Modeling Ecosystem Service Conflicts in China's Lake Poyang

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Abstract

This paper develops a model of ecosystem service management that takes into account the conflict between fishing operations and conservation of endangered and threatened waterfowl, specifically Siberian Cranes. The model is calibrated to fit the example of the China's largest freshwater lake, Lake Poyang, the wintering ground for the last surviving population of Siberian Cranes. It captures important features of the lake's hydrology, ecosystem, and economics to investigate the impact of uncoordinated and coordinated management of fishing and bird conservation. The coordinated (joint) management problem is a three-state nonsmooth hybrid dynamic problem that is within-year continuous and between-year discrete. It is solved by the novel pseudo-spectral method from aerospace engineering. The current regulations do not account for the externality fishing imposes on the endangered cranes, which results in their population size decreasing over time. In general, we find prolonging the fishing season extends the cranes' winter feeding and enhances survival but at a cost to the fishery. Then we examine compensation schemes for fishery communities that induce crane conservation. With the decline in natural landscape quality, importance grows for working landscapes to provide ecosystem services.

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Contents

1 Introduction

Lake Poyang is China's largest freshwater lake. It is a seasonal lake whereby a vast region floods under monsoon conditions and then recedes as the dry autumn-winter season unfolds. The lake provides important winter habitat for numerous endangered and threatened species of cranes and other waterfowl, including the last surviving population of Siberian Cranes. Ever since the 12th century, local villages have constructed and maintained low dikes that trap water and fish in sub-lakes when the surrounding lake recedes. Local villages auction temporary user rights to individual contractors to extract fish from adjacent sub-lakes. Contractors execute a slow draining of the sub-lakes that allows low-cost harvesting of escaping fish, generating proceeds that are partly returned to the village.

Draining the lakes also exposes tubers, which are prime feed for critically endangered Siberian cranes and other species. The conflict emerges because the sub-lake drawdown that is dynamically optimal for within-season fishery production is not optimal for tuber foraging for the wintering wildfowl populations. As China's wealth has grown, the market value of tourism services associated with crane viewing and photography has grown, leading to conflicts within the various lake-side villages over how to trade-off multiple users of near-shore lake use. In addition, the central government is promoting the preservation of unique habitat and endangered species, actions that signal the growing recognition of non-market ecosystem values. Several private, state and NGO stakeholders have begun to monetize crane and wildfowl populations by developing infrastructure for viewing and photographing cranes during their winter feeding season at Lake Poyang. The state has also designated certain areas as refuges for cranes, encouraging modifications of traditional fisheries practices in ways that preserve some private values but that also enhance wildfowl habitat. This evolution of institutions reflects a changing economic reality for China, one where growing wealth is raising the value of natural nonmarket services from the ecosystem, precipitating changes in traditional institutions that favored marketed services.

The conflict between ZQH fishery and Siberian Crane habitat raises several interesting research questions. For example, how do the profit-maximizing motivations of the ZQH fishery impact the crane population over time? How would various modifications of ZQH fishery operations within a season increase the food available for cranes and the crane population? How might different policies incentivize local fishers to modify their current fishing practice? To answer these questions and understand the complicated interactions between local fishing practices, water level change, tuber exposure, and crane populations, this paper constructs a novel structural model of the inter-annual hydrology of Lake Poyang coupled to a model of lake-bottom vegetation and intra-annual crane population biology. The within-year continuous population dynamics (consumes resource and dies continuously) and between-year discrete reproduction of the cranes add discrete and continuous components to the system.

Utilizing the hydrologic-bio-economic model and state-of-the-art pseudospectral numerical methods, we generate several dynamic simulation results from our baseline deterministic model to discuss the responses to the changing conflicts between local fisheries use and crane and wildfowl habitat use. Specifically, we determine optimal sub-lake drawdown for crane populations with various bio-economic conditions under coordinated and uncoordinated management, where the uncoordinated management stems solely from profit maximizing fishery decisions. We find that decisions that are dynamically optimized for the fisheries drain the sub-lake earlier than desirable for optimal crane population habitat provision. Simulation results show a 21% decrease in the crane population over 5 years of fishery operation. We also find extending the water draining to the end of the wintering season secures the cranes' winter feeding and enhance the crane population but at a cost of fishery revenue. The fishery revenue reduction, the opportunity cost for crane conservation, can be used for minimum compensation payments from the government to incentivize season extensions. The government could also subsidize post-season fish market or pay the fishers to maximize end-of-season crane population in the sublake.

The remainder of the paper proceeds as follows. Section 2 describes the background of Lake Poyang, the Siberian crane, and the fishery. Section 3 introduces the deterministic hydrologic-bio-economic model for joint management. Section 4 talks about the results. Section 5 discusses about future extensions. Section 6 concludes.

2 Background

2.1 Lake Poyang

Lake Poyang in Jiangxi Province, is China's largest freshwater lake, one of the largest freshwater wetlands in Asia (Figure 1). The lake is fed by five tributary rivers (Gan, Fu, Xin, Rao and Xiu) from the south, and connects to China's largest Yangtze River through a narrow outlet channel in the north. The lake basin is affected by subtropical monsoon weather. During part of summer, flooding from the five tributary rivers and a reverse flow from Yangtze River contribute to dramatic seasonal hydrological fluctuations in Lake Poyang. In summer, the lake's area can exceed 4000 km^2 while in winter it reduces to less than 1000 km^2 [Shankman et al., 2006]. In autumn receding water levels expose a maze of isolated sub-lakes. These sub-lakes are connected to the main lake body via rivers. The difference between summer high and winter low water levels can be as much as 11 meters [Harris, 2016].

The lake is a complex landscape that jointly provides ecosystem services like flood control, water purification, and fish supply, benefiting around 200 million people in the watershed. The unique hydrology also supports rich aquatic biodiversity and makes the basin the most important waterbirds wintering site in East Asia. Lake Poyang regularly hosts 400,000 waterbirds every winter, including

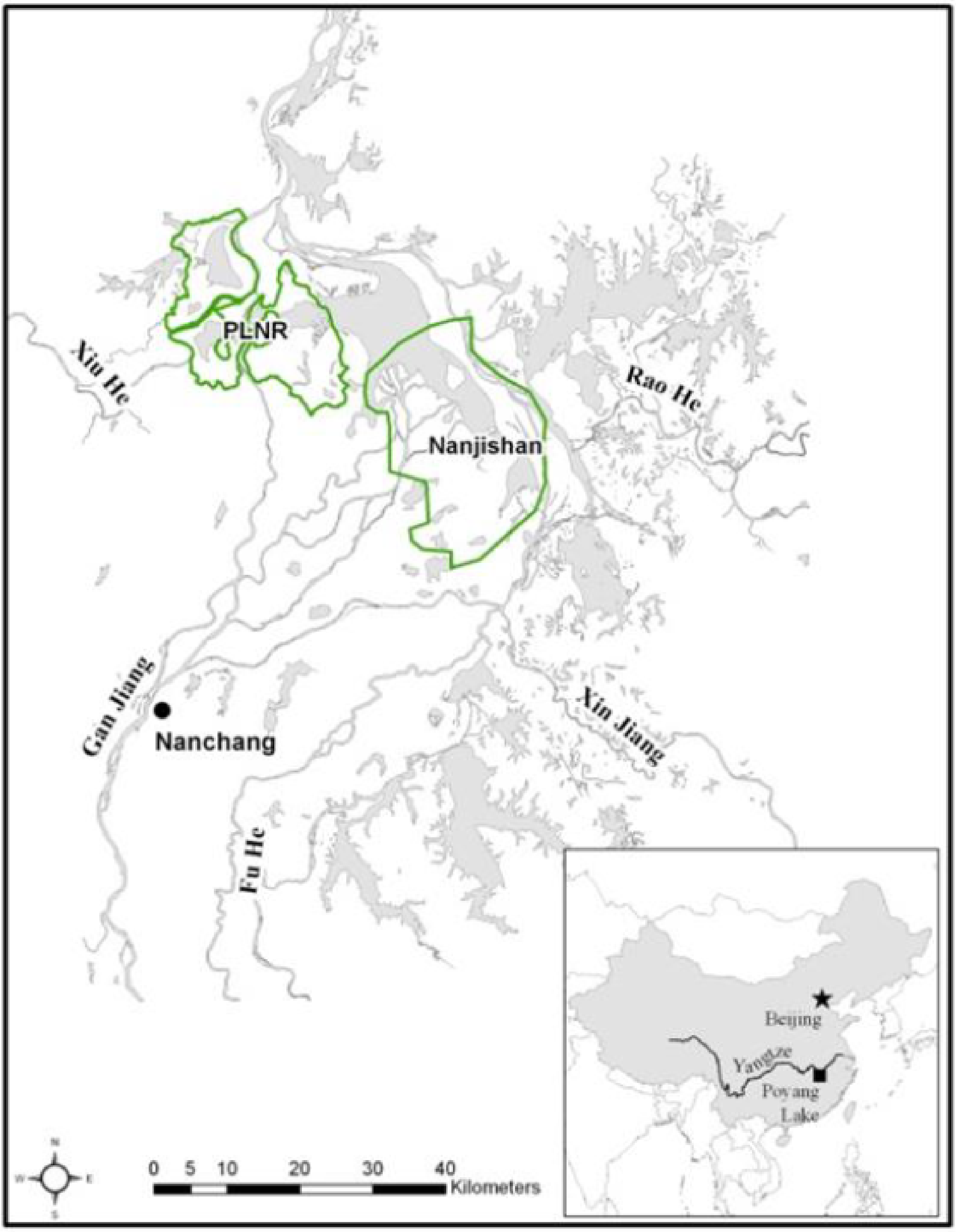


Figure 1: Map of Poyang Lake, with the Poyang Lake Nature Reserve (PLNR) and the Nanjishan Nature Reserve highlighted

Source: International Crane Foundation

95% of the charismatic and Critically Endangered Siberian crane (*Grus leuceogeranus*)[Wu et al., 2009].

2.2 The Siberian Crane

The Siberian crane is also known as the Siberian white crane or snow crane. Adults are nearly all snowy white, with the black primary feathers visible only in flight. Adults have an average height of 5 ft and average weight of 13 lbs [International Crane Foundation, 2019]. The Siberian crane holds the longevity record for all crane species. A Siberian crane living at the National Zoological Park of the Smithsonian Institute reached the age of 62 and another crane named Wolf is in the Guinness Book of World Records for the age of 83 [Birdorable Blog, 2019]. The lifespan is unknown for wild Siberian cranes but predicted longevity is shorter than highest lifespans reached in captivity [Friedman, 1992]. The average lifespan for Siberian cranes in captivity is about 36.2 years for males and 32.3 years for females [Flower, 1938].

The Siberian crane is the most aquatic member of its family, breeding and wintering in wetlands, and preferring wide expanses of shallow freshwater with good visibility. This species is mainly vegetarian but omnivorous in the breeding ground and the wintering ground [Johnsgard, 1983; del Hoyo, 1997][1]. During the non-breeding season, it feeds mainly on roots, bulbs, tubers (especially of sedges), rhizomes, sprouts and stems of aquatic plants, and sometimes aquatic animals if these are readily available [del Hoyo, 1997]. Therefore, the most important habitat component is the presence of aquatic plant roots, winter buds, and tubers[2]. [Jia et al., 2013; Burnham et al., 2017] show that *Vallisneria* tubers are critical food source for Siberian cranes. For efficient forage, soil conditions

[1] The Siberian crane is known to be omnivorous, feeding on both animal and plant matter, depending on the season, life stage and habitat. The diet is broader including both plants and animals during summer.

