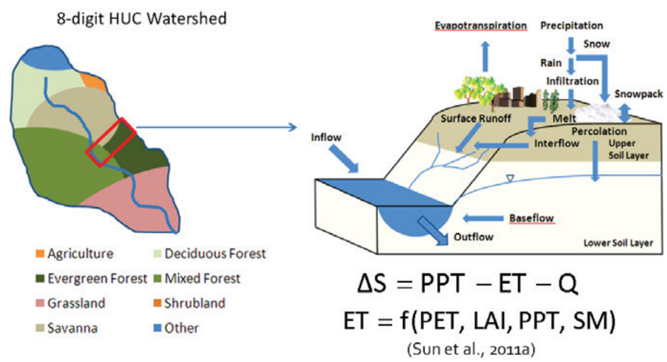

Figure 1. Schematic of the hydrologic processes simulated by the WaSSI-CB model.

Ecosystem GEP, Re, and NEE are estimated using actual evapotranspiration (AET) and water use efficiency parameters (Table 1) that were derived from measured site-level water and carbon fluxes for a variety of land cover types monitored by the FLUXNET (Sun et al. 2011 a).

Similarly, potential biodiversity of reptiles, birds, amphibians, mammals, vertebrates, and tree species richness are estimated as a function of PET and AET (Table 2; Currie and Paquin 1987, Currie et al. 1991).

While WaSSI-CB was designed to make projections regarding the potential diversity of multiple groups of biota, this paper focuses on tree species richness. The effects of development, habitat fragmentation, and forest management were neglected to simplify this hypothetical study, and HUC watersheds where total forest cover (sum of deciduous, evergreen, mixed forest, and savanna) was less than 10 percent of the total watershed area were excluded.

Table 1. Model parameters for estimating GEP as a function of AET, GEP = a*AET [g $C/m^2/mo$] and Re as a function of GEP, Re = m + n*GEP [g $C/m^2/mo$], after Sun et al. (2011 a).

Land cover class	a	m	n
Crop	3.13	40.6	0.43
Deciduous	3.2	30.8	0.45
Evergreen	2.46	9.9	0.69
Mixed forest	2.74	24.4	0.62
Grassland	2.12	18.9	0.64
Shrubland	1.35	9.7	0.56
Savanna	1.26	25.2	0.53
Water/urban/barren	1.53	9.7	0.56

Table 2. Model parameters for estimating potential biodiversity as a function of annual PET or AET, after Currie and Paquin (1987) and Currie et al. (1991).

Group	Model
Birds	1.40+0.00159*PET (PET<525 mm)
	2.26–0.0000256*PET (PET≥525 mm)
Mammals	1.12[1.0–exp(–0.00348*PET)]+0.653
Amphibians	0 (PET<200 mm)
	3.07[1.0–exp(–0.00315*PET)]
Reptiles	0 (PET<400 mm)
	5.21[1.0–exp(–0.00249*PET)]–3.347
Vertebrates	1.49[1.0–exp(–0.00186*PET)]+0.746
Trees	185.8/[1.0+exp(3.09–0.00432*AET)]

County-level 2005 annual U.S. Geological Survey (USGS) water demand and groundwater withdrawal estimates by sector (Kenny et al. 2009) were rescaled to the 8-digit HUC watershed scale, adjusted for population, and disaggregated to the monthly scale using regional regression relationships. Return flows by sector were computed using return flow percentages from the 1995 USGS report (Solley et al. 1998). The total water supply in each HUC watershed is the sum of surface water supply at the watershed outlet predicted by WaSSI-CB, total groundwater withdrawals, and the total return flow. Total water demand is the sum of the water use by all sectors in each watershed. The water supply stress index (WaSSI) is computed as the ratio of water demand to water supply (Sun et al. 2008). The WaSSI-CB model currently does not account for water storage in reservoirs or anthropogenic water diversion projects such as interbasin transfers and assumes that all surface water is available for human use.

Intergovernmental Panel on Climate Change (IPCC) AR4 scenarios A1B and B2 were assessed using downscaled CSIRO-Mk2.0, CSIRO-Mk3.5, HADCM3, and MIROC3.2 global circulation models for future scenarios according to the 2010 U.S. Forest Service Resources Planning Act Assessment to account for changes in population (Zarnoch et al. 2010) and climate (Coulson et al. 2007). WaSSI-CB results for all future climate scenarios were averaged to represent the mean (ensemble) response to climate change among these scenarios. Water use for the domestic sector was assumed to vary with watershed population projections according to an empirical per capita water use function. Water use for all other sectors was held constant at the 2005 level. Groundwater withdrawal rates from all sectors were also held constant at the 2005 level.

Results

Water Supply Stress

Total surface water supply for the conterminous United States was predicted to decrease as a result of climate change over the next 60 years from approximately 2.0 trillion m^3/yr in 2000 to 1.6 trillion m^3/yr in 2060 (Figure 2), due in large part to the effects of increasing temperature on ET, but also to decreasing PPT in some parts of the country.

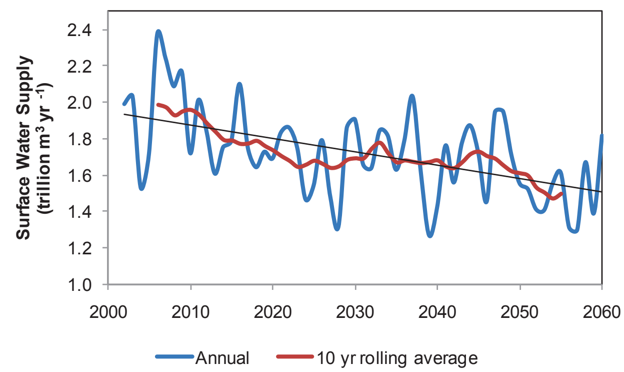

Figure 2. Predicted total U.S. surface water supply through 2060.

Changes in surface water supply will vary considerably across space (Figure 3), with the largest decreases in parts of the Great Plains region and the largest increases in the Southwest. These extreme changes in surface water supply may be misleading because surface water supplies are naturally low in these arid and semiarid environments. As a result, small absolute changes in supply can lead to large percentage changes. Much of the Great Plains region depends on declining groundwater supplies, so despite the lack of dependence on surface water, the Great Plains will likely continue to experience decreases in total water supply in the early part of the 21st century. The large percentage increases in surface water supply in parts of the Southwest are not significant in terms of absolute water supply, so these increases will have minimal effect on water supply in this region.

The WaSSI-CB model predicted that the total water demand in the United States will increase by 6 percent from 2001 to 2060 due to increasing population, with the largest increases in expanding metropolitan areas. The combined effect of decreasing water supply and increasing water demand resulted in increases in the water supply stress index (WaSSI) in most HUC watersheds. A long-term WaSSI value of 0.4 is commonly used as a threshold to identify watersheds experiencing some level of water supply stress (e.g., Alcamo 2000). Using this threshold, the Southwest and southern Great Plains regions were projected to experience water stress in 2051–2060 (Figure 4). Metropolitan areas of the east (e.g., Charlotte, NC; Atlanta, GA; South FL) were also projected to experience water stress.

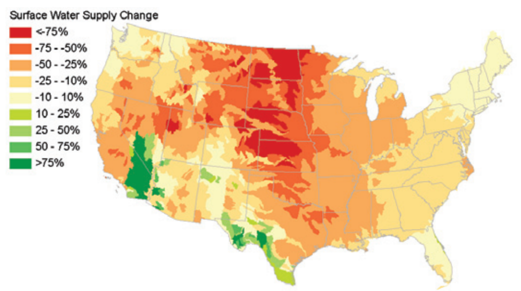

Figure 3. Change in mean annual surface water supply: 2051–2060 vs. 2001–2010.

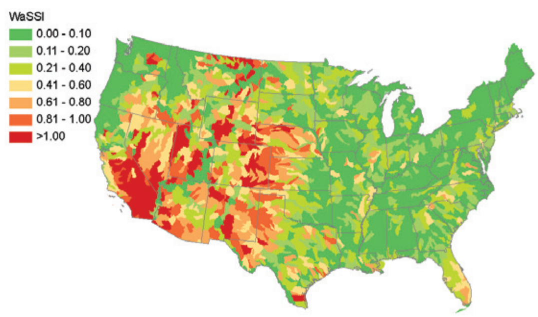

Figure 4. Mean annual Water Supply Stress Index (WaSSI) for 2051–2060.

Carbon Sequestration

Annual WaSSI-CB modeled NEE varied from a carbon source of 145g C/m^2/yr to a strong carbon sink of −1117 g C/m^2/yr (Figure 5). Carbon sequestration was highest in the Southeast, where abundant water and energy were available to drive ET and ecosystem productivity, and lowest in the West (excluding the Pacific Coast), where water was a major limitation. The total net annual carbon sequestration in the United States was 2.68 Pg C/yr during 2001–2010.

Carbon sequestration potential was largely projected to increase (NEE was more negative) across New England, the Upper Midwest, and Pacific Northwest and decrease across most of the Great Plains and Southwest regions (Figure 6) as a result of climate change. Areas that were carbon sources (NEE was positive) either in 2001–2010 or 2051–2060 are shown in gray. Ecosystem NEE is driven by AET, thus carbon sequestration potential will increase in areas with increasing AET and decrease in areas with decreasing AET. Regions where AET is historically energy-limited (i.e., high latitudes) were projected to have the largest increases in NEE as a result of increases in temperature. Regions where AET is historically water-limited (e.g., the Great Plains and Southwest) were projected to experience decreases in NEE due primarily to increases in temperature, but also to decreases in PPT in some areas. The predicted total net annual carbon sequestration in the United States was 2.81 Pg C/yr during 2051–2060, an increase of 4.9 percent from 2001–2010.

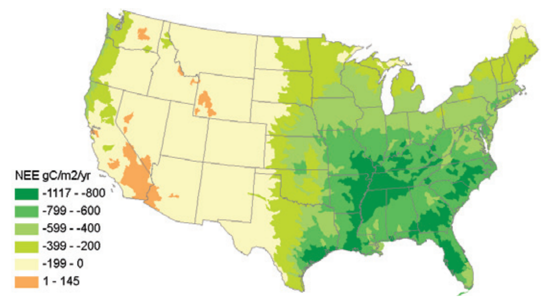

Figure 5. 2001–2010 mean annual net ecosystem carbon exchange (g C/m^2/yr).