[2] [Chiba, 2018] found that an immature Siberian Crane in Niigata, Japan mainly forage on water chestnut tubers during the 2016/2017 wintering season while other foods like rice grains, earthworms, grasshoppers and fishes are negligible.

must allow digging to occur and water cannot be so high as to prevent access to the benthic zone[3]. The cranes feed in water within 25 to 68 centimeters depth (about as deep as their long legs allow them to wade). Most of the daylight hours during the wintering period are spent foraging.

Siberian cranes are migratory. They arrive on the northeastern Siberian breeding grounds in late May and eggs are generally laid in June. Incubation takes about 29 days. Two eggs hatch but only one chick typically survives and is raised. This chick fledges within 70 to 80 days and reaches sexual maturity in three years. The main autumn migration begins towards the end of September [Johnsgard, 1983]. Scientists also reported the recruitment rate of the Siberian crane based on observations in India to be around 10% or less [Johnsgard, 1983].

The population of the Siberian crane is thought to have decreased rapidly over the last three generations[4] [BirdLife International, 2018]. There is only one remaining subpopulation of the Siberian crane. The current size of the eastern subpopulation, which breeds in northeastern Siberia and winters in Lake Poyang in China, is estimated to be 3500 to 3800 [Wetlands International, 2012], and makes up about 95% of the whole population of the Siberian crane [Wu et al., 2009]. The western subpopulation was believed to be extirpated, but one individual was seen in Iran in 2010 [Wikipedia, 2019]. A central subpopulation nested in western Siberia and wintered in India. There were 60-70 cranes seen in the mid-1970s, but the population then declined rapidly. The last sighting in India was documented in 2002 [Bove, 2019]. See Figure 2 for the migrating routes, breeding, and wintering sites.

The greatest threats to the population now are habitat loss and degradation in China, highly affected by human activities such as fisheries, hydraulic engineering, and wetland reclamation for fisheries or agriculture. Construction of the Three Gorges Dam(TGD) has also changed the hydro-

[3] The benthic zone is the ecological region at the lowest level of a water body.

[4] The generation length of the Siberian crane is 13 years [BirdLife International, 2018].

Figure 2: Migration routes, breeding and wintering sites
Source: Wikipedia

logic pattern of the lower Yangtze River, resulting in lower water levels in winter[5]. Poyang Lake thus drains more rapidly into the Yangtze River during the low water period.

In summary, besides longevity, the Siberian crane has one of the longest and most arduous migratory routes, one of the lowest recruitment rates of all cranes, and highly specialized foraging requirements among all the cranes [Johnsgard, 1983]. The population wintering in Lake Poyang is the last surviving group.

2.3 The ZQH Fishing Practice

Local communities around Lake Poyang depend primarily on fishery and aquaculture. Autumn-winter fishing practice, called ZhanQiuHu(ZQH), applies to most of the sub-lakes in Lake Poyang

[5] TGD starts water storage on September 15th from 145 meter to meet the target water level of 175 meter. The water level is no higher than 158m by the end of September. By the end of October, the dam implements downstream water supplements while storing water to 175m. With insufficient inflow, TGD will continue water storage in November.

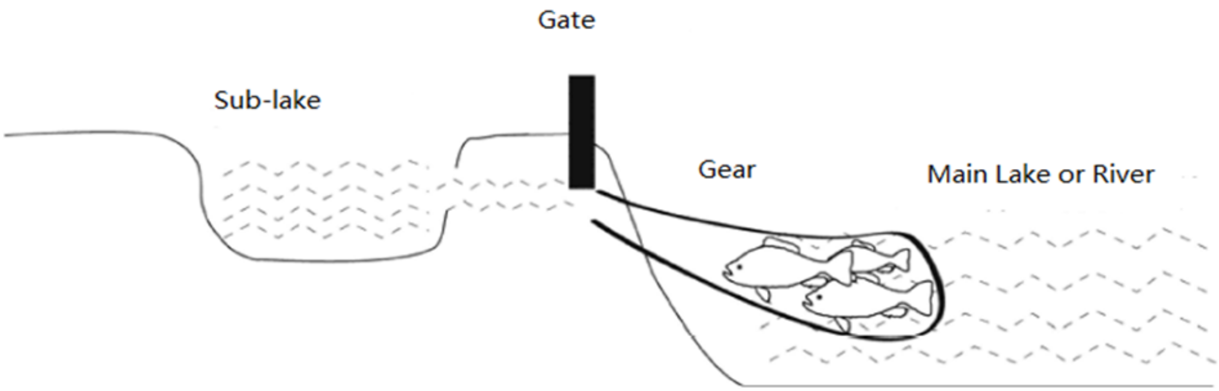


Figure 3: The ZQH Fishing Practice in Autumn-Winter
Source: Zeng [2014]

for hundreds of years[6].

Local villages own the user rights of the sublakes. They could allocate temporary user rights via auction to individual contractors on a 2 or 3-year lease contract. Historically, local fishers constructed short dikes around the sub-lakes in the early spring which maintain the water depth after summer floods recede. Then the local fishers lift the water gates to discharge the sub-lake water into the main lake body. Fish naturally flow into the very fine-meshed fishing nets set at the gate (See Figure 3). More recently, fishers have continued draining the sub-lakes by electric pumps to collect as much fish as possible by early February to maximize short-run profits during the lucrative Chinese New Year period.

2.4 The Conflict

ZQH fishing practice is considered a key determinant of crane habitat. ZQH fishing practice in the sublakes slowly draws down the water and exposes tubers at an ideal speed. Without ZQH fishing,

[6] Two stories mentioning the ZQH fishing practice suggest that it existed in Lake Poyang area as early as 1141 in *Record of the Listener* by Hong Mai(1123-1202)[Mai, 2018].The book spoke widely about incidents that are mythical, fantastic, and supernatural. More importantly, it provides rich material to understand every day life in Song Dynasty (960-1279) China.

the sublakes either remain full or experience quick water drawdown as the main lake. However, ZQH fishing starts early and ends early, which impose negative externality on Siberian cranes.

The timeline of ZQH fishing practice and the activity of the Siberian crane is shown in Figure 4 and Table 1. The Siberian crane winters in Lake Poyang from late October or early November to the end of March, mainly foraging on tubers of the submerged aquatic macrophyte *Vallisneria* in the shallow water and mud flats on the periphery of Lake Poyang [Wu and Ji, 2002]. Tuber stock and accessibility significantly affect foraging behavior. Vallisneria grows from April to October and forms tubers from July to October [Li et al., 2015]. Photosynthesis and tuber formation can both be enhanced and constrained by light intensity, which varies with fluctuating water depth and clarity of the lake in summer time [Wu et al., 2009] [7]. In the winter, tuber accessibility by cranes is also determined by water levels and tuber location. Draining water in October and November exposes abundant subsurface food for wintering cranes. However, if the lake is drained dry by January or February, it will cause food shortages since the Siberian cranes stay until the end of March and can't forage in dry soils. Tuber consumption, influenced by water levels, determines fat accumulation by the cranes during the wintering period. Insufficient fat reserves may delay migration and subsequent breeding. Siberian Cranes experience such a short breeding season that late breeding might influence the fledging of the juvenile cranes in time to undertake migration [Meine and Archibald, 1996]. This will reduce the recruitment of the Siberian crane population, with a reproduction rate of less than 10%.

There is thus a conflict between privatized ZQH fishing stakeholders and public goods stakeholders interested in the crane population or more generally, biodiversity. The two nature reserve

[7] Yuan et al. [2012] argue that when the water level is too high or too low, tuber production is affected. At a low water level, water clarity decreases due to turbulence and turbidity. High turbidity at low water levels (below 13.5m) is attributed to wave-induced sediment resuspension at the lake periphery, common in shallow lakes [Scheffer, 1997]. At a high water level, light attenuates with water depth. In both cases, tuber production decreases because of less photosynthesis.

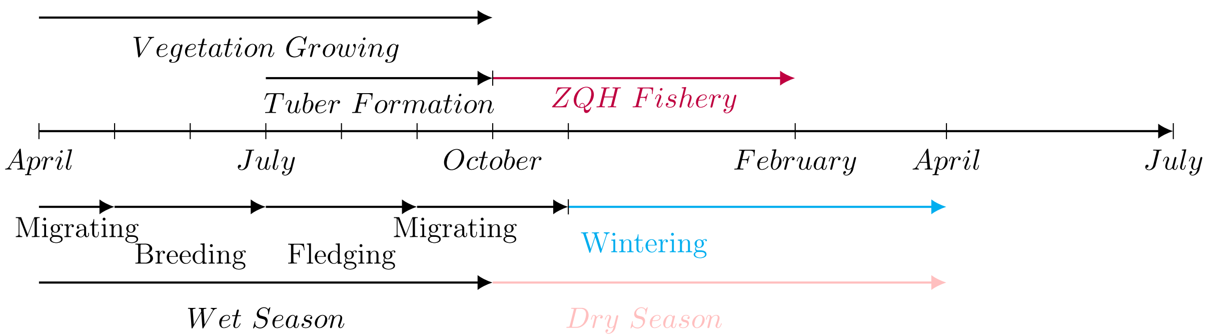


Figure 4: Timeline of the ZQH Fishery/Cranes/Tubers

Year	Birds Arrival	ZQH Fishery
2011-2012	October 26	November 4 - December 15 (Shahu and Dahuchi†)
2012-2013	October 23	October 12 - December 9 (Shahu and Dahuchi)
2013-2014	October 23	October 20 - November 17 (Shahu and Dahuchi)
2018-2019	November 7	October 28 - February 1 (Xiabeijia Lake‡)
2019-2020	November 4	Mid Oct. - (Sanni Lake‡)

- †: Shahu and Dahuchi are rented to and controlled by the Nature Reserve.
- ‡: Xiabeijia Lake and Sanni Lake are controlled by ZQH contractors.

Table 1: Timing of Crane Arrival and ZQH Fishery Opertaion

bureaus rent the user-rights of five sublakes in Lake Poyang from 2000 to 2020. However, there are more than 100 sublakes and the nature reserve bureau cannot control the water discharge regimes of the sub-lakes owned by individual contractors. The current system does not account for the spillover effect of the ZQH fishery on cranes.

3 Research Questions and Models

To understand the impact of ZQH fishery on the Siberian crane population under coordinated and uncoordinated management, we derive a hydrologic-bio-economic model of the ZQH fishery, the Siberian crane population, the *Vallisneria* tuber stock, and water discharge (see Figure 5). To start, we develop two separate models, one within-year continuous model for the ZQH Fishery problem and one hybrid discrete-time/continuous-time model for the crane population problem.