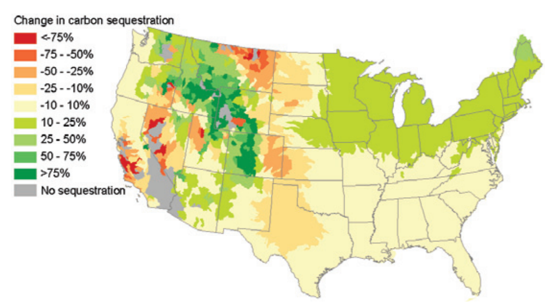

Figure 6. Change in mean annual carbon sequestration: 2051–2060 vs. 2001–2010.

Potential Tree Species Richness

Predicted potential tree species richness, or the number of tree species per unit area, assumes equilibrium conditions. The highest potential tree species richness was predicted for the Southeast, followed by the northern Pacific coast (Figure 7). These trends followed the spatial pattern of predicted AET across the United States. The Southeast, with abundant water and energy, had the highest AET rates and tree species richness. AET and tree species richness were water-limited in the Southwest and energy-limited in the Northeast, upper Midwest, and Pacific Northwest.

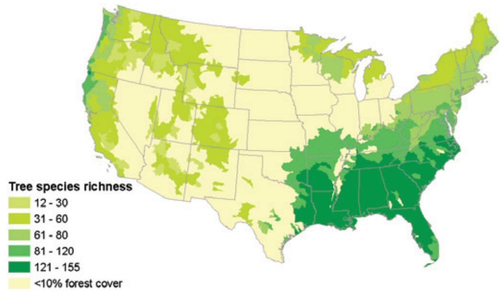

Figure 7. Historic tree species richness.

Tradeoffs Between Water and Carbon

Water yield and carbon sequestration are important societal services forested ecosystems provide. Unfortunately, managing forest resources to maximize one ecosystem service comes with a penalty in the other. To illustrate the tradeoffs between water and carbon, we developed a hypothetical scenario in which 20 percent of all forest land cover in the conterminous United States was converted to shrubland. This scenario may be a potential management option if increasing water supply were a top priority.

Water supply under this scenario had modest increases (up to 15 percent) in HUC watersheds dominated by forest land cover, particularly where the watersheds are in a "headwater" landscape position receiving minimal flow from upstream watersheds (Figure 8). This is partly because many of the "headwater" watersheds are dominated by forest cover, but also because the effects of this management strategy diminish in downstream watersheds as surface water supply was affected by nonforest land covers.

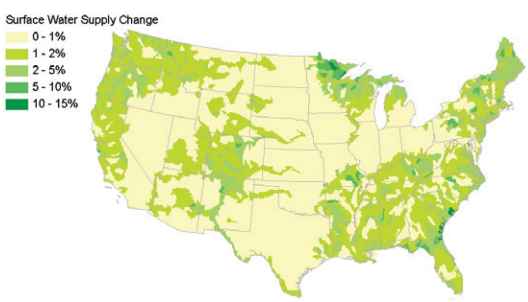

Figure 8. Change in 2001–2010 mean annual surface water supply due to a 20 percent forest conversion to shrubland.

While reducing forest cover by 20 percent increased water supply in some watersheds, this management option led to decreases in carbon sequestration potential over much of the East, Rocky Mountains, and Pacific Northwest (Figure 9) primarily because forest was the dominant land cover in these watersheds. The total net annual carbon sequestration in the United States under this scenario was 2.57 Pg C/yr during 2051–2060, a decrease of 4.1 percent from the 2001–2010 baseline case.

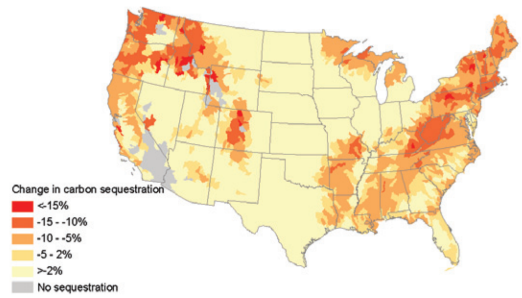

Figure 9. Change in 2001–2010 mean annual carbon sequestration due to a 20 percent forest conversion to shrubland.

On a regional basis, decreases in carbon sequestration (1–9 percent) as a result of this management action were greater than increases in surface water supply (0.4–1.6 percent) (Figure 10). The greatest effect occurred in regions with substantial forest cover and high AET (Northeast, Southeast, Northwest), and the least effect occurred in regions with minimal forest cover and (or) low AET (Midwest, Great Plains, and Southwest).

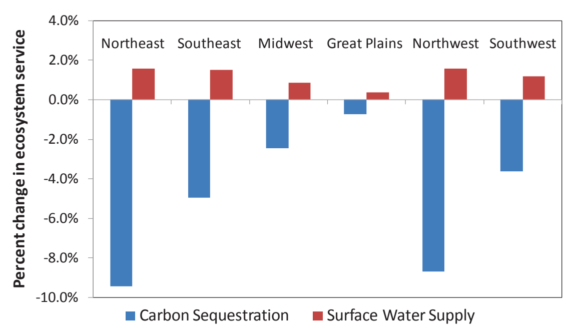

Figure 10. Change regional in 2001–2010 total annual surface water supply and total annual carbon sequestration due to a 20 percent forest conversion to shrubland.

Conclusions

In this paper, we showed how the WaSSI-CB model may be used to predict biodiversity and the effects of climate, population, and land cover change on water resources and carbon fluxes in the next 50 years, and we explored tradeoffs between water and carbon for a hypothetical management scenario where 20 percent of forest cover was converted to shrubland. Model projections indicated that surface water supply will decrease in much of the conterminous United States by 2060, and with water demand likely to increase as a result of population growth, water supply stress was projected to increase. Carbon sequestration potential was largely projected to increase across New England, the Upper Midwest, and Pacific Northwest, and decrease across most of the Great Plains and Southwest regions. Converting 20 percent of forest cover to shrubland led to modest increases in surface water supply and larger decreases in carbon sequestration as one might expect, but the change in water supply and carbon sequestration was highly sensitive to location and dominant land cover type.

The WaSSI-CB model is a work in progress, and several areas are currently under development: (1) reservoir storage; (2) interbasin transfer; (3) limitations on water withdrawal due to aquatic ecosystem needs; and (4) the effect of both climate change and land use change on water quality.

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The Urban Fishery: An Application of System Robustness

Meagan B. Krupa

Abstract

The conceptual framework of robustness applied to a case study of a common pool resource—the Lower Ship Creek Fishery in Anchorage, AK. I apply the robustness framework rather than resilience theory to address the management of this fishery because engineered systems, such as a hatchery fishery, operate independently of some ecological variables within the system. There is a need to distinguish between the socioeconomic and ecological components of the system and use interdisciplinary methods to study their interrelationships because of the unintended effects of engineered components that are relatively insensitive to ecological feedbacks. For example, engineered hatchery fish continue to thrive despite declining stream conditions. I explore the interrelationship of socioeconomic and ecological systems and then use Ostrom's design principles to define, assess, and suggest opportunities for increasing the robustness of an urban fishery.

Keywords: common pool resource, salmon, fishery, hatchery, robustness, management

Introduction

Every summer residents and visitors gather for a unique experience on a creek in downtown Anchorage, AK. Surrounded by industrial yards, the State's railroad, interlocking road systems, and the city's port, pulses of salmon carried by Cook Inlet's world record tides enter Ship Creek. The anglers enter the creek by descending down specially designed staircases built to withstand tides and ice flow. Standing shoulder to shoulder on the banks of Ship Creek, anglers fish for salmon. Undercover patrols move up and down the creek to ensure safety and regulatory compliance. Anchorage's children line up on a child-sized fishing platform to cast their first line into salmon-filled waters. Benches, garbage cans, fish cleaning stations, and restrooms are conveniently located and regularly maintained.

To visitors from cities like Seattle and Baltimore who take buses to see the salmon fishery, Ship Creek appears to have defied the odds. Here, in The Last Frontier, the salmon have seemingly prevailed over the effects of urbanization. Or have they? What many visitors and residents do not realize is that the two salmon species are the product of a carefully engineered hatchery fishery, fueled by a complex network of inter- and intra-institutional arrangements and cost structures.

The above description is what a robust Lower Ship Creek Fishery might look like if it was supported by the appropriate social and economic frameworks. Today's fishery has all the people and fish with few of the amenities needed to sustain them. Declining water quality and quantity, erosion, and barriers to fish passage have substantially altered the creek. Lower Ship Creek is a semiengineered system sitting at the crossroads between wilderness and concrete. In light of this position, the question that managers face is how to create a robust urban fishery when some of the components are engineered and others are natural. Managers need to be able to identify the characteristics that decrease the robustness of this social-ecological system (SES)[*] and then understand the ecological and socioeconomic context that produces these characteristics.

An SES is an ecological system linked to and affected by one or more social systems. It is defined as the subset of social systems in which some of the interdependent relationships among humans are mediated through interacting biophysical and nonhuman biological units (Anderies et al. 2004).

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[*] For convenience, a list of acronyms is given at the end of the paper.

Although this urban fishery SES is singular, its challenges are not unique. Increasing urbanization in the lower Pacific Northwest states of Washington, Oregon, Idaho, and California have pushed wild salmon populations to the brink of extinction (Netboy 1980, Nehlsen et al. 1991, Cone and Ridlington 1996, Huntington et al. 1996, National Research Council 1996, Gresh et al. 2000). Widespread public support has leveraged millions of restoration dollars to prevent the loss of salmon populations, and still they are disappearing (Lee 1993; McGinnis 1994, 1995). While the reasons for the failure of salmon restoration in the lower Pacific Northwest are complicated, one of the main drivers may have been the allocation of funds to address the biophysical symptoms, rather than the socioeconomic causes of these symptoms.