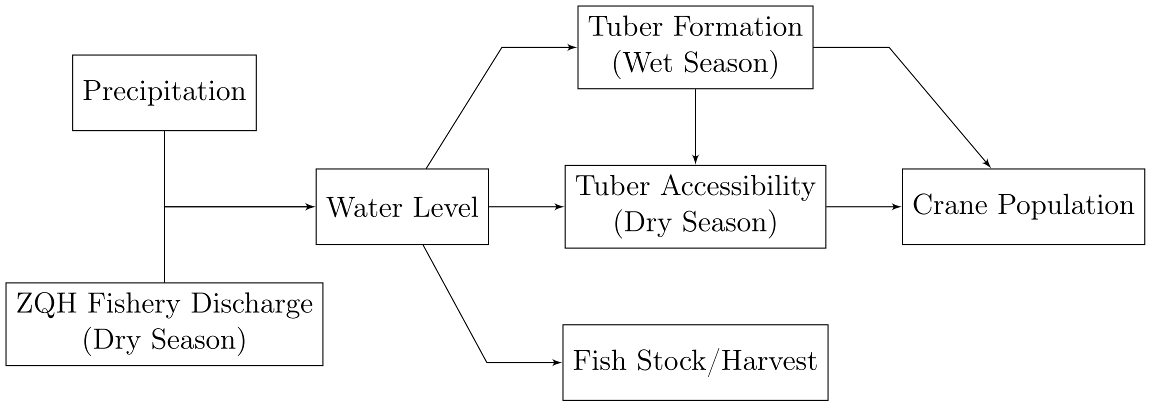


Figure 5: Ecological relationships between the ZQH Fishery and Siberian Cranes

3.1 Modeling and Assumptions

We focus on a representative sub-lake of the nine sub-lakes within Poyang Lake National Natural Reserve (PLNNR), which are among the most important crane and waterbirds wintering sites.

3.1.1 Modeling the lake as a half-sphere

To capture the relationship among water level, the surface area of the lake (relevant to tuber exposure), and the volume of the lake (relevant to fish harvest), we model the lake as a half sphere with radius R (See Figure 6). The half sphere approximates the saucer-like lake.

If the lake is full, the initial water level $h(0)$ is R. The surface area and the volume of the half sphere are

$$S_{\frac{1}{2}\text{sphere}} = 2\pi R^2 \tag{1a}$$

$$W_{\frac{1}{2}\text{sphere}} = \frac{2}{3}\pi R^3 \tag{1b}$$

If the water level decreases to $h(t) < R$ or if the lake starts with an initial water level $h(0) < R$, the lake is a spherical cap with height $h(t)$. The surface area and the volume of the spherical cap

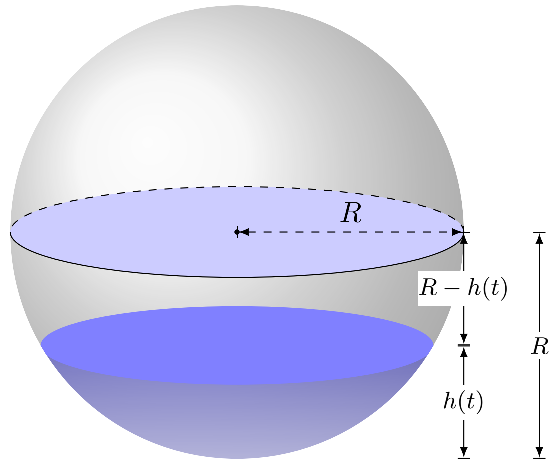


Figure 6: Lake as a half sphere

are

$$S(t) = 2\pi R h(t) \tag{2a}$$

$$W(t) = \frac{\pi}{3}(h(t))^2(3R - h(t)) \tag{2b}$$

3.1.2 Draining lake

Assume the ZQH fishery operator or the Nature Reserve staff chooses the aperture size of the discharge pipe $AP(t)$. The outlet velocity $v(t)$ follows

$$v(t) = C_v\sqrt{2gh(t)} \tag{3a}$$

where $C_v = 0.97$ reflects the incompressibility of water. $g = 9.8\frac{m}{sec^2}$ refers to acceleration of gravity. The flow volume $V(t)$ is then

$$V(t) = C_d AP(t)\sqrt{2gh(t)} \tag{3b}$$

where $C_d = C_v \times C_c$. $C_c \in [0.42, 0.97]$ depending on the shape of the pipe. The aperture size may be restricted within $[\underline{AP}, \overline{AP}]$. No fish flow out if the flow/aperture size is too small, therefore $AP(t) \geq \underline{AP}$. There is a maximum outlet size due to technology constraint, so $AP(t) \leq \overline{AP}$.

3.1.3 The mode of the ZQH fishery

We model the ZQH fishing practice as a sequence of independent within-year decisions. We begin with the following assumptions. See Table 2 for parameters and variables used in the model.

Harvest, revenues, costs and the objective functions The fish are uniformly distributed at the representative lake and are passive towards water flow (no behavior that draws them toward or away from outlet). Harvest $H(t)$ is proportional to flow volume $V(t)$, the proportion q is determined by the initial fish stock X_0 and initial volume of the sublake W_0:

$$H(t) = qV(t), q = \frac{X_0}{W_0} \tag{4a}$$

Profit $\pi(t)$ equals to the revenue from harvest $H(t)$ minus water discharge costs. Marginal cost is assumed to increase with water flow because larger amount of water release may cause fish bruising, which can result in lower market prices. Larger flow may also destroy fishing nets and gates.

$$\pi(t) = \quad pH(t) - \alpha V(t) - \beta V^2(t) \tag{4b}$$

State variables There are two state variables: fish stock $X(t)$ and water volume $W(t)$. Both variables are functions of water level $h(t)$. There is no growth in the fish population $X(t)$ within the fishing season so that fish decreases by harvest $H(t)$:

$$\dot{X}(t) = -H(t) \tag{4c}$$

Water volume $W(t)$ decreases by released water flow $V(t)$:

$$\dot{W}(t) = -V(t) \tag{4d}$$

Endpoint conditions The initial water level $h(0) = R$, ending water level $h(T) = epsilon$. Initial fish stock X_0 given as 20. Initial water volume $W(0) = \frac{\pi}{3}(h(0))^2(3R - h(0)) = \frac{2\pi}{3}R^3$. The ending fish stock and water volume are free.

This is a finite-horizon problem with fixed start date and ending date. The ZQH contractor ends the fishing season by the Spring Festival. There are two main reasons for this assumption. First, the strong market and high price of the fish disappear after the Spring Festival. Second, the rainfall after the Spring Festival increases the main lake water level so that water discharge and fish harvest may become impossible. To avoid the loss, the ZQH contractor will release water and reach the target water level before the festival. Therefore T^f is set to be the Spring Festival, February 1st [8]. Price after T^f is set to be 0.

The time variable representing days within a season is $t = t_0, \cdots, T^f$. The fishing season starts on a fixed day $t_0 = 0$, November 1st[9]. The season ends on February 1st, so the season length is $T^f = 93$ days.

The optimization problem With the assumptions above, the economic model of fish harvesting is that ZQH contractor chooses the size of aperture $AP(t)$ to maximize the present value of the

[8] The Spring Festival falls between January 21st and February 20th. In this analysis, Spring Festival is set to be February 1st.

[9] Table 1 reflects that the ZQH season start date differs across years and sublakes. The ZQH contractors usually start to release water when the water level difference between the sub-lake and main lake is sufficiently large (the main lake water level drops below a certain threshold which marks the beginning of the lake's dry season). The paper starts with the simplified assumptions of a fixed start and end date. The choice of optimal start and end dates will be incorporated in future research.

total revenue $\pi(t)$.

$$\begin{aligned}
\max_{AP(t)} \quad & \int_0^{T^f} e^{-rt}\{pH(t) - \alpha V(t) - \beta V^2(t)\}dt \\
\text{s.t.} \quad & \dot{X}(t) = -H(t) = -qV(t) && \text{Fish Stock} \\
& \dot{W}(t) = -V(t) && \text{Water Volume} \\
& W(t) = \tfrac{\pi}{3}(h(t))^2(3R - h(t)) \\
& V(t) = C_d AP(t)\sqrt{2gh(t)} && \text{Water Flow} \\
& t_0 = 0, T^f = 93, X_0, h_0, h_T \text{ given}
\end{aligned} \tag{5}$$

The model can be reframed as a problem with one state variable water level $h(t)$ (see derivation in Appendix A.1)).

$$\begin{aligned}
\max_{AP(t)} \quad & \int_0^{T^f} e^{-rt}[pqZAP(t)\sqrt{h(t)} - \alpha ZAP(t)\sqrt{h(t)} - \beta Z^2 AP^2(t)h(t)]dt \\
\text{s.t.} \quad & \dot{h}(t) = \tfrac{-ZAP(t)\sqrt{h(t)}}{\pi(2Rh(t) - h^2(t))} \\
& Z = C_d\sqrt{2g} \\
& t_0 = 0, T^f = 93, X_0, h_0, h_T \text{ given}
\end{aligned} \tag{6}$$

3.1.4 The crane population model

The high metabolic rate of birds implies continual energy consumption and the need for a constant supply of food [Biebach, 1996]. Fat is a significant (but not exclusive) source of energy reserves when demand exceeds intake in situations such as migration [Blem, 1980; Bull et al., 1996]. Fat reserve affects the fitness of the bird and its reproduction rate at the end of the season. The mortality rate increases if there is no sufficient intake and the fat level falls. For generalists such as the Siberian crane, habitat and diet shift (from shallow water to meadow, and from tubers to rice grains) under extremely adverse conditions for survival. However, significantly different behavior patterns are observed in alternative habitats compared to optimal habitats. Jia et al. [2013] found that the Siberian cranes allocate significantly less time foraging and more time alerting in the wet meadow. The diet and habitat shift provide refugia for the cranes, but multi-year dependence on an alternative habitat can negatively harm the population level. Burnham et al. [2017] observed a lower juvenile to adult ratio of Siberian crane after the meadow foraging due to low *Vallisneria* tuber densities across sublakes because of the flood in Lake Poyang in 2010. Therefore, we model food shortage leading to lower wintering survival and lower reproduction success of the Siberian crane, which reduce the population.

For the bird problem, we begin with a simple model of the winter foraging and fattening strategy based on the dynamic state variable models of willow tits and juvenile salmon in Clark and Mangel [2000]. To reduce model complexity, we ignore social interactions at wintering ground, migration, and breeding. This model also does not include predation risk and hoarding behavior because there is little evidence documented in the crane literature of either. The conceptual model is useful to describe and understand the within-season and between-season dynamics of the crane population.

The interaction between consumers (e.g., predators) and resources (e.g., prey) is a fundamental focus of ecology [Murdoch et al., 2003]. There are two approaches to study such interactions: continuous-time models to capture population dynamics and discrete-time models for reproduction occurring in discrete pulses determined by season. Discrete-time models are a tradition for the host-parasitoid system (Nicholson-Bailey host parasitoid model) and plant-herbivore interactions [Edelstein-Keshet, 2005]. Such an approach, however, ignores the within-season population dynamics due to different processes [Hastings and Gross, 2012]. Therefore Singh and Nisbet [2007] and Murdoch et al. [2003] have used hybrid discrete/continuous-time models or semi-discrete models to represent within-season interactions with discrete between-season dynamics of host-parasitoid system. In the bird problem, the between-season discrete-time model is appropriate for the crane reproduction once per year. The processes of water discharging, foraging and mortality occur continuously during the dry season and are best represented by the continuous-time model. Therefore a hybrid approach is most appropriate to model the dynamics of various within-year processes in continuous time and reproduction as a discrete event.

For the initial model covering a 150-day wintering period (from November 1st to March 31st) at Lake Poyang, we begin with the following assumptions. There are three state variables: water level $h_j(t)$, crane population $B_j(t)$, and crane energy reserve $E_j(t)$. See Table 3 for parameters and variables used in the model.

Tuber growth and exposure Tubers are uniformly distributed at the bottom of the lake. Suppose we start with an initial water level $h_j(0)$ and initial tuber stock M_j. The surface area of the lake $S_j(0)$ is

$$S_j(0) = 2\pi R h_j(0) \tag{7a}$$

The area density of the tuber stock will be $\frac{M_j}{S_j(0)}$. The birds only forage on the newly exposed tubers by a fraction of $\rho \in (0, 1]$. The exposed surface area will be the negative change rate of surface area. From Equation 2a and Equation 14 , the change rate of surface area is

$$\begin{aligned} S_j(t) =& \ 2\pi R h_j(t) \\ \Rightarrow \dot{S}_j(t) =& \ 2\pi R \dot{h}_j(t) \\ =& \ \tfrac{-2RC_d AP_j(t)\sqrt{2gh_j(t)}}{(2Rh_j(t) - h_j^2(t))} \\ =& \ \tfrac{-2RZAP_j(t)\sqrt{h_j(t)}}{(2Rh_j(t) - h_j^2(t))} \end{aligned} \tag{7b}$$

Energy reserves dynamics The accessible tubers per crane at time t year j is the accessible tubers divided by bird population $B_j(t)$.

$$C_j(t) = \frac{-\dot{S}_j(t) M_j}{S_j(0) B_j(t)} = \frac{-\dot{h}_j(t) M_j}{h_j(0) B_j(t)} = \frac{2RZAP_j(t)\sqrt{h_j(t)} M_j}{(2Rh_j(t) - h_j^2(t))(2\pi R h_j(0)) B_j(t)} = \frac{ZAP_j(t)\sqrt{h_j(t)} M_j}{\pi h_j(0) B_j(t)(2Rh_j(t) - h_j^2(t))} \tag{7c}$$

Rate of fat accumulation increases while foraging. There is a fixed daily metabolic cost c for the cranes. There is no difference in the metabolic rate between foraging activity and rest. If a crane forages a fraction ρ of the exposed tubers, the energy reserve dynamics are given by:

$$\dot{E}_j(t) = \rho C_j(t) - c \tag{7d}$$

Within-season population dynamics The impact of accessible tuber per capita on crane population is asymmetric. The wintering mortality rate at t increases with the reduction in energy reserve because of insufficient tuber intake ($\dot{E}_j(t) < 0$). With a low density of the preferred *Vallisneria* tubers, some Siberian cranes will switch to other food such as rice and lotus root [Jia et al., 2013; Burnham et al., 2017]. The cranes spend more time alerting and less time foraging with diet shift. We assume the risk of mortality is larger in the suboptimal wintering ground. If the tuber intake is sufficient to offset the metabolic cost, ($\dot{E}_j(t) > 0$), there is no mortality. Because reproduction takes place after the wintering period at the breeding grounds, there is no within-year increase in crane population.

$$\dot{B}_j(t) = \quad min[0, exp(\zeta \dot{E}_j(t)) - 1]B_j(t) \tag{7e}$$

End-of-season conditions We use two time variables t, an index of the day in the winter season, and j, an index of the year. $t = 1, 2, \cdots, T^b$, and $j = 1, 2, \cdots, J$, where T^b is the length of the winter season (150 days from November 1st to March 31st) and J is the year horizon. The state variable $E_j(t)$ represents energy reserves of cranes at the end of day t of year j. On each day t of year j, the aperture size $AP_j(t)$ is chosen. The water level of the lake falls and tubers are exposed. Energy reserves increase while foraging. Crane population $B_j(t)$ of day t of year j stays stable or decreases during the wintering season and increases via reproduction at the end of the season.

We assume the initial water level $h_j(0) = R$ and ending water level $h_j(T) = \varepsilon$ for every year j. The initial energy reserve per crane $E_j(0)$ is 5 every year. The initial crane population $B_1(0)$ is set to be 3000. End of season crane population and energy reserve are free.

We also assume that the initial tuber stocks are the same across years, $M_j = M$, so that foraging in year j doesn't affect the initial tuber stock in year $j+1$, M_{j+1}. Sponberg and Lodge [2005] finds no detectable carryover effects of waterfowl exclosure on *Vallisneria Americana* aboveground biomass in subsequent growing seasons despite a significant reduction of tubers during winter. The shifting habitat and diet behavior of Siberian cranes after an abnormal flood in 2010 in Jia et al. [2013] and Burnham et al. [2017] support this assumption[10].

Between-season population growth Insufficient energy reserves at the end of the wintering season T of year j may lead to low reproduction success. The cranes might stay longer at Lake Poyang or stop at extra migration sites to for energy necessary for migration. Both may delay the whole breeding process whereby the juveniles might not have enough time to fledge and therefore die in the cold winter of Siberia. The survival rate of the juvenile at year j f_j is a function of the end-of-season energy reserve $E_j(T)$.

$$\begin{aligned} f_j = &\quad 1 - exp(-pE_j(T)) \\ \frac{\partial f_j}{\partial E_j(T)} &\quad = pexp(-pE_j(T)) > 0 \end{aligned} \tag{7f}$$

The reproduction of the Siberian cranes happens after the winter season at the breeding grounds. With n as the reproduction rate and d as the natural death rate of the cranes, the crane population

[10]When the tuber density in a wintering ground drops below a threshold, the Siberian cranes will leave for new places or new food. The tuber stock won't be depleted and may recover next year.

coming back to Lake Poyang in year $j+1$ can be modeled as

$$B_{j+1}(0) = (1 + nf_j - d)B_j(T) \tag{7g}$$

The crane's fitness is characterized as the adult survival rate and reproductive success reflected by the juvenile survival rate.

The optimization problem The above model can be used for predictive exercises, such as exploring how various decisions by operators of the fishery system influence the cranes. The model can also be used for normative exercises. For examples (and as a comparison with above), we might ask what draw-down policy is most beneficial to the crane population? Answering this requires postulating a benefit function for the crane population and an objective function. There are various ways to set up the objective function for the bird's problem. One choice is to maximize the bird population at beginning of year $J+1$, $B_{J+1}(0)$ with a finite J, by choosing the aperture size of day t of year j.

The second choice might maximize the discounted sum of crane conservation benefit minus water discharge cost $\Sigma_{j=1}^{J} \int_0^{T^b} e^{-rt}[g(B_j(t)) - \alpha ZAP_j(t)\sqrt{h_j(t)} - \beta ZAP_j^2(t)h_j(t)]dt$, by choosing the aperture size of day t of year j. The crane conservation benefit from bird watching and bird photography tourism is an increasing function of crane population at day t of year j, $g(B_j(t)) = \omega log(B_j(t)), \omega > 0$. This is an integrated goal to combine social development with biodiversity conservation in the landscape. The crane conservation benefit is a flow of instantaneous return of the crane population, while the returning crane population of year $J+1$ is a terminal value.

$$
\begin{aligned}
\max_{AP_j(t)} \quad & \textstyle\sum_1^J \int_0^{T^b} e^{-rt}[\omega log(B_j(t)) - \alpha Z AP_j(t)\sqrt{h(t)} - \beta Z^2 AP_j^2(t) h_j(t)]dt \\
\text{s.t.} \qquad \dot{h}_j(t) = {} & \tfrac{-Z_j AP_j(t)\sqrt{h_j(t)}}{\pi(2Rh_j(t)-h_j^2(t))} && \text{water level} \\
C_j(t) = {} & \tfrac{-\dot{h}_j(t) M_j}{h_j(0) B_j(t)} && \text{accessible tuber per capita} \\
\dot{E}_j(t) = {} & \rho C_j(t) - c && \text{energy reserve} \\
\dot{B}_j(t) = {} & min[0, exp(\zeta \dot{E}_j(t)) - 1] B_j(t) && \text{bird population} \\
f_j = {} & 1 - exp[-pE_j(T)] && \text{juvenile survival rate} \\
B_{j+1}(0) = {} & (1 + nf_j - d) B_j(T) && \text{crane reproduction} \\
Z_j = {} & C_d \sqrt{2g} \\
B_1(0), \quad & E_j(0), h_j(0), h_j(T), M_j, T^b \text{ given} \\
B_j(T), \quad & E_j(T) \text{ Free}
\end{aligned}
\tag{8}
$$

A one-year version of the model is shown in Figure 7. We can relax various assumptions in a more complicated model to explore the importance of alternative mechanisms. For example, theoretical works show that the size of the fat reserve depends on the trade-off between storage costs and anticipated needs [Lima, 1986; Witter and Cuthill, 1993]. To account for this trade-off relationship, we could model daily metabolic costs that increase with the level of fat reserves instead of a fixed daily cost in Assumption ??. Also, the deterministic model doesn't consider Alee effects whereby the population goes extinct if it falls below a critical positive threshold level [Clark and Mangel, 2000].

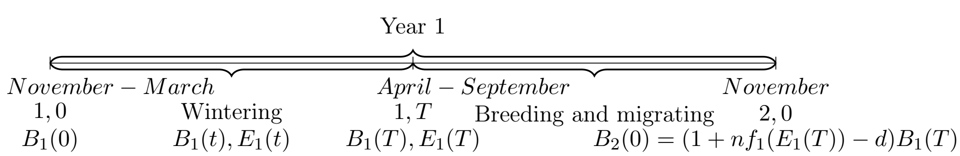


Figure 7: Timeline for the one-period birds problem

3.1.5 Joint management

Under the coordinated management system, the optimal policy chooses the size of the aperture within year to maximize the present value of total revenue from fishery and the crane conservation benefit minus the water discharge cost, subject to the state equation of water level and other constraints in the fishery system and bird-tuber system. The joint management time horizon within each year is from November 1st to March 31st, with $t_0 = 0$, $T^b = 150$.

$$
\begin{aligned}
\max_{AP_j(t)} \quad & \textstyle\sum_1^J [\int_0^{T^b} e^{-rt}\{pqV_j(t) + \omega log(B_j(t)) - \alpha V_j(t) - \beta V_j^2(t)\}dt] && \\
\text{s.t.} \quad & \dot{h}_j(t) = \frac{-ZAP_j(t)\sqrt{h_j(t)}}{\pi(2Rh_j(t) - h_j^2(t))} && \\
& V_j(t) = ZAP_j(t)\sqrt{h_j(t)} && \text{water flow} \\
& C_j(t) = \frac{-\dot{h}_j(t)M_j}{h_j(0)B_j(t)} && \text{accessible tuber per capita} \\
& \dot{E}_j(t) = \rho C_j(t) - c && \text{energy reserve} \\
& \dot{B}_j(t) = min[0, exp(\zeta \dot{E}_j(t)) - 1]B_j(t) && \text{bird population} \\
& f_j = 1 - exp[-pE_j(T)] && \text{juvenile survival rate} \\
& B_{j+1}(0) = (1 + nf_j - d)B_j(T) && \text{crane reproduction} \\
& Z = C_d\sqrt{2g} && \\
& X_0, h_0, h_T, E_0, B_1(0), M_j \text{ given} && \\
& t_j(0) = 0, T_j = T^b = 150 &&
\end{aligned}
\tag{9}
$$

3.2 Numerical Methods

The fishery problem is a single within-year optimal control problem with one state variable and one control variable. The Appendix Section C solves the problem analytically using Pontryagin conditions. We also solve the problem numerically using using BVP4C in MATLAB.