What methodological approach can best help managers delineate the socioeconomic causes of biophysical degradation within an urban SES, and can this approach be used to better achieve the goals identified by users and public infrastructure providers that contribute to robustness? I propose that the robustness framework and Ostrom's (1990) institutional design principles can help sport fishery managers contextualize the biophysical problems associated with the management of sport fisheries by evaluating the institutional robustness of this urban SES.

The complex interactions between the components of SESs have been studied in commercial fisheries (McHugh 1975, Finlayson and McCay 1998, Acheson 2003), but urban sport fisheries have received little attention. I define hatchery fish as fish produced from brood stock by artificial spawning in a hatchery environment. Conversely, wild fish are produced by natural spawning in natural fish habitat by parents that were spawned and reared in natural fish habitat.

The Lower Ship Creek Fishery SES is examined because it contains clearly identifiable interactions between the biological and social systems. The social interactions then can be studied to determine how and why biophysical symptoms are produced. When anglers (resource users) fish Lower Ship Creek, they interact not only with each other and the fish, but also with public infrastructure providers, who interact with each other as well. Public infrastructure providers are the agencies, businesses, and organizations that directly or indirectly contribute to the operation and maintenance of the fishery.

Theoretical Background

I examine the SES's response to the engineered component (the hatchery fishery) through the robustness framework. I chose to apply a robustness framework rather than resilience theory because robustness encompasses the unique attributes of this SES, which has relatively weak feedbacks among its designed and self-organized components. Although robustness is a more appropriate analytical framework than resilience for this SES, this study acknowledges that the robustness of semiengineered systems contributes to the overall resilience of communities. For example, the robustness of the Lower Ship Creek sport fishery contributes to the resilience of Anchorage, AK, by increasing local food and recreation options and supporting a diverse set of businesses.

Numerous studies have explored traditional and modern management in social-ecological systems (Berkes and Folke 1998, Gunderson and Holling 2002, Gunderson and Pritchard 2002, Berkes et al. 2003, Dasgupta and Mäler 2004, Folke 2004, Walker et al. 2006, Prediger et al. 2011). Most of these studies have focused on identifying the ecological and social sources of resilience that would enable the system to persist in its current state or management techniques that might increase the system's resilience. While the goals of this study are similar, the semiengineered characteristics of an urban fishery SES are different.

Holling (1996) distinguished between two types of resilience: engineering resilience and ecological resilience. Engineering resilience assumes that ecological systems exist close to a stable steady-state and measures the ability of a system to return to this steady-state following a perturbation (Pimm 1984). An example of engineering resilience is a bridge, which one would prefer to be close to its stable steady-state. When wind causes the bridge to oscillate and leads to its destruction, an undesirable steady-state is reached.

The concept of ecological resilience addresses the amount of change or disruption that a system can sustain before changing to an alternative state characterized by a different set of critical processes, structures, and interactions (Walker et al. 2004). Although this "tipping point" approach is conceptually consistent with robustness and appropriate to many natural resource issues, it may not provide answers for managers of semiengineered systems, where structures and interactions among components are more tightly constrained by human design.

Robustness first emerged in the field of engineering. The robust design methods, or the Taguchi Methods, make companies more competitive through more efficient development processes. Taguchi et al. (2000) define robustness as the state where the technology, product, or process is minimally sensitive to factors causing variability (either in the manufacturing or user's environment) and aging at the lowest unit manufacturing cost. The Taguchi Methods greatly improve engineering productivity by consciously considering the noise factors (environmental variation during the product's usage, manufacturing variation, and component deterioration) and the cost of failure in the field (Phadke 1989). Companies such as Ford, Minolta, NASA, and Xerox have all successfully used these methods (Taguchi et al. 2000).

Similar to what occurs manually in engineering, biological systems naturally develop responses to survive variable conditions. Developmental biology uses the concept of developmental robustness to describe the ability of an organism to continue to grow despite encounters with disturbances (Keller 2002, Felix and Wagner 2008). Robustness is also used in the field of community ecology (MacArthur and Wilson 1967, Tilman et al. 1996).

The field of social science uses the concept of robustness in the study of the institutional governance of common pool resources. Shepsle (1989) stated that social systems were considered robust if they were long-lived and governed by operational rules that had been devised and modified over time according to a set of collective choice rules. Because of the diverse range of operational and collective choice rules found in different social systems, it became apparent that more general design principles were needed to characterize common-pool resource institutions.

When Ostrom (1990) derived a set of design principles from studies of small-scale, long-enduring institutions for governing common-pool natural resources, she did not initially connect them with the concept of robustness. These principles were based on years of field work and case studies of simple and self-contained to complex and linked systems and have been well tested over the last two decades (De Moor et al. 2002, Kaijser 2002, Dietz et al. 2003). Ostrom (1990) eventually paired the concept of robustness with the design principles by stating that a social-ecological system is likely to be robust if it meets many (but perhaps not all) of these principles (Ostrom 1999, 2002, 2005; Ostrom et al. 2003).

Since SESs contain both engineered and biological components, they also experience variability and develop responses to disturbance. As applied to social-ecological systems, robustness is defined as "the maintenance of some desired system characteristics despite fluctuations in the behavior of its component parts or its environment" (Carlson and Doyle, 2002, p. 2539). Levin and Sugihara (2007, p. 27) clarify the difference between the use of robustness in engineering and ecology by stating, "complex adaptive systems are systems in which whatever robustness exists has to emerge from the collective properties of the individual units that make up the system; there is no one planner or manager whose decisions completely control the system."

An SES that is subjected to a particular type and degree of variability may become highly optimized to tolerate that variability and become more sensitive to new disturbances (this characteristic of adaptive systems is referred to as highly optimized tolerance, or HOT) (Carlson and Doyle 2002). Therefore, robustness emphasizes the cost-benefit tradeoffs associated with systems designed to cope with uncertainty (Anderies et al. 2004, Janssen and Anderies 2007). This emphasis is especially relevant to an urban fishery SES, where the engineered components often generate a tradeoff through the replacement of wild fish by hatchery fish. Perceived environmental problems, social conflicts, and economic fluctuations all produce challenges, but with the proper infrastructure, no single shock is likely to bring ruin to a robust system.

The National Research Council (1999, 2002), the Millennium Ecosystem Assessment (2003), and the Consortium for Sustainable Development (International Council for Science, Initiative on Science and Technology for Sustainability, and Third World Academy of Science; Walker et al. 2004) all have focused increasing attention on the concepts of robustness, vulnerability, and risk. More recently, Janssen et al. (2007) examined the robustness of SESs to spatial and temporal variability to determine why some long-lived SESs persist in the face of change and others do not. Anderies et al. (2007) applied the robustness framework to sustainability science to extract broader themes for the management of resources under uncertainty. Levin and Lubchenco (2008) have applied robustness to the management of marine ecosystems.

Both ecological resilience and robustness denote the ability of a system to maintain its macroscopic functional features (e.g., species diversity) rather than the unattainable possibility of constancy (Webb and Levin 2005). The functional robustness or resilience of an ecosystem can be maintained despite some species extinction under conditions where other functionally similar species maintain the same ecosystem properties.

Although ecological resilience and robustness are frequently used interchangeably (Adger et al. 2005, Levin and Lubchenco 2008), there are important differences. Ecologically resilient systems, for example, are generally characterized as evolved systems that demonstrate high diversity, ecological variability, modularity, slow variables stabilized by tight feedbacks, social capital, innovation, overlap in governance, and sustained ecosystem services (Walker and Salt 2006). The characteristics of ecologically resilient systems are often poorly developed in human-designed and human-operated systems.

Unlike the ecological resilience perspective, which often considers human activities as perturbations of an ecological system, robustness considers SESs where humans develop institutional feedback loops to respond to perturbations (Janssen and Anderies 2007). Robust systems are generally characterized as partly designed systems with both self-organized and designed components (Anderies et al. 2003). Crafted institutional arrangements aim to stimulate and support a particular performance of an SES, just as engineers design systems to meet certain design criteria (Janssen and Anderies 2007). Since urban hatchery fisheries are partly designed systems that contain both engineered (i.e., hatchery fish) and biological (i.e., nutrient cycling) components, robustness is a fitting framework for this particular case study.

The timeframe of analysis differs between resilience and robustness as well. Robustness focuses on the ability of an SES to maintain its social and (or) ecological domain of attraction within a specified time frame (Anderies et al. 2003). A system may be robust during one time period and not in another; such is not the case with resilience, which seeks to attain resilience without lapses over a long time period.

SES robustness depends largely upon the ability of its public infrastructure providers to respond to coinciding occurrences of economic, social, and ecological changes (Anderies et al. 2004). When one resource collapses, managers have the ability to achieve the desired outcome through the substitution of another valued good. Management decisions rely upon feedbacks between both slow (e.g., evolution, long-lived institutions) and fast variables (e.g., pollution event, organizational collapse) (Carpenter and Gunderson 2001). Managers are able to make predictions based on slow variables, but the self-organizing properties of ecological and social systems cause increased uncertainty over time (Levin 2000). It is therefore important to examine both self-organized and engineered components when determining robustness.

The hatcheries, which provide public infrastructure, are an engineered component within the SES that lacks many of the characteristics thought to characterize a resilient system. The hatcheries eliminate the diversity and number of species through several mechanisms. They produce larger numbers of targeted sport fish species than the lower creek could naturally support (Alaska Department of Fish and Game 2007). They remove ecological variability by artificially controlling population levels and restricting genetic diversity. Hatchery fish are immune to natural sources of population variability because they are raised in a controlled environment until they are large and strong enough to be released and therefore are not as susceptible to the effects of instream scouring, temperature changes, predation, or pollution. Hatchery fish, therefore, also are unlikely to experience stress related to the high number of pollution events within Lower Ship Creek. For example, the Ship Creek watershed and Cook Inlet experienced 11 spills of petroleum and other organic compounds from October 1995 to July 2002 (U.S. Environmental Protection Agency 2002).