The multiyear crane problem and the multiyear joint problem include three state variables and are within-year continuous and between-year discrete. The state variable crane population carries over years and experiences a between-year jump by the discrete reproduction event. This jump discontinuity in state makes the nonlinear problem nonsmooth. We use GPOPS-II, a MATLAB software to solve this nonsmooth and nonlinear optimal control problems with three state variables [Patterson and Rao, 2014]. GPOPS-II uses the Gauss pseudospectral method and sparse nonlinear programming.

Solving an optimal control problem using a direct method[11] requires the approximation of three types of mathematical objects: the integration in the objective function, the differential equation of the control system, and the state-control constraints. In a pseudospectral method, the continuous functions are approximated using polynomials at a set of carefully selected quadrature nodes (Gaussian quadrature collocation points in GPOPS-II)[12]. The optimal control problem is thus transcribed to a nonlinear programming problem and the NLP is solved using solvers like SNOPT or IPOPT. Using the global polynomial with the Gaussian quadrature collocation points, the pseudospectral method converges exponentially if the solutions are smooth[Kang et al., 2008].

The discontinuities and switches in states, controls, cost functions and dynamic constraints in the hybrid optimal control problem[13] are allowed by pseudospectral knotting method [Ross and

[11]An indirect method to optimization problems works by analytically constructing the necessary and sufficient conditions for optimality, which are then solved numerically. A direct method attempts a direct numerical solution by constructing a sequence of continually improving approximations to the optimal solution.

[12]The terms pseudospectral and orthogonal collocation have the same meaning. In a Gaussian quadrature (orthogonal) collocation method, the state is typically approximated using a Lagrange polynomial where the support points of the Lagrange polynomial are chosen to be points associated with a Gaussian quadrature[Eide et al., 2021]. The most well developed Gaussian quadrature methods are those that employ either Legendre-Gauss (LG) points, Legendre-Gauss-Radau (LGR) points, or Legendre-Gauss-Lobatto (LGL) points. There three sets of points are obtained from the roots of a Legendre polynomial and/or linear combinations of a Legendres polymoial and its derivatives. All three sets of points are defined on the domain $[-1, 1]$, but differ significantly in that the LG points include niether of the endpoints, the LGR points include one of the endpoints, and the LGL points include both of the endpoints[Garg et al., 2011].

[13]A hybrid optimal control problem combines a continuous system with a discrete system.

Fahroo, 2004; Ross and D'Souza, 2005]. Figure 8 shows a nonsmooth nonlinear problem with jump in state at t_1 and dynamics switch at t_2. The hybrid optimal control problem is treated as a three-phase problem where each phase is a continuous problem. The state jump and dynamics switch are pseudospectral knots, where the value of the function is allowed to be multivalued. Therefore the information is passed across phases in the form of discrete event conditions (boundary conditions) localized at the pseudospectral knots linking each phase.

In the crane problem and joint problem, each wintering season is treated as a phase. At the end of the wintering season, the crane population reproduces in Siberia and creates a jump in the state variable. The initial crane population of phase $i + 1$ as a function of the ending crane population and ending energy reserve of phase i is coded as discrete event constraints.

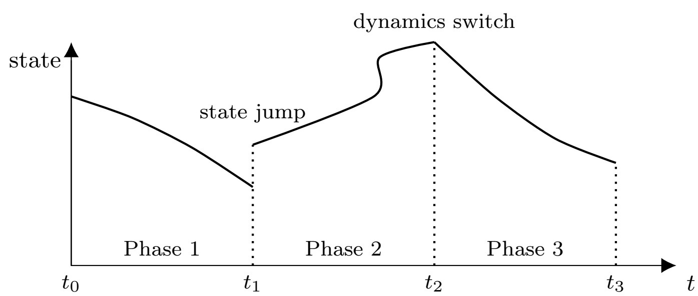


Figure 8: A (nonsmooth) multi-phase optimal control problem

4 Results

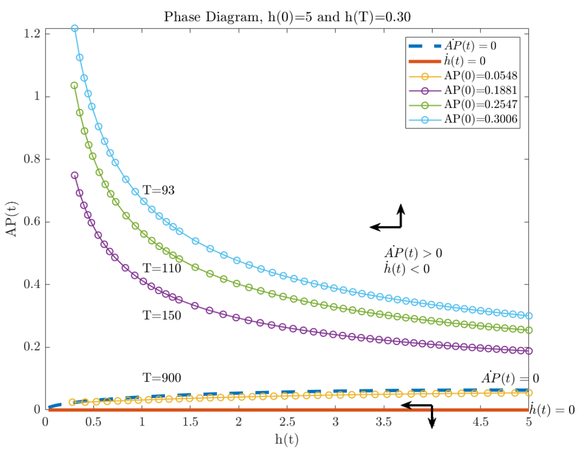
The fisher-tuber-bird system model forms the basis for examining various questions about how water draw-down decisions affect the crane population under different management regimes. This is relatively straightforward given that ZQH operators make a sequence of independent within-season decisions to drain the lake in a manner that maximizes each (identical) season's profits. Thus we model the draw-down decision that is optimal from the perspective of the ZQH fishery, plug that into the bird-tuber model, and assess the implications for the crane population in the uncoordinated system. Then we look at the optimal draw-down decision with coordinated management accounting for both fishery profit and crane conservation benefit.

4.1 Fishery System

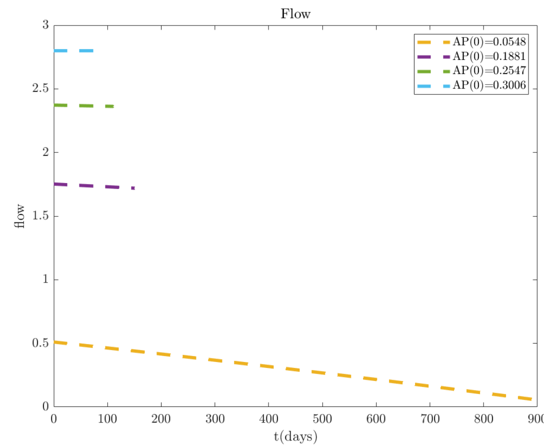
Phase diagrams Specifying the initial water level of the representative sublake as 5 meters and required the ending water level to be 0.3 meter, Figure 9 shows the numerical phase diagram with a few trajectories. There is a fairly rich variety of qualitative patterns to solution trajectories, ranging from those that start with a small aperture and decrease steadily with a extra long time horizon, to those that start with a wide aperture and increase till the end with a short time horizon. Note that with within-year horizons, the optimal path involves a wider aperture held over the short period until the ending volume hits the target. The shorter the time horizon, the more the optimal path is dictated by the simple need to drive the water level from an initial level to a targeted end level. As more time is allowed to optimize, economics begin to play a role in dictating the shape of the optimal trajectory. Two factors are at play: keeping the flow flat to keep costs low, and increasing benefits by having a larger aperture size and flow. Discounting also influences the trajectory, by tilting optimal flow paths to the present in order to capture fisheries benefits earlier [14] (Note: these points emerge more clearly when the phase diagram was computed using a higher discount rate in Figure 9c).

Figure 10 shows the optimal path of aperture size and the water level with fixed season length of 93 days. Aperture size $AP(t)$ increases over time to maintain a relatively stable and unchanging water flow and minimize cost. Because the cost is quadratic in water flow which depends on both the aperture size and water level ($V(t) = ZAP(t)\sqrt{h(t)}$). Harvest is proportional to water flow Harvest(t) $= qV(t)$). Therefore, same aperture size releases more water and harvests more fish with

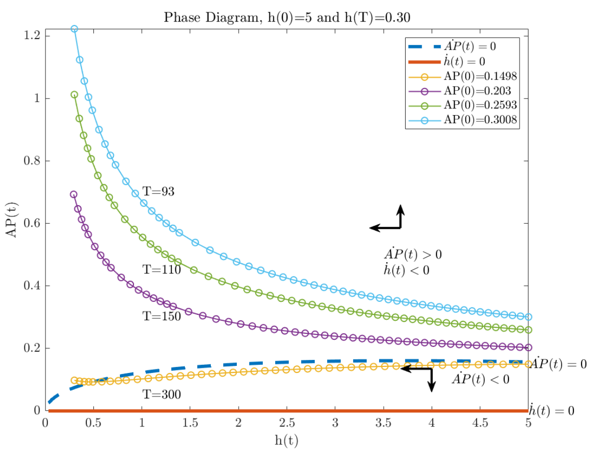
[14] Water level is higher at the beginning of the season and larger flow would yield more fish catch.



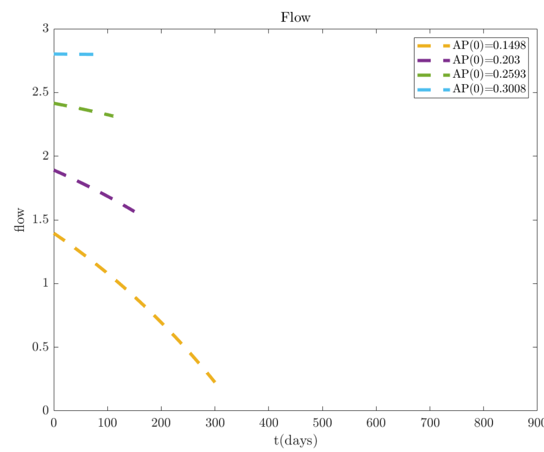
(a) discount rate $r = 0.0002$



(b) flow



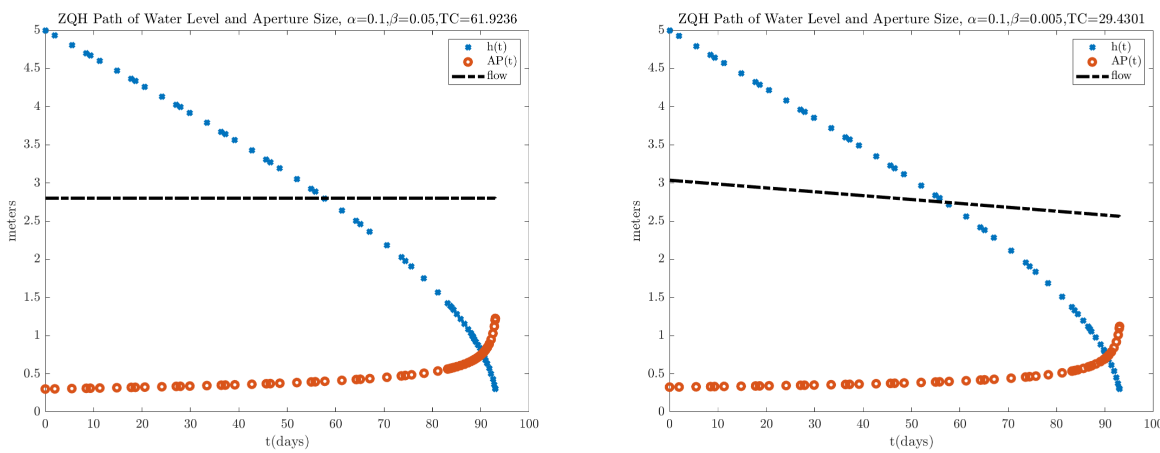
(c) discount rate $r = 0.002$



(d) flow

Figure 9: Numerical Phase Diagram

a higher water level. Flow $V(t)$ is flat with a large quadratic cost coefficient $\beta = 0.05$ (Figure 10a), while it is downward sloping with a small quadratic cost coefficient $\beta = 0.005$ (Figure 10b). With discounting and small cost, it's optimal to harvest more fish with a larger flow at the beginning given the water level is higher, so that the discounted profit is higher. Without discounting, flow will be constant within season. There is no carryover effect from year to year. Therefore ZQH contractor will repeat the same path every year.