Despite the cumulative effects of urbanization, the hatcheries do not respond to these feedbacks and continue to produce large numbers of salmon because they are produced in a controlled environment. Wild fish populations, which spend their growth phase in the stream, generally decline in response to urbanization (Klein 1979, Steedman 1988, Limburg and Schmidt 1990, Wang et al. 1997, Yoder et al. 1999).

The hatcheries are managed under a single agency (Alaska Department of Fish and Game 2007) rather than under overlapping governance among agencies. The Alaska Department of Fish and Game (ADFG) does not seek innovation in managing fish stocks (Alaska Department of Fish and Game 2003 a). Most importantly, the hatcheries do not address all of the ecosystem services affected by its production. Since little feedback on the social and ecological effects of the fishery influence the ADFG decisions that drive the fishery, resilience theory fails to adequately address the complexity of this and other engineered systems.

Although biologists know approximately how many fish will annually return to Ship Creek, the effect of this component on the greater SES is not known. Management challenges increase when engineered components interact with natural components because the artificial optimization of one system can produce negative effects on other components of the system. One agency may reap the benefits from a well engineered system, while others pay the costs.

Robustness and Ostrom's (1990) design principles may allow managers to better understand the character of and interactions between the components of this semiengineered, urban SES to reduce effects that decrease the robustness of this SES.

Methods

In order to help managers better address the causes of biophysical degradation, I (1) identify and describe the relevant socioeconomic and ecological systems; (2) outline the desired system characteristics, as formally defined by resource users and public infrastructure providers; (3) discuss the interactions within and between these systems, using the concepts of strategic interaction established by Anderies et al. (2004); and (4) use Ostrom's design principles to identify opportunities for increased SES robustness (Anderies et al. 2004).

The SES, its relevant components, and the interactions between the social and ecological systems were defined and analyzed using Anderies et al.'s (2004) framework. The ecological and social components include the components that most directly influence the fishery. For example, the ecological components of water quality and water quantity can affect hatchery production, which controls the fishery. Lower Ship Creek's public infrastructure providers and recreational and subsistence users are the social components that most directly affect the fishery.

The next step is to identify the desires of the public infrastructure providers and users in order to determine whether common goals can be established for the SES and identify potential sources of conflict. The desired social-ecological components of this SES are formally defined by the mandates and missions of public infrastructure providers, including municipal, State and Federal agencies, nonprofit organizations, and local businesses, and by the results of a standardized questionnaire that was sent to each public infrastructure provider. The desired social-ecological components of both subsistence and recreational anglers are inferred from user surveys conducted by the Anchorage Waterways Council (AWC; Figure 1), as well as from the general interests and activities of the two groups.

Once the ecological and social components are identified, the interactions within and between these systems will be discussed using Anderies et al.'s (2004) concepts of strategic interaction. I assessed the fit of this SES to Ostrom's (1990) design principles by

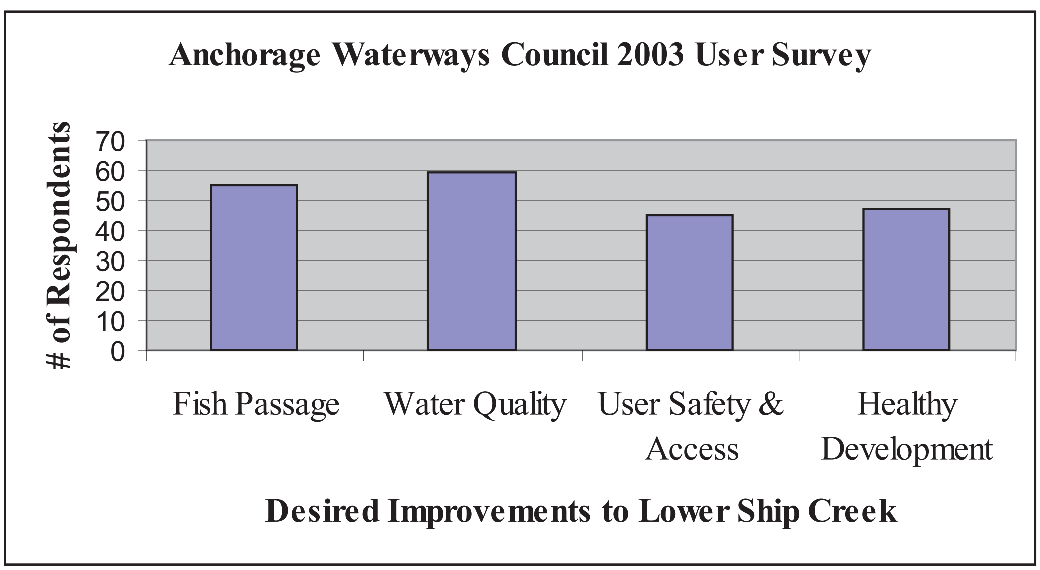

Figure 1. User survey, 2003

applying each of the principles to the Lower Ship Creek Fishery SES to determine which principles this SES failed to meet. I then analyzed the failed principles to identify opportunities to increase the overall robustness of this SES.

Components of the Lower Ship Creek Fishery SES

This SES is located within the Municipality of Anchorage (MOA) in downtown Anchorage, AK. The SES encompasses the last 1.45 km of Ship Creek and extends from the Knik Arm Power Plant Dam (KAPP) to the mouth of the creek at Cook Inlet (Note: KAPP Dam is also known as Chugach Power Plant).

The Ecological System

I define the Lower Ship Creek Fishery SES in terms of its ecological system (this section) and its social system (next section) (Figure 2, Tables 1, 2). The fishery under examination includes hatchery-produced chinook salmon (*Oncorhynchus tshawytscha*) and coho salmon (*Oncorhynchus kisutch*). The ecological components that most directly influence the fishery are the quantity and quality of water available for use by the hatcheries. Lower Ship Creek experiences a tidal range of 11.3 meters, which is the second highest range in North America (National Marine Fisheries Service 2002). The strength and height of these tides pose engineering challenges for the construction and maintenance of public infrastructure and streambank stabilization projects.

Historically, Ship Creek supported wild runs of all five Pacific salmon species—chinook, coho, pink (*Oncorhynchus gorbuscha*), chum (*Oncorhynchus keta*), and sockeye (*Oncorhynchus nerka*)—as well as Dolly Varden (*Salvelinus malma*), rainbow trout (*Salmo gairdneri*), and stickleback (*Gasterosteus aculeatus*) (Alaska Department of Fish and Game 2007). The run sizes of the original five salmon populations are unknown, but it is known that current hatchery-supported runs greatly exceed historical numbers (Alaska Department of Fish and Game 2007).

Two State-run hatcheries located on military bases now annually stock Ship Creek's popular fishery. The Fort Richardson Hatchery was built in 1958 and expanded in 1984. The Elmendorf Hatchery was built in 1965 and expanded in 1976. Ship Creek was first stocked with chinook salmon smolts in 1966 and coho smolts in 1968 (Alaska Department of Fish and Game 2007). A limited chinook salmon fishery first opened in 1970 (Alaska Department of Fish and Game 2007).

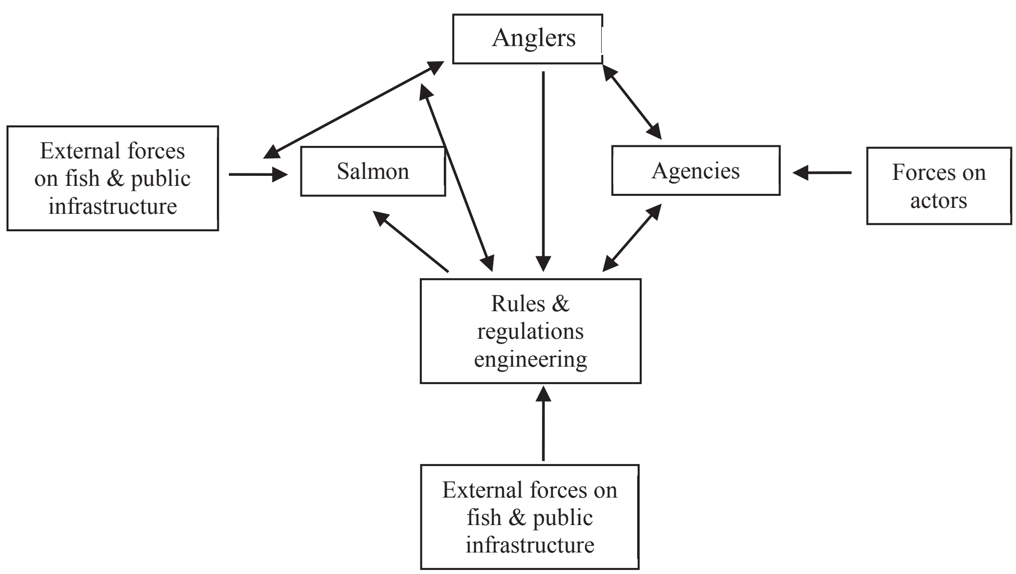

Figure 2. A conceptual model of the Ship Creek Fishery SES. Adapted from Anderies et al. (2004). Linkages are defined in Table 1.

Table 1. Lower Ship Creek Fishery SES linkages. Adapted from Anderies et al. (2004).

Linkages	Potential problems
Between fish and anglers	"Endless" availability of fish, free riding
Between users, businesses, the military, and agencies	Conflicting political agendas, free riding, inadequate inter/intra-agency information and communication, refusal to pay associated maintenance costs
Between public infrastructure and agencies	Unequal investments into the fishery, partitioning of responsibilities in ways that ignore interactions
Between public infrastructure and fish	Ineffective implementation of regulations, poor engineering and inappropriate construction
Between public infrastructure and fish dynamics	Unintended consequences
Between anglers and public infrastructure	Free riding
External forces on fish and public infrastructure	Destroyed fishery (via disease), collapsed public infrastructure (due to funding shortages)
Between forces on social actors	Increased demand, conflict

At present, the hatcheries continue to stock large runs of chinook and coho salmon in this SES. Declining wild runs of chum and pink salmon and Dolly Varden still spawn in the creek, but their numbers are undocumented. Sport fishing for salmon is permitted within the last 1.45 km of the creek, from the KAPP Dam to the mouth (Alaska Department of Fish and Game 2007).

The hatcheries had an agreement with Elmendorf Air Force Base (EAFB) and Fort Richardson Army Base (FRAB) that allowed the hatcheries to take excess heated water from the base power plants and combine it with surface water from Ship Creek. This agreement enabled the hatcheries to maintain a year-round rearing program. With the addition of heated water, the hatchery was able to produce ocean-ready smolts in one year instead of two years (Alaska Department of Fish and Game 2011 a). The closure of both military plants has resulted in considerable declines in the State's salmon stocking programs (Alaska Department of Fish and Game 2011 a).

The hatcheries, which now utilize Ship Creek surface water for their operations, are also concerned with the creek's water quantity and quality. Water quantity (instream flow) is a concern because it is a scarce resource that may be over-allocated. Instream flow is defined as the quantity of water that flows past a given point in a stream channel during one second. The lack of hydrologic data in Alaska is perhaps the most limiting factor in determining instream flow reservations, but other factors include costly and lengthy studies and administrative processes and expensive application fees (Harle and Estes 1993). Under the current adjudication system, permitted water use may exceed supply during peak use times because many water rights applications are still pending (Estes 1998).

According to fecal coliform monitoring data collected by the Municipality of Anchorage from 1989–1994, the water quality criteria for drinking water and contact recreation were exceeded at various times (U.S. Environmental Protection Agency 2004). Since 1990, the Alaska Department of Environmental Conservation (ADEC) has listed Ship Creek from the Glenn Highway bridge to its mouth at Cook Inlet as a 303(d) Impaired Waterbody due to the presence of petroleum hydrocarbons, oil, grease, fecal coliform bacteria, and biological community alteration from urban runoff and industrial spills (U.S. Environmental Protection Agency 2002, 2004).

In 2007, the presence of disease (*Myxobolus cerebralis)* in Ship Creek (Arsan 2006) forced ADFG's Elmendorf Hatchery to limit the introduction of hatchery fish to land-locked systems. To prevent further losses in production related to changes in water quantity or quality, the State has constructed the $96 million Jack Hernandez State Fish Hatchery facility that will implement well-water reuse systems on the banks of Ship Creek (Alaska Department of Fish and Game 2011 a).

Other exogenous controls, such as oceanic and climatic cycles and predation, also influence the survival rate of both wild and hatchery salmon populations (Carpenter et al. 1992). Major climatic and oceanic shifts have significantly altered salmon survival in the Pacific Northwest (Anderson 2000). Predators, such as marine mammals and birds, are often identified as additional factors contributing to salmon decline (Smith et al. 1998). While the effects of these variables are difficult to quantify, they should be considered because they could play an important role in the long-term robustness of the system.

The Social System

The social components that most directly influence the fishery are the public infrastructure providers and resource users. The public infrastructure providers directly or indirectly support the operation and maintenance of the fishery by providing services such as fish production or trash removal services. Resource users consume the production of the fish and contribute to the public infrastructure providers via annual fees.

The public infrastructure providers and the resource users interact within a complex network of private land ownerships and Federal and State jurisdictions. Resource users that purchase a fishing license and follow regulations are allowed to participate in the fishery. Ownership of the land surrounding Lower Ship Creek is complicated. The State of Alaska owns and has jurisdiction over the streambed of Ship Creek. The MOA owns and has jurisdiction over a 30-foot setback on either side of the creek and is responsible for the maintenance of the infrastructure, such as trails, benches, and lighting, that exists within this setback. The MOA also owns the newly constructed bridge near the mouth of the creek. The Alaska Railroad Corporation (ARRC) owns the land adjacent to the last 1.4 km of Lower Ship Creek. Although much of the ARRC land is long-term leased to local businesses, the ARRC has ultimate jurisdiction over these lands. The ARRC also owns a railroad bridge that crosses over the creek within the fishery.

The State of Alaska's Sport Fish Division of the ADFG has management authority under Title 16 and Title 41 in the State of Alaska's statues, makes all decisions regarding the sport fishery on Ship Creek, and is responsible for maintaining garbage cans and portable toilets during the fishery openings. The Habitat Division of the ADFG has jurisdiction over the quantity of water in Lower Ship Creek because it has obtained a water right that established a minimum instream flow. Another State agency, the Alaska Department of Environmental Conservation (ADEC), has jurisdiction over Ship Creek's water quality and can impose sanctions if water quality standards are not met under the Coastal Zone Management Act. The U.S. Environmental Protection Agency (EPA) also has jurisdiction over water quality and can impose sanctions under the National Environmental Protection Act (NEPA). The EPA and U.S. Army Corps of Engineers (USACE) can impose sanctions under Sections 401 and 404 of the Clean Water Act. The USACE can also impose sanctions under Section 10 of the Rivers and Harbors Act. The Alaska State Troopers have legal jurisdiction and the ability to impose sanctions under Title 11 in the Alaska Statutes. The National Marine Fisheries Service (NMFS) has regulatory authority under the Magnuson-Stevens Fishery Conservation and Management Act and the Marine Mammal Protection Act. The U.S. Fish and Wildlife Service (USFWS) has the ability to provide comments on any development actions within Lower Ship Creek but is not a regulatory authority. Both NMFS and USFWS have regulatory authority under the Endangered Species Act. The U.S. Geological Survey (USGS) collects hydrologic data on Ship Creek but does not have regulatory authority and rarely comments on development actions.

Several of these agencies are working to improve the aesthetic appeal and environmental quality of Lower Ship Creek (see "Public Infrastructure Providers" below for more details). The SES is valued by residents because of the creek's unique history and accessibility. The creek once supplied Alaska's Native residents, the Dena'ina, with abundant salmon runs and is Anchorage's original town site. Most recently, Mayor Mark Begich identified the Ship Creek Revitalization Project as one of the top priorities of his administration (Municipality of Anchorage 2007). Many current residents learned how to fish on Ship Creek and are now teaching their children how to catch a salmon in downtown Anchorage. Local businesses recognize the economic potential of the SES and are interested in drawing more people to Ship Creek.

The Lower Ship Creek Fishery SES provides the highest economic benefit to the state of any hatchery program, contributing an advertised $7.3 million to the economy (King 2004). An annual average (1996–2005) of 47,000 angler days of effort produce an average catch of 8,900 chinook salmon and 16,500 coho salmon (Alaska Department of Fish and Game 2007). This SES also benefits Grace Alaska's Downtown Soup Kitchen, which organizes two salmon derbies each summer (Alaska Department of Fish and Game 2007). Ship Creek's hatcheries represent two of the three State-run hatcheries and supply fish for local creeks throughout Alaska, including Upper Cook Inlet, Resurrection Bay, and Prince William Sound (Alaska Department of Fish and Game 2003, Loopstra and Hansen 2005).

Although this easily accessed fishery provides large socioeconomic benefits, it also imposes the external costs commonly associated with common pool resources (Hardin 1968, Ostrom 1990, Ostrom and Field 1999, Dietz et al. 2003, Schlüter and Post-Wostl 2007). As the ADFG has increased the release of hatchery fish over the years (Figure 3), no provisions have been made for the fishery's infrastructure. The lack of public infrastructure, such as bathrooms, fish cleaning stations, and garbage cans, and an increase in trespassing, illegal fishing, angler conflicts, and erosion create annual problems within the fishery (Alaska Railroad Corporation 1999, Anchorage Waterways Council 2011 a). The MOA, ARRC, local law enforcement entities, NMFS, AWC, ADFG, and other resource agencies have all spent money to mitigate pollution by updating and constructing infrastructure (National Marine Fisheries Service 2002, National Oceanic and Atmospheric Administration 2005, Alaska Railroad Corporation 2006, Anchorage Waterways Council 2011 a, Municipality of Anchorage 2007).

Interaction of Ecological and Social Subsystems

The interaction of the ecological and socioeconomic components of the SES determines the system's robustness. As demand for one ecological component increases, the socioeconomic components can react by limiting or compensating for that increase. For example, during the 1970s and early 1980s when groundwater extracted from aquifers near Ship Creek was the principal source of the MOA water supply, areawide declines in groundwater levels resulted in near-record low streamflows in Ship Creek (Moran and Galloway 2006). Because of variable flows and water quality of Ship Creek, its use as a water supply was minimized to maintain flows for aquatic and riparian habitat and to mitigate fecal coliform contamination (Alaska Department of Environmental Conservation 2004). The MOA now receives most of its water supply from Eklutna Lake.

The pressures that have been exerted on Ship Creek's ecosystem processes have created a management need for the maintenance of this fishery's socioeconomic components. As more users come to Ship Creek in search of salmon, public infrastructure providers will be pressured to maintain and (or) expand services to deal with trespassing and safety issues. Since agencies work within existing and sometimes opposing mandates and users have different needs, it is beneficial to carefully examine the formally defined interests of both users and public infrastructure providers.

Desired Ecological and Socioeconomic Components

The major components of this SES can be divided into the categories of essential and desirable. The essential components include the minimum ecological components needed to maintain a robust fishery. A robust urban fishery will include (1) efficient hatcheries, (2) public infrastructure, and (3) sufficient water quality and quantity to sustain hatchery production. The desired components include the characteristics desired by stakeholders within the SES and will be discussed below (Table 2). If either the

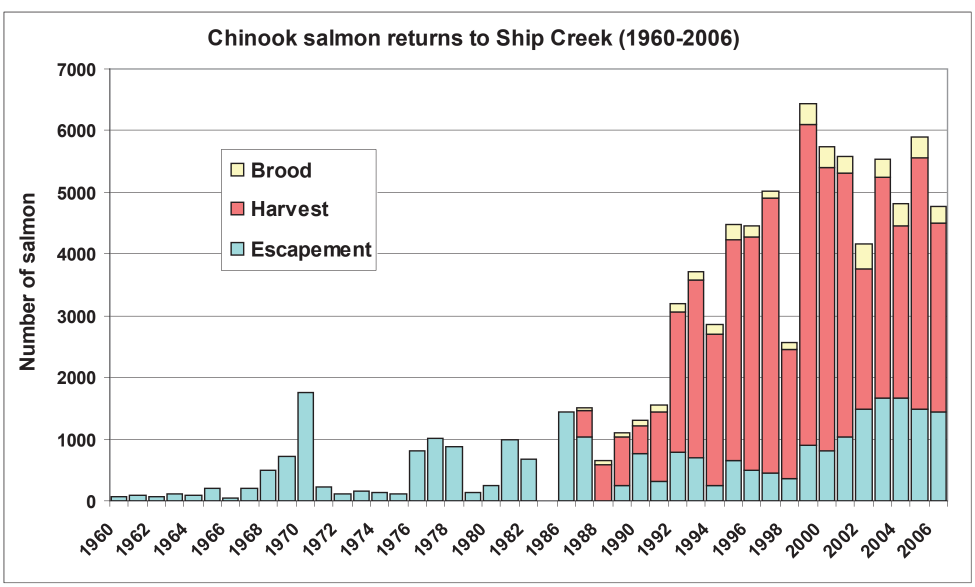

Figure 3. Ship Creek Chinook Salmon returns for 1960–2006. (Alaska Department of Fish and Game 2007)

social (public infrastructure) or ecological (water quality and quantity) components collapse, then this SES would lose its robustness (see "Assessing Robustness" below).