(a) Large quadratic cost $\beta = 0.05$, flat flow

(b) Small quadratic cost $\beta = 0.005$, earlier payoff with larger flow

Figure 10: Fishery Path

4.2 Bird and Tuber system

We illustrate the multiyear crane and tuber system that is within-year continuous and between year discrete using the one-year version in this section. In a year with sufficient tubers for the crane population [15], the Nature Reserve chooses the aperture size $AP(t)$ that maximizes the conservation benefit minus the water discharge cost. The optimal path of aperture size and water level is shown as orange in Figure 12a. Water is continuously released to expose tubers to the cranes. The aperture

[15] In a year with sufficient tubers for the crane population, it is possible to avoid wintering mortality with continuous water draw-down. The crane population is within the carrying capacity of the environment. While in a year with insufficient tubers, it is impossible to avoid the wintering mortality.

size increasing over time is to maintain the relative flat flow to minimize the cost. Within-season change in energy reserve and crane population is plotted in orange in Figure 12b. In a year with sufficient tubers, the Nature Reserve avoids crane mortality within the year and accumulates energy reserves. The initial crane population of year 1 is calibrated to be closer to the current population estimate of 3000, and the population coming back next year will be 3029 with an increase of around 1%.

4.3 Impact of Fishing Practice on Crane Population

Now we plug the fishery path into the crane population dynamics to see the impact of fishery on crane population. We get the within-season change of the Siberian crane population and the individual energy reserve (blue paths in Figure 12b). The initial Siberian Crane population at Year 1 is 3000. From Figure 12b, the Siberian Crane at the end of Year 1 dropped by 5.5% to around 2834. The final energy reserve is also lower than that of the bird model, so that the juvenile survival rate will be lower. The fewer surviving adult cranes and the fewer surviving new born juveniles lead to a smaller crane population of 2861 coming back at Year 2 with a decrease of 4.6%.

The negative externality of the fishery on the crane population comes from the timing difference in operation (Figure 11). The fishing season ends early by the Spring Festival and leaves no tubers exposed to the cranes between the Spring Festival and the end of March. The wintering mortality rate increases for the cranes as they have to shift habitat to find food. This juvenile survival rate may fall because the breeding process will probably delay due to insufficient energy reserve. Both lead to a smaller population of the critically endangered Siberian crane.

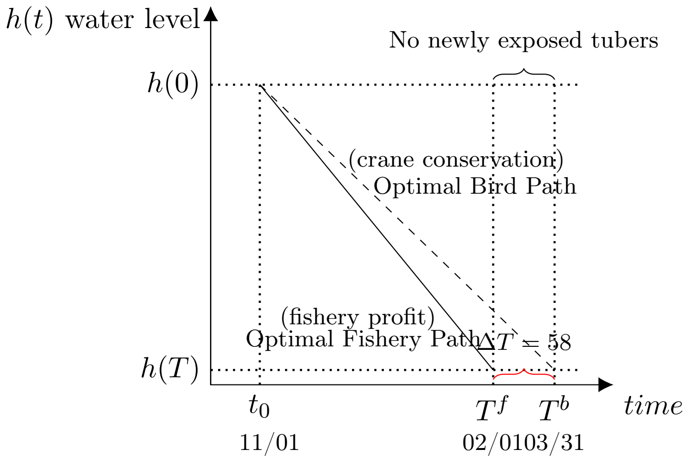
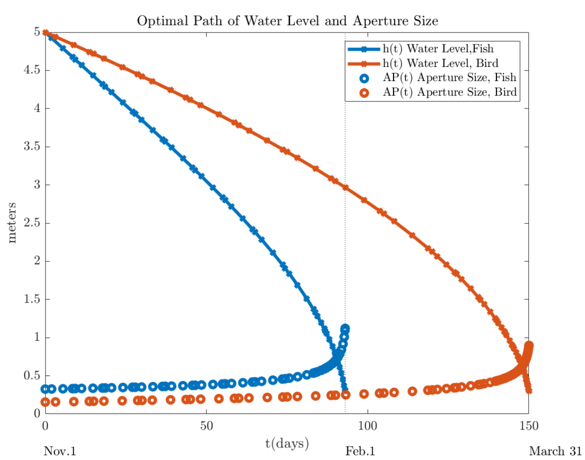
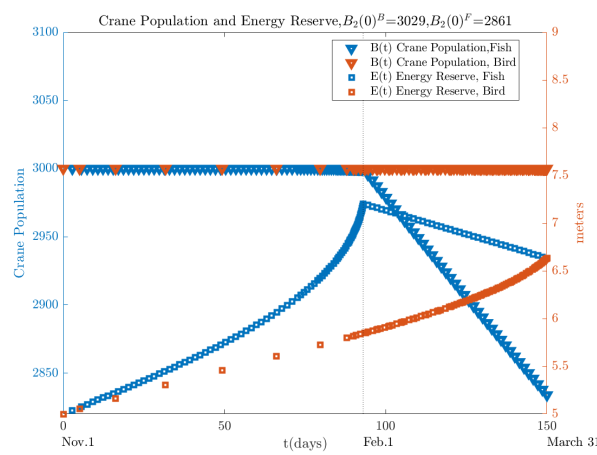


Figure 11: Comparison of Fishery Path and Bird Path of Water Level



(a) Path of Water Level and Aperture Size



(b) Path of Crane Population and Energy Reserve

Figure 12: Impact of fishing practice on crane population

4.4 Joint Management - A 5-Year Simulation

The individual ZQH contractor repeats the optimal path of aperture size and water level of the fishery model year by year. The bird problem is a complicated multi-year optimal control problem that is within-year continuous and between-year discrete. Therefore, the joint management problem is also a multiyear hybrid problem. This section simulates the effect of three management regimes of fishery only, crane conservation only, and joint management with sufficient tubers over a five-year horizon[16].

4.4.1 Fishery only

To mimic the current system, Figure 13 shows a 5-year simulation with only fishery profit included in the objective function. Water release stops on February 1st every year, leaving the water level at the target 0.3 meter from February 1st to March 31st. The crane population remains unchanged during the water release. But due to the early stoppage of fishery operation and no tuber exposure, the crane population drops by 21% from the initial 3000 to 2370 over the five years.

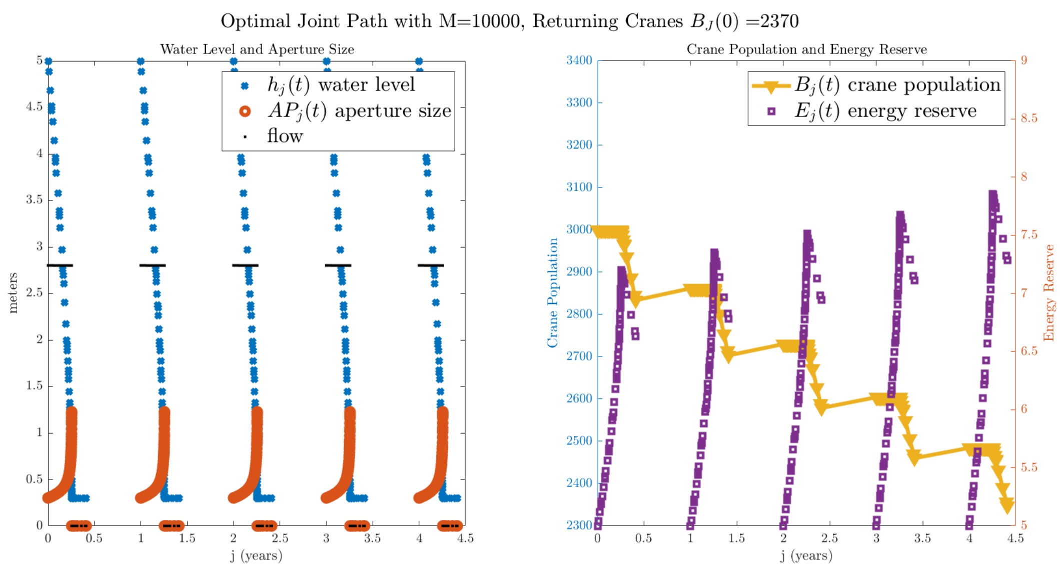


Figure 13: Fishery profit only, no water release after Feb 1st, cranes 3000 ↓ 2370 by 21%

[16]Results with insufficient tuber are in the Appendix Section E.

4.4.2 Crane conservation only

If we instead only focus on the crane conservation benefit in the objective function, Figure 14 shows the five-year simulation results. Water discharge extends to March 31st, the end of the wintering season for the Siberian cranes. There is no crane death within the wintering season and a steady increase via reproduction. The crane population increases by 5% from the initial 3000 to 3150 over the five-year. The water flow is upward sloping because of cost minimization and discounting. Since every year is sufficient in tuber, there is no within-year crane death with continuous water draw-down. Then the large flow is pushed to the end of the year to avoid high cost because of discounting.

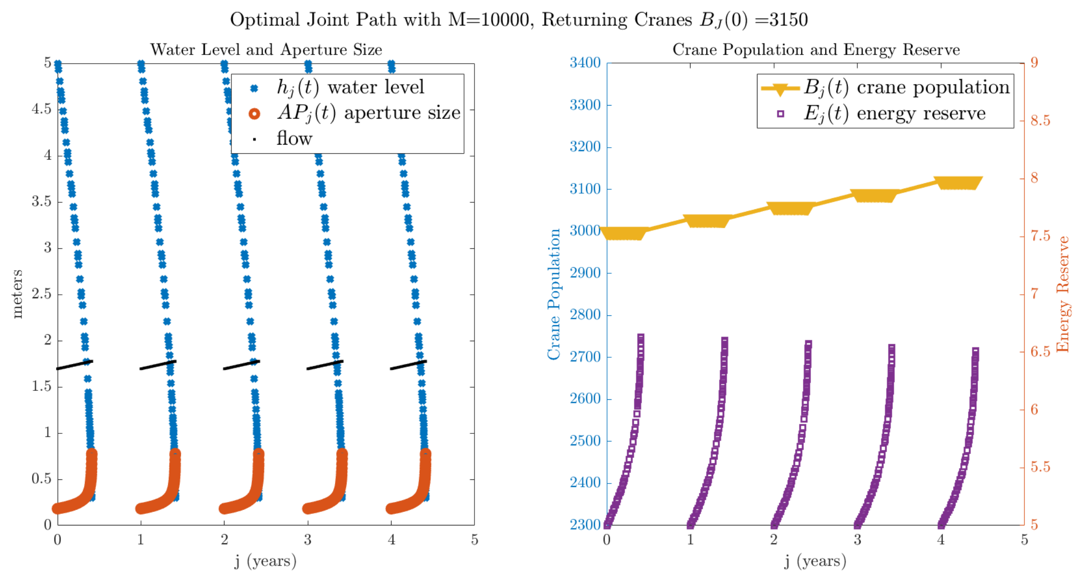


Figure 14: Crane conservation benefit only, water release till March 31st, cranes 3000 $\uparrow$ 3150 by 5%

4.4.3 Joint fishery and crane management

Figure 15 shows the five-year simulation results considering both fishery revenue and the crane conservation benefit. Water release covers the whole wintering season from November 1st to March 31st. Yet there are two sets of aperture sizes/water flows. Because of sufficient tubers, there is no within-season crane death with continuous water draw-down. Fish price drops to zero after February 1st, therefore the social planner will catch as much fish as possible to maximize the fishery revenue via maximizing the water flow before February 1st. The social planner has to leave some water to prevent crane mortality from February 1st to March 31st. Thus, through the joint management, water releases continuously during the whole wintering season. The crane population increases by 5% from the initial 3000 to 3150 over the five year while most of the fishery revenue is reserved.