Table 2. Public infrastructure providers' desired social and ecological components of the Lower Ship Creek Fishery.

Desired social and ecological components	Infrastructure providers
Improved water quality, contaminant removal	EPA, AWC, ARRC
Restored fish passage and habitat	USFWS, ADFG, NMFS, AWC
Increased stream/riparian function	USFWS, AWC
Angling opportunity	USFWS, MOA, ADFG, AWC
Decreased erosion	ARRC, AWC
Decreased trespassing, safety issues	ARRC
Construction of new hatchery and visitor center	ADFG, MOA
Maximized harvest, minimized maintenance costs	ADFG
Increased economic activities in district	MOA

Public Infrastructure Providers

Removing Ship Creek from the 303(d) List of Impaired Waterways is a high priority for both the ADEC and the EPA, which both possess regulatory authority within Lower Ship Creek (U.S. Environmental Protection Agency 2006). The mission of both organizations includes the protection of human health and the environment (U.S. Environmental Protection Agency 2011 a, Alaska Department of Environmental Conservation 2008). In May 2004, the EPA approved the ADEC's total maximum daily load (TMDL) plan to impose controls on Ship Creek that will improve water quality by reducing fecal coliform bacteria (U.S. Environmental Protection Agency 2004). A TMDL is a calculation of the maximum amount of a pollutant that a waterbody can receive and still meet water quality standards and an allocation of that amount to the pollutant's sources (U.S. Environmental Protection Agency 2011 b). The EPA is working with the ARRC to monitor Ship Creek's water quality for petroleum (U.S. Environmental Protection Agency 2006). This monitoring will enable the ADEC to determine the best recovery actions for Ship Creek, which may involve the development of a TMDL or similar recovery plan for petroleum (U.S. Environmental Protection Agency 2006).

The mission of the U.S. Fish and Wildlife Service (USFWS) is "to work with others to conserve, protect and enhance fish, wildlife, and plants and their habitats for the continuing benefit of the American people" (U.S. Fish and Wildlife Service 2011). The USFWS has the ability to provide comments on actions taken within Lower Ship Creek, but it does not have any regulatory authority. The primary short-term goal for USFWS on Ship Creek is to remove barriers to anadromous and resident fish passage through partial or complete dam removal or fish-way improvement so that the creek is largely barrier free by 2012 (M. Roy, written response to author's Ship Creek questionnaire, 2007). The long-term goal of the USFWS for Ship Creek is to create a barrier free, urban system that achieves a socially accepted balance of augmented and natural fish runs providing ample angling opportunity, relatively natural stream function, and substantially improved riparian function (M. Roy, written commun., 2007).

In accordance with its mission of "creating development opportunities for the highest public benefit, using innovation, partnerships, sound planning, and incentives," the MOA is interested in sustaining the Ship Creek's unique urban fishery, natural values, and economic activities (Municipality of Anchorage 2007, 2008). The MOA would also like to see a new hatchery and visitor center built on EAFB (Municipality of Anchorage 2007). As a land owner, the MOA has to grant permission for projects within the 30-foot setback on either side of the creek (see earlier discussion).

The primary mission of the ADFG is "to protect, maintain, and improve the fish, game, and aquatic plant resources of the state and manage their use and development in the best interest of the economy and the well-being of the people of the state, consistent with the sustained yield principle" (Alaska Department of Fish and Game 2011 b). The ADFG lists Ship Creek as anadromous in its "Catalog of Waters Important for the Spawning, Rearing or Migration of Anadromous Fishes" (Alaska Department of Fish and Game 2008). It is an important designation because Ship Creek is technically afforded protection from any activities that would harm the habitat of anadromous fish under Alaska Statute 41.14.870 (Alaska Department of Fish and Game 2007).

The goals of the ADFG's Ship Creek hatcheries include (1) generating at least 50,000 angler days of opportunity directed at stocked chinook and coho salmon, (2) meeting the brood stock goals of 500 chinook salmon and 1,000 coho salmon, (3) maximizing the harvest of surplus hatchery salmon, (4) improving existing hatchery operations, and (5) accommodating future plans for a new fish hatchery and (or) visitor facility adjacent to the creek (Alaska Department of Fish and Game 2007). The ADFG is also interested in restoring fish passage to upper Ship Creek and reducing or minimizing operation and maintenance requirements caused by debris, sedimentation, and icing on Ship Creek (Alaska Department of Fish and Game 2007).

The mission of the ARRC is to be profitable while delivering safe, high quality service to their freight, passenger, and real estate customers and to foster the development of Alaska's economy by integrating railroad and rail-belt community development plans (Alaska Railroad Corporation 2011). As the landowner of most of the property and the entire streambed within the SES, the ARRC is concerned about trespassing and safety issues associated with the fishery and pedestrian traffic and the effect that these issues may have on their leaseholders (Alaska Railroad Corporation 2006). The ARRC is currently working with the EPA to search for and identify possible contaminants and devise strategies for either eliminating or mitigating risks according to the Comprehensive Environmental Response, Compensation, and Liability Act regulatory guidelines (U.S. Environmental Protection Agency 2002, Alaska Railroad Corporation 2007).

The NMFS provides for the stewardship of living marine resources through science-based conservation and management and the promotion of healthy ecosystems (National Marine Fisheries Service 2011). The agency defines Knik Arm, including the Ship Creek estuary, as essential fish habitat (EFH) under the Magnuson-Stevens Fishery Conservation and Management Act for natural runs of migrating and (or) rearing chinook salmon, coho salmon, pink salmon, and chum salmon (Mecum 2006). In the past five years, the NMFS has contributed a considerable amount of money through federal grants for fish passage and habitat restoration projects to benefit natural runs of salmon adjacent to and on Ship Creek (National Marine Fisheries Service 2002, National Oceanic and Atmospheric Administration 2005, Municipality of Anchorage 2007).

The mission of the nonprofit organization Anchorage Waterways Council (AWC) is "to protect, restore, and enhance the waterways, wetlands, and associated uplands of Anchorage" (Anchorage Waterways Council 2011 b). The AWC would like to see the removal of the lower three dams on Ship Creek, improved water quality, the restoration of wild runs in addition to the hatchery runs, and the construction of angler infrastructure (Anchorage Waterways Council 2011 a).

There are fundamental differences between the missions of the ARRC and the other public infrastructure providers, such as the AWC and State and Federal agencies. Any efforts to improve angler opportunities, fish and wildlife habitat, or water quality fall outside of the ARRC's primary mission to provide safe transportation and improve Alaska's economy.

While each of the public infrastructure entities works under different mission statements, most of their goals are related. The Federal natural resource agencies (USFWS, NMFS) and the nonprofit organization (AWC) are all concerned with the restoration of fish and wildlife habitat, including fish passage, and stream and riparian functions. The EPA and ARRC are concerned with improving water quality. In addition to these goals, the Federal agencies and nonprofit organization are also interested in maintaining angler access and opportunity. The AWC, MOA, and ARRC are all concerned with preventing erosion. Since most of the goals of the public infrastructure providers are compatible, a broadly desirable outcome is possible without having to address the major tradeoffs often associated with common-pool resources.

Resource Users

All resource users fish Lower Ship Creek, but there is varying interest in fish and wildlife restoration, fish passage, and water quality among resource users. According to a user survey conducted by the Anchorage Waterways Council (AWC) in 2003 (Figure 1), users are primarily interested in improving the water quality of the creek. Other concerns documented by the AWC survey in order of importance to users are fish passage, user safety and access, and "healthy" development. "Healthy" development is defined as non-industrialized development, such as bait shops, that supports the Lower Ship Creek Fishery. While the survey did show that both residents and visitors participate in the fishery, the exact ratio of these user types is unknown. Based on the observations of volunteers conducting the surveys, the fishery's resource users can be separated into two categories, as fishing for (1) recreation or (2) subsistence, as determined by the type of fishing gear used. Recreational users tended to use more expensive and elaborate fishing gear than subsistence users.

Subsistence users rely upon Ship Creek's salmon as a food source and spend a considerable amount of time fishing the creek. They are concerned about any effect that could decrease their ability to catch fish. They want high returns of fish populations and catch limits and low licensing fees. An increase in licensing fees could prevent their participation in the fishery and (or) lead to an increase in illegal fishing efforts since many of the subsistence users have low incomes. They do not support dam removal because the dam currently impedes fish movement and traps fish within the Lower Ship Creek fishing area. Its removal would therefore decrease their ability to catch fish.

Recreational users tend to spend less time on the creek and do not rely upon Ship Creek salmon as a food source. They want an aesthetically pleasing and safe environment for their sport fishing experience. They generally support the restoration of fish passage through dam removal because it would make catching fish more difficult and enhance their fishing experience. Increased licensing fees do not curtail their involvement in the fishery.