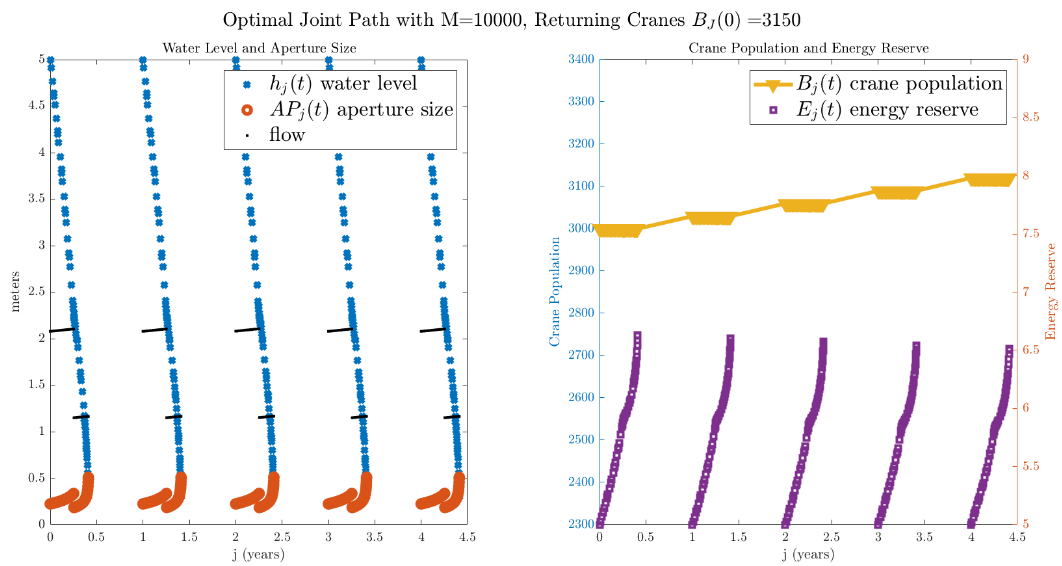


Figure 15: Joint Management, by extending water release season, cranes 3000 $\uparrow$ 3150 by 5% while preserving some fishery revenue

4.4.4 Policy options

In the joint fishery and crane management, the fishery revenue decreases by 25.5% because the lake is not drained and some fish is not harvested before the Spring Festival. The fishery revenue reduction measures the opportunity cost for crane conservation and can be used as the minimum compensation payments from the government to incentivize the fishery to extend the draining season. Alternatively, the government could pay the fishers for end-of-season crane population or fitness conditions to incentivize the ZQH contractors to adjust the fishing season. It may also work to develop or subsidize the post-Spring Festival fish market. This market-based approach offers economic rewards to offset the income loss of the contractors to extend the season.

The results also suggest the possibility of Coasian negotiations where the Nature Reserve controls the water draw-down and compensates the ZQH contractors for their losses. Since local villages own the user rights of the sub-lakes for centuries, the Nature Reserve can either permanently purchase or rent the sub-lake rights. There are currently four such sub-lakes. In those sub-lakes, the Nature Reserve rents the user rights to ZQH contractors at a lower price, requiring that the water draw-down to cater to waterfowls following the guidance.

5 Future Extensions

5.1 Lake Shape Approximation

The current paper approximates the sub-lake as a spherical cap. This approximation uses fewer parameters to construct the relationship between water level, surface bottom area, and water volume, than other approximations such as a cylinder or a cuboid. The more general relationship of area, capacity, and water depth without any shape assumption will be explored in the future.

5.2 Projected Model - Introducing Stochasticity

The deterministic model discussed above is a first step in understanding the complicated Lake Poyang system. In contrast to the simple deterministic model, weather variables vary randomly from year to year. We would also like to explore how this complicated system is likely to evolve under climate change, whose symptoms include sustained changes in temperature, precipitation patterns, and the frequency and intensity of droughts and storms [Hurd et al., 2002]. Climate change is projected to alter both inter-and intra-annual rainfall, the timing and length of monsoon and dry periods, and conditions in the Siberian landscape where birds breed after wintering in Lake

Poyang. There are feedbacks associated with this system that are both detrimental and helpful to crane and wildfowl survival in the long term. For example, summer precipitation at the wintering grounds affects tuber growth in a nonlinear way. The stochastic simulation model will be used to identify critical mechanisms that influence crane and wildfowl survival in the Lake Poyang system and mitigation strategies that might counter adverse climate impacts on the cranes.

5.2.1 Impact of precipitation and temperature on Siberian Cranes

Precipitation in the wintering grounds during summer affects the water level and therefore tuber production. Tuber growth suffers under both too much rainfall and too little rainfall [Wu et al., 2009; Yuan et al., 2012], introducing important non-linear influences on post-wintering conditions and possible hysteresis impacts on interannual survival of crane and other wildfowl populations. In 1998, the greatest flood in a century occurred in the Yangtze River, threatening wintering waterfowl at Lake Poyang by causing tremendous reductions in food. Cui et al. [2000] found biomass and density of three dominant species including *Vallisneria spiralis* reduced significantly. The wintering population of Siberian Crane decreased by 65%, Hooded Crane decreased by 30%, White-naped Crane decreased by 74%, Common Crane by 79%, Great Bustard by 95%, Swan Goose by 65% and Swan by 74% [Zhao and Wu, 1999].

Besides precipitation at wintering grounds, the crane population can also be influenced by fluctuations in temperature at breeding grounds. Germogenov et al. [2013] argued that the nesting success of Siberian cranes in the breeding grounds is positively correlated to the summer average temperature taken over two time periods, 21-31 May and 1-10 June. Burnham et al. [2017] therefore hypothesized an alternative explanation for the decline in juvenile to adult ratios in that conditions on the cranes' breeding grounds were anomalous relative to 2010 and 2012, although the temperatures on the nesting grounds between 2010 and 2012 were considered either "good" or "very good".

5.2.2 Impact of precipitation on fishery

Heavy moosoon rains during the summer time at Lake Poyang area may bring floods and probably a higher initial fish stock. Lake Poyang is a main flood outlet for the Yangtze River and it has five tributary rivers. More fish may be trapped in the sub-lakes after flood water recedes when the sub-lakes are connected to the main lake for a long time.

Rainfall in the fishing season may shorten the season. With stochastic weather and climate events, there exists the risk of heavy rainfall that prevents the ZQH contractors to discharge water to the target level. Reed [1984] demonstrated that when fires, or other unpredictable catastrophes, occur in a time-dependent Poisson process and cause destruction, the policy effect of the risk of fire is equivalent to adding a premium to the discount rate that would be operative in a risk-free setting. Under climate change, the risk might be larger because of more extreme precipitation events [17]. The uncertainty of heavy rainfall will further shorten the fishing season and escalate the conflict between the ZQH fishery and crane conserving.

5.2.3 Model modification

This paper uses water level information at the beginning of the season as a measure of past precipitation and runoff. The initial conditions (dry season starting day, initial water level, tuber stock, fish stock,etc.) are constructed using statistical correlations from previous data. In the stochastic

[17] The climate is unequivocally warming while the changes in precipitation in a warming world are not uniform [Pachauri et al., 2014]. [Pachauri et al., 2014] summarize that extreme precipitation events over most mid-latitude land masses and wet tropical regions will very likely become more intense and more frequent in the warming world. Projections also show that the area affected by monsoon systems will increase and monsoon precipitation is likely to intensify, while El Ni no-Southern Oscilla-tion (ENSO) related precipitation variability on regional scales will likely intensify [Pachauri et al., 2014]. [Sheffield and Wood, 2008] and [Brown et al., 2011] argue that precipitation variability and extreme events will increase as a consequence of an acceleration of the hydrologic cycle.

setting, the initial conditions may vary across years. Climate change may be incorporated with a trend of decreasing mean and increasing variability in water level.

The fisher-tuber-bird problem under stochasticity will require a different objective function, constraints, and optimization strategy. We may want to safely maintain the endangered species away from extinction. Therefore, we can set a quasi-extinction threshold (QET) to prevent the population from reaching small sizes at which viability is threatened by demographic stochasticity and Allee effects according to population viability analysis [Hastings and Gross, 2012]. The QET is similar to the safe minimum standard in Margolis and Nævdal [2008]. Recent work by Donovan et al. [2019] explores algorithms for finding policies that maintain the crane population above some viability threshold $\underline{B}$ over a rolling horizon with some confidence level $Pr(\cap_j^{j+J} B_{j+1}(0) > \underline{B})$.

6 Conclusions

With the loss of natural habitat due to human activities, working landscapes become important to preserve biodiversity and provide ecosystem services. Working landscapes include farmlands, ranches, forests, wetlands, and water bodies. They provide market goods such as crops, timber and fish as well as non-market goods such as clean water and wildlife habitat. Non-market ecosystem services are often ignored by landowners and governments, leading to under-investment in the natural system and therefore a market failure. It is a fundamental premise of welfare economics that uncoordinated joint production of market and nonmarket goods is likely inefficient.

This paper constructs a novel structural hydrological-bio-economic model to investigate the comparative impacts of uncoordinated and coordinated management of fishery and crane conservation in Lake Poyang. The model captures features of the ecosystem under current deterministic climate conditions. The joint management problem is a multi-year three-state hybrid optimal control problem which is continuous within-year and discrete between-year. From the results, the ZQH operators make a sequence of independent within-season decisions to drain the lake in a manner that maximizes each identical season's profit. We find that the current fishing practice leads to a large and prompt reduction in the crane population due to the early stoppage of water release under uncoordinated management. Joint management accounting for both fishery revenue and crane conservation benefit results in a season extension that secures the crane winter feeding and enhances the crane survival, at a cost of fishery revenue.

In the future, we plan to generalize the model to explore management under stochastic weather conditions to understand the mechanisms and policy options when rainfall and other weather variables are expected to vary. The stochastic model can then be used to understand how future management might need to change as distributions of rainfall and temperature variables shifts. This provides insight into the conflicting ecosystem service management of wetlands under climate change, and may lead to more efficient and cost-effective natural resource management.

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Appendices

A Fishery Model

Table 2: Variable and parameter definitions with values and sources in fishery system

State and Choice Variable	Label	Range	
	Variables continuous within year		
$AP(t)$	size of aperture at t	[$\underline{\text{AP}}$, $\overline{AP}$]	
$h(t)$	water level at t	[0, R]	
$V(t)$	flow volume at t	[0, $C_d\bar{A}P\sqrt{2gR}$]	
$S(t)$	surface area under water at t	[0, $2\pi R^2$]	
$W(t)$	water volume at t	[0, $\frac{2}{3}\pi R^3$]	
$H(t)$	harvest at t		
$X(t)$	fish stock at t	[0, X_0]	
$\pi(t)$	profit at t	(-∞, $\frac{a^2}{2b}$]	
t	day	[1, T]	
Parameter	description	Value	Source
p	fish price	10	Guess
α	water discharge cost coefficient	0.1	Guess
β	water discharge cost coefficient	0.2	Guess
R	radius of the half sphere lake	5	Guess
q	proportion of fish harvest by discarging flow volume $V(t)$	$\frac{X_0}{W_0} = 0.0764$	
r	daily discount rate	0.0002	Guess
g	acceleration of gravity	1.98 m/sec^2	
C_v	incompressibility of water	0.97	
C_c	contraction coefficient (sharp edge aperture 0.62, well rounded aperture 0.97)	0.97	
$C_d = C_c \times C_v$	flow discharge coefficients	0.9409	
X_0	initial fish stock	20	Varied
h_0	initial water level	R	Varied
h_T	final water level	0.3	Varied
t_0^f	fishing season start	November 1st	Data
T^f	fishing season length	93	Data

A.1 Derivation of $\frac{dh}{dt}$

A.1.1 Method 1

Radius of slice h:

$$radius(h) = \sqrt{2Rh - h^2} \tag{10}$$

Area of the circle of the slice with height h

$$A(h) = \pi(radius)^2 = \pi(2Rh - h^2) \tag{11}$$

Water volume W up to h is

$$\begin{aligned} W(h) &= \int_0^h A(s)ds = \int_0^h \pi[2Rs - s^2]ds \\ \Rightarrow \frac{dW}{dh} &= A(h) \\ \Rightarrow \frac{dW}{dt} &= \frac{dW}{dh}\frac{dh}{dt} = A(h)\frac{dh}{dt} \end{aligned} \tag{12}$$

Because outlet flow volume is

$$\begin{aligned} \frac{dW}{dt} &= -V = -C_d AP(t)\sqrt{2gh(t)} \\ \Rightarrow -C_d AP(t)\sqrt{2gh(t)} &= A(h)\frac{dh}{dt} \\ &= \pi[2Rh(t) - h^2(t)]\frac{dh}{dt} \end{aligned} \tag{13}$$

$\frac{dh}{dt}$ becomes

$$\frac{dh}{dt} = \frac{-C_d AP(t)\sqrt{2gh(t)}}{\pi(2Rh(t) - h^2(t))} \tag{14}$$

if $h(t) \neq 0$. $h(t) \neq 2R$ always holds because $h(t) \in [0, R]$.

A.1.2 Method 2

The alternative way to derive $\frac{dh}{dt}$ starts from the Equation 2b, which is an integration of $W(h) = \int_0^h A(s)ds = \int_0^h \pi[2Rs - s^2]ds$

$$\begin{aligned} W(t) &= \frac{\pi}{3}(h(t))^2(3R - h(t)) \\ \Rightarrow \frac{dW(t)}{dt} &= 2\pi Rh(t)\frac{dh}{dt} - \pi h^2(t)\frac{dh}{dt} \\ \Rightarrow -V(t) &= (2\pi Rh(t) - \pi h^2(t))\frac{dh}{dt} \\ \Rightarrow \frac{dh}{dt} &= \frac{-V(t)}{2\pi Rh(t) - \pi h^2(t)} \\ &= \frac{-C_d AP(t)\sqrt{2gh(t)}}{\pi(2Rh(t) - h^2(t))} \end{aligned} \tag{15}$$

if $h(t) \neq 0$.

B Fishery problem with fixed AP

B.1 Derivation of the relationship between T and AP

Assuming $AP(t) = AP$, the ordinary differential equation 14 can be solved by separating variables.

$$\begin{aligned}
\tfrac{2Rh-h^2}{\sqrt{h}}dh &= -\tfrac{C_d AP\sqrt{2g}}{\pi}dt \\
\int \tfrac{2Rh-h^2}{\sqrt{h}}dh &= -\int \tfrac{C_d AP\sqrt{2g}}{\pi}dt \\
\tfrac{4}{3}Rh^{\frac{3}{2}}(t) - \tfrac{2}{5}h^{\frac{5}{2}}(t) &= -\tfrac{C_d AP\sqrt{2g}}{\pi}t + \tfrac{4}{3}Rh(0)^{\frac{3}{2}} - \tfrac{2}{5}h(0)^{\frac{5}{2}} \\
\Rightarrow t &= \tfrac{\pi[(\frac{2}{5}h^{\frac{5}{2}}(t) - \frac{2}{5}h^{\frac{5}{2}}(0)) - (\frac{4}{3}Rh^{\frac{3}{2}}(t) - \frac{4}{3}Rh^{\frac{3}{2}}(0))]}{C_d AP\sqrt{2g}}
\end{aligned} \tag{16}$$

or

$$\begin{aligned}
\tfrac{2Rh-h^2}{\sqrt{h}}dh &= -\tfrac{C_d AP\sqrt{2g}}{\pi}dt \\
\int_{h(0)}^{h(t)} \tfrac{2Rh-h^2}{\sqrt{h}}dh &= -\int_{h(0)}^{h(t)} \tfrac{C_d AP\sqrt{2g}}{\pi}dt \\
\Rightarrow t &= \tfrac{\pi[(\frac{2}{5}h^{\frac{5}{2}}(t) - \frac{2}{5}h^{\frac{5}{2}}(0)) - (\frac{4}{3}Rh^{\frac{3}{2}}(t) - \frac{4}{3}Rh^{\frac{3}{2}}(0))]}{C_d AP\sqrt{2g}}
\end{aligned} \tag{17}$$

If we set $h(0) = R$, and $h(T) = \varepsilon$, the time to drain the lake with given aperture size AP is

$$T = \pi \frac{\frac{14}{15}R^{\frac{5}{2}} + \frac{2}{5}\varepsilon^{\frac{5}{2}} - \frac{4}{3}R\varepsilon^{\frac{3}{2}}}{C_d AP\sqrt{2g}}. \tag{18}$$

Or the aperture size AP with given T is

$$AP = \pi \frac{\frac{14}{15}R^{\frac{5}{2}} + \frac{2}{5}\varepsilon^{\frac{5}{2}} - \frac{4}{3}R\varepsilon^{\frac{3}{2}}}{C_d T\sqrt{2g}}. \tag{19}$$

The present value of profit $\pi(t) = e^{-rt}\{p(t)qZAP\sqrt{h(t)} - \alpha ZAP\sqrt{h(t)} - \beta ZAP^2 h(t)\}$ could be calculated at each time point $t \in [0, T]$. The total profit over the horizon can be approximated by `trapz` function in MATLAB.

The numerical solution when $h(T) = \varepsilon = 0.3$, $T = 93$ is $AP^* = 0.4144$, $\pi = 16.8965$. Other parameters: $\alpha = 0.1$,$\beta = 0.2$,$p = 10$ (See Figure 16).

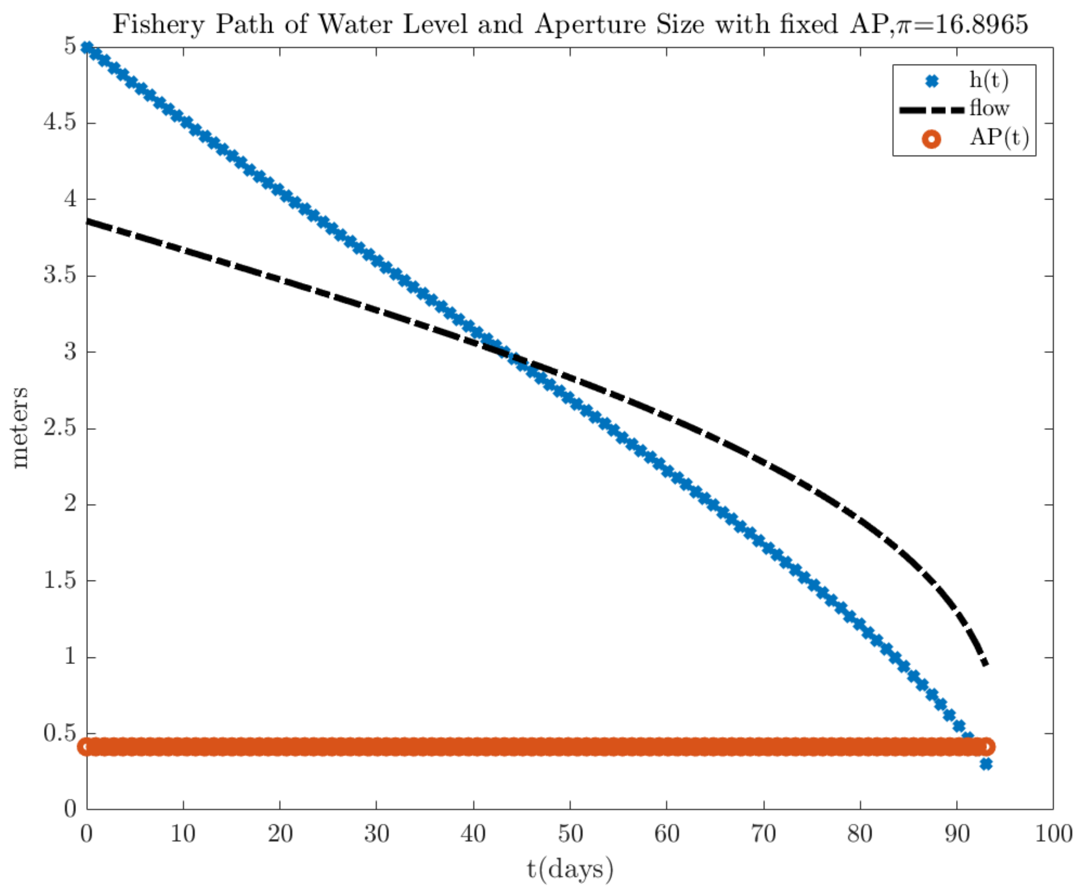


Figure 16: Fixed Aperture Size

C Fishery problem with $AP(t)$

C.1 Analytical Solution using Optimal Control Theory

C.1.1 Set up the Hamiltonian

$$G^{CV}(t) = pqZAP(t)\sqrt{h(t)} - \alpha ZAP(t)\sqrt{h(t)} - \beta ZAP^2(t)h(t) + \lambda^{CV}(t)\frac{-ZAP(t)\sqrt{h(t)}}{\pi(2Rh(t) - h^2(t))} \quad (20)$$

C.1.2 The Pontryagin conditions

$$\max_{AP(t)} G^{CV} \Rightarrow \frac{\partial G^{CV}(t)}{\partial AP(t)} = pqZ\sqrt{h(t)} - \alpha Z\sqrt{h(t)} - 2\beta Z^2 AP(t)h(t) - \lambda^{CV}(t)\frac{Z\sqrt{h(t)}}{\pi[2Rh(t) - h^2(t)]} = 0 \quad (21a)$$

$$\begin{aligned}\dot{\lambda}^{CV}(t) - r\lambda^{CV}(t) = & -\frac{\partial G^{CV}(t)}{\partial h(t)} \\ = & -pq\frac{ZAP(t)}{2\sqrt{h(t)}} + \frac{\alpha ZAP(t)}{2\sqrt{h(t)}} + \beta Z^2 AP