Subsistence and recreational users do have common interests as well. All users benefit from using public infrastructure to safely access the creek to fish. Several accidents over the years have affected both recreational and subsistence users' abilities to safely participate in the fishery. In 2005, three failing culverts at the mouth of Ship Creek were removed to improve recreational and subsistence user safety. Most users are also interested in the construction of a new hatchery because it would increase the fishery's robustness. Currently, there is widespread concern that the outdated hatchery facility will be unable to sustain current fish release levels because of inefficient production methods and the lack of an uncontaminated water supply (Alaska Department of Fish and Game 2011 a).

Results: Assessing Robustness

An SES can broadly be considered as robust if it "prevents the ecological systems upon which it relies from moving into a new domain of attraction that cannot support a human population, or induces a transition that causes long-term human suffering" (Anderies et al. 2004, p. 7). Since the examination of cost-benefit tradeoffs is inherent to the robustness framework (Anderies et al. 2004, 2006), it is beneficial to conceptualize the strengths and weaknesses of societies and ecosystems.

Using Ostrom's (1990) design principles derived from studies of long-enduring institutions for governing resources, the robustness of this SES can be assessed based on the ability of the public infrastructure providers to create a flexible yet inclusive management structure that allows the SES to adapt to changes in angler numbers, stream conditions, and development pressures (Table 3).

Clearly Defined Boundaries

The Ship Creek fishery has clearly defined boundaries (Table 3). The ADFG defines the salmon fishery 1.45 km from 15 meters below the KAPP Dam to the mouth of the creek at Cook Inlet. Anyone who has purchased a sport fishing license from ADFG and abides by the fishing regulations has a right to fish the creek.

Graduated Sanctions

Graduated sanctions do exist within the Lower Ship Creek Fishery. The bail schedule for sport fish violations takes into account the severity of the violation. A single violation only receives one penalty, with increasing numbers of violations carrying different penalties. However, if violators harvest too many fish, they are fined a species-dependent set amount for each fish they have taken over the legal bag limit. For example, in the winter of 2008 an individual was caught with more than 100 fish over his limit on another Anchorage creek. His fine amounted to more than $7,000 (D. Bosch, Alaska Department of Fish and Game, Sport Fish Division, personal commun., 2008).

Conflict Resolution Mechanisms

Ship Creek anglers and officials have access to low-cost local arenas to resolve conflict. The most obvious conflicts occur between anglers during peak fishing times when space is limited and the fish are running. Safety concerns are usually quickly addressed by the troopers or the ARRC police because of the creek's easy access. Plain-clothed troopers and the ARRC police patrol the creek on a daily basis. Citizens may contact the ADFG or the Alaska State Troopers with their concerns.

Minimal Recognition of Rights to Organize

The rights to organize are present within this system. If users wanted to create their own institution, they could do so and claim rights to participate in management decisions. However, the necessary institutional framework and social networks are currently lacking, and the diverse and scattered populations of users and their negative opinion of the agencies that govern their actions make organization highly unlikely. It is unclear whether the users could form a group that adequately represents all interests and work cooperatively with governing organizations.

Proportional Equivalence between Benefits and Costs

There is a disproportionate relationship between the benefits and costs of this SES (Krupa and Valcic 2011). The costs of maintaining this fishery are currently not accounted for while the benefits are routinely advertised as producing $7.3 million annually to the State of Alaska (King 2004). The SES benefits include revenues associated with the purchase of sport fishing permits (ADFG), tourism (local businesses, MOA), annual salmon derby entrance fees (nonprofit organization), and outfitting (local businesses). The SES costs include all facilities, services, and programs supporting the fishery as well as the costs paid to mitigate the problems created by the fishery (externalities). These costs are primarily borne by the MOA, ARRC, State of Alaska, ADFG, EAFB, FRAB, local businesses, and nonprofit organizations (Alaska Railroad Corporation 2006, Alaska Department of Fish and Game 2007, Anchorage Waterways Council 2011 a, Municipality of Anchorage 2007). The ADFG has not responded to these mounting costs by limiting the total allowable catch (TAC), which reduces user traffic. In fact, the number of angler user days has increased each year (Figure 3).

Collective-Choice Arrangements

There is no effective collective-choice arrangement on Ship Creek between the resource users and the ADFG. All rules regarding the fishery's TAC and openings are determined by the Sport Fish Division of the ADFG with survey input from Ship Creek anglers. However, there is no forum for dialogue with anglers or any mechanism for input from other public infrastructure providers. Since the other public infrastructure providers are directly affected by changes to the SES, their inclusion in the decisionmaking processes would likely increase this SES's robustness.

Table 3. Design principles derived from studies of long-enduring institutions for governing resources. Adapted to the Lower Ship Creek Fishery from Ostrom (1990).

Principles that characterize Ship Creek	**Principles that do not characterize Ship Creek**
Clearly defined boundaries	Proportional equivalence between benefits and costs
The physical boundaries of the resource system (Lower Ship Creek Fishery) and the anglers with rights to harvest salmon are clearly defined.	Rules do *not* allocate costs and benefits proportionately among infrastructure providers.
Graduated sanctions	Collective-choice arrangements
Users who violate fishing regulations receive graduated sanctions (depending on the seriousness and context of the offense) from officials accountable to publicly elected officials.	Anglers that harvest salmon are *not* included in the group who can modify harvest and protection rules.
Conflict resolution mechanisms	Monitoring
Anglers and enforcement officials have rapid access to low-cost local arenas to resolve conflict among users or between users and officials.	Monitors do *not* adequately audit biophysical conditions and user behavior, so infrastructure providers have no strong basis to manage adaptively for robustness.
Minimal rights to organize	
Anglers' rights to organize are not challenged by external governmental authorities, and users have long-term tenure rights to utilize the fishery.	

The ADFG is a State agency governed by the Alaska Board of Fisheries with several departments that provide different services and goals. Differing agendas can produce intra-agency tension between different departments, but there are opportunities for cooperation. One of the goals identified by the entire ADFG as a State agency is to optimize public participation in fish and wildlife pursuits (Alaska Department of Fish and Game 2011 b). The mission of the Habitat Division of ADFG is to preserve the State's fish and wildlife resources by protecting the areas they need to complete their life cycles (Alaska Department of Fish and Game 2011 c). This effort includes maintaining fish passage and instream flow. The ADFG therefore has incentive to work with public infrastructure providers to reduce erosion and protect fish and wildlife habitat within the fishery.

One potential challenge to including the public infrastructure providers in decisionmaking processes is their shifting roles within different scenarios. For example, the MOA's involvement in projects on Ship Creek has drastically increased with the election of Mayor Mark Begich. Another challenge is that the ADFG personnel who decide TAC are often politically appointed by the Governor and therefore are subjected to public scrutiny and influence.

Monitoring

The lack of user and biophysical monitoring restricts the system's robustness. Although the ADFG, Alaska State Troopers, and ARRC all monitor user licensing and behavior on Ship Creek, enforcement remains a problem in this easily accessed fishery. The salmon fishery below the KAPP Dam is closed nightly from 11 p.m. to 6 a.m. from May 25 to July 13, but the Alaska State Troopers routinely catch people catching fish during this period (Alaska State Troopers 2007). The ARRC also closely monitors user behavior to ensure their safety and prevent trespassing on its railroad tracks and bridges.

The USGS currently monitors the quantity of water in Ship Creek at two gauge stations. The AWC, EPA, and ADEC monitor the water quality of Ship Creek, but other biophysical characteristics, such as fish habitat and morphology, go unmonitored. Due to a lack of biophysical monitoring, the ecological (and resulting social and economic) costs and benefits of restoration projects are largely unknown and therefore are a source of conflict among public infrastructure providers.

Interactions

By evaluating the strengths and weaknesses of the relationships between the public infrastructure providers and resource users, the SES fails to meet three of Ostrom's (1990) seven design principles. The SES does not have (1) a proportional equivalence between benefits and costs, (2) collective-choice agreements, and (3) sufficient user and biophysical monitoring (Table 3).

In lacking the design principles of proportional equivalence between benefits and costs, collective-choice agreements, and sufficient user and biophysical monitoring, SES robustness decreases. The development of a proportional equivalence between benefits and costs and collective-choice agreements would address the problems of free riding and subtractability of use through the creation of rules (Anderies et al. 2004) but would fail to address the problem of enforcing these rules. User and biophysical monitoring would play a vital role in enforcing these rules and increasing SES robustness. If addressed in unison, these three opportunities could increase SES robustness and sustain the resource.

Conclusion

The challenges of regulating an urban engineered combat fishery are real but not insurmountable. Urban managers may be able to utilize the design principles (Ostrom 1990) within the robustness framework to distinguish the socioeconomic and ecological components of engineered systems and use this knowledge to more effectively maintain engineered systems. Future research into the similarities between interacting public infrastructure providers and resource users in other urban engineered SESs as well as the SES's ability to meet the design criteria would provide further insight into the components of robustness.

Urban systems possess great social, economic, and ecological value and can be maintained despite uncertain conditions, but this will require a paradigm shift within the public infrastructure providers. Currently, the six strongest providers sit at opposite ends of the engineered to wild spectrum (Figure 4). The other two providers, the ADEC and EPA, are mainly concerned with water quality and therefore are less concerned with the creek's engineering or wildness (Figure 4).

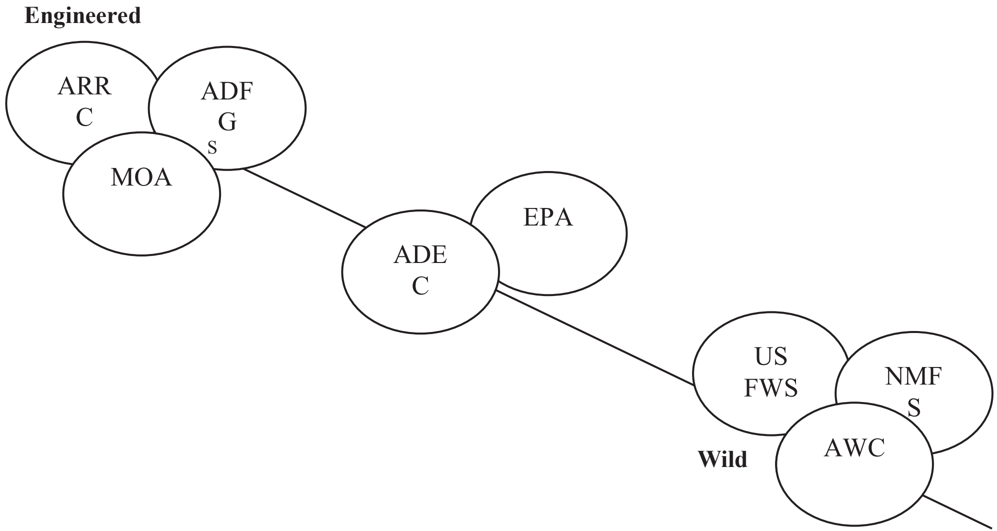

Figure 4. The paradigm divide within public infrastructure providers on Lower Ship Creek. (See the end of the paper for a list of abbreviations.)

Lower Ship Creek is neither engineered nor wild. It is a unique combination of biophysical components reacting with an engineered resource in an urban setting. The current challenges within this SES are the result of the public infrastructure providers' failure to address both of these components in their management efforts.

Currently, the USFWS, NMFS, and AWC are all trying to restore the creek to a more natural condition by improving the creek's overall fish and wildlife habitat and fish passage, but they are largely ignoring the need for the system's engineered and social components. Costly fish and wildlife habitat restoration is extremely difficult if not impossible to maintain within a highly trafficked area such as Lower Ship Creek. The MOA, ARRC, and ADFG are trying to engineer the creek on a reach by reach basis to meet public needs and expectations, but they are generally failing to consider the biophysical components of the creek in their project designs, which has cost agencies a considerable amount of money and has resulted in failed projects.

The good news is that no legal barriers prevent the public infrastructure providers from working together. In fact, many agency mandates and funding sources require the formation of partnerships (AWC, MOA, USFWS, and NMFS). All of the providers have partnered on a variety of reach-scale projects on Ship Creek. The challenge is to get these groups to work together within a more robust institutional framework to maintain Lower Ship Creek's biophysical and engineered components and create a robust fishery (Table 4).

Creating a Proportional Equivalence of Benefits and Costs

Studies of irrigation systems have shown that appropriation and provisions are two major sources of collective-action problems (Tang 1992, Lee 1994). Appropriation problems are time-independent and the result of how a limited resource is allocated (Ostrom 1990). Provision problems are time-dependent and the result of how the responsibility for building, repairing, or maintaining resource systems is assigned, as well as the appropriators' well being (Ostrom 1990). This urban fishery SES experiences problems of ineffective appropriation with provisions.

The high production of hatchery fish and the associated increases in use are causing appropriation problems within this SES. The first step in creating a proportional equivalence of benefits and costs is for the ADFG to address the appropriation problem by decreasing the total allowable catch (TAC) until adequate public infrastructure is in place to prevent further degradation to existing infrastructure and stream conditions or give actors in the system the choice of either reducing TAC or increasing infrastructure (Table 4). Physical (i.e., public) infrastructure is an important component of a robust SES because it determines the degree to which a commons can be exploited, the amount of waste produced by the use of the resource, and the effectiveness of resource and user monitoring (Dietz et al. 2003). For example, the use of relatively inexpensive barbed wire on grazing lands has decreased the cost of enforcing property rights (Krell

Table 4. Opportunities to increase the robustness of the Lower Ship Creek Fishery using three of Ostrom's (1990) design principles that this SES failed to meet.

Creating a proportional equivalence of benefits and costs	Developing collective-choice agreements	Increasing user and biophysical monitoring
Step One	Step One	Step One
ADFG decreases TAC until adequate public infrastructure is in place to prevent further degradation to existing infrastructure	ADFG creates a formal process for including public infrastructure provider input in their annual hatchery operation plans	ARRC and State Troopers increase patrols of Lower Ship Creek and strictly enforce existing ADFG fishing and ARRC trespassing regulations
Step Two	Step Two	Step Two
Public infrastructure providers identify improvements and maintenance costs needed to support the fishery at future TAC levels	Public infrastructure providers work together to define specific roles in the implementation of improvements and maintenance efforts	EPA and ADEC develop a long-term funding plan to support AWC's water monitoring efforts and USGS's water quantity monitoring at two existing sites
Step Three	Step Three	Step Three
Public infrastructure providers establish a cost-sharing agreement for improvements and maintenance costs needed to support the fishery at future TAC levels	The MOA's Watershed Task Force monitors these agreements and settles disputes through arbitration	Public infrastructure providers include a monitoring component into the design of every improvement and maintenance effort

2002). On Lower Ship Creek, the addition of walkways and staircases would decrease the need for and cost of conducting streambank restoration projects.

Provision problems within this SES exist because of inequities and confusion in the assignment of resource system responsibilities. For example, the ADFG currently benefits from the fishery but pays very few of its infrastructure costs. A more equitable cost sharing framework, such as the one established by a group of irrigators in Japan (Sarker and Itoh 2001), would enable the agencies to share project costs.

Therefore, the next step is for public infrastructure providers to work with the ADFG to identify improvements and maintenance costs needed to support the fishery at future TAC levels. These costs include both improvements (i.e., bathrooms and walkways) and ongoing maintenance (i.e., garbage removal and infrastructure repair) efforts. The public infrastructure providers can then establish a formal cost-sharing agreement for improvements and maintenance costs needed to support the fishery. Past projects, such as the removal of three failing culverts at the mouth of the creek, have been delayed because of disputes over who pays what costs. A formal cost-sharing agreement would reduce future cost disputes and animosity among providers.

Developing Collective-Choice Agreements

Effective governance requires the collection and communication of factual information about socioeconomic and ecological conditions so that managers can make appropriate decisions. Dialogue between the public infrastructure providers and users allows for the correct use of information, building of social capital, and the ability to change and deal with inevitable conflicts (Dietz et al. 2003). Sarker and Itoh (2001) state that sound coordination between social and physical capital has significantly contributed to the success of Japanese irrigation management.

Currently, there is a gap between the public infrastructure providers and users. This gap could lead to the construction of infrastructure that does not match the needs of the users. The creation of a linkage between public infrastructure providers and users has proven to be an important component of robust SESs (Levine 1977, Moore 1989, Lam 1996). When the bureaucrats from the Indonesian government introduced new rules and infrastructure into a rice production system and ignored the indigenous rules of the users, water shortages and pest outbreaks ensued (Lansing 1991). Although the individual characteristics of long-lasting common-pool resource SESs differ greatly, they all have resource users linked to public infrastructure providers (Coward 1979, Siy 1982, Martin and Yoder 1983, Laitos 1986, Maass and Anderson 1986, Blomquist 1992).

The ADFG is in a good position to bridge the existing gap between public infrastructure providers and users. The inclusion of public infrastructure providers into the annual hatchery planning process would enable the development of collective-choice agreements that would define specific roles in the implementation of relevant improvements and maintenance efforts (Table 4). The existing Mayor's Watershed Task Force would then monitor these agreements and settle disputes through mitigation.

Increasing User and Biophysical Monitoring

Increasing user and biophysical monitoring would protect the investment of improvements and maintenance costs on Lower Ship Creek. An increase of patrols would increase user safety through the strict enforcement of existing ADFG fishing and ARRC trespassing regulations. The AWC and USGS currently monitor water quality and quantity, respectively. Both of these organizations have experienced funding shortages that cut monitoring efforts in the past. To prevent future monitoring gaps, the EPA and ADEC could develop a long-term funding plan to support the AWC's water monitoring efforts and the USGS's water gauging at their two existing sites (Table 4). Another way to support user and physical monitoring efforts is for public infrastructure providers to fund and include a monitoring component in the design of every improvement and maintenance effort.

With the presence of night time violations and nonpoint source pollution within this SES, managers should be aware that monitoring and enforcement efforts may become economically inefficient (Colby 1995, Berkes and Folke 1998, Heal 1998). Combining user education and outreach with monitoring and enforcement may prove to be a more effective solution.

Coordination and Implementation

The Mayor's Watershed Task Force may be in a good position to bring the public infrastructure providers together to discuss the issue of robustness in its entirety and specifically address the implementation of each of the above steps (Table 4). Currently, the Task Force is a multiagency advisory team that provides information and advice on the prioritization of restoration projects in Anchorage. In this capacity, it would be difficult for the team to implement steps toward increased robustness. The good news is that the Task Force is seeking to upgrade its status to a municipal board. If the Task Force formalized its existence as a board within the municipal structure, it could assume an increased role in watershed management and create more opportunities for multiagency involvement in decisionmaking processes.

As a municipal board, the team could establish a broad vision for Ship Creek as well as other creeks within the Municipality and use this vision to work toward increased robustness. The specific steps within the general goals of creating a proportional equivalence of benefits and costs, developing collective-choice agreements, and increasing user and biophysical monitoring could become milestones on the way to a more robust Ship Creek (Figure 2).

The popular Lower Ship Creek Fishery can demonstrate the robust management of an engineered fishery. A robust fishery has the ability to take pressure off other wild stocks while creating a sense of ownership within the greater community. Anchorage managers have a great opportunity to save time and money by robustly managing this engineered urban fishery for the thousands of people who wander down to the banks of Lower Ship Creek each summer. It is hoped that other managers will learn from the opportunities derived from this case study to increase the robustness of other creeks throughout Alaska and the world.

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List of Abbreviations

ADEC	Alaska Department of Environmental Conservation
ADFG	Alaska Department of Fish and Game
ARRC	Alaska Railroad Corporation
AWC	Anchorage Waterways Council
EAFB	Elmendorf Air Force Base
EFH	essential fish habitat
EPA	U.S. Environmental Protection Agency
FRAB	Fort Richardson Army Base
HOT	highly optimized tolerance
KAPP	Knik Arm Power Plant Dam
MOA	Municipality of Anchorage
NEPA	National Environmental Protection Act

NMFS	National Marine Fisheries Service
SES	social-ecological system
TAC	total allowable catch
TMDL	total maximum daily load
USACE	U.S. Army Corps of Engineers
USFWS	U.S. Fish and Wildlife Service
USGS	U.S. Geological Survey

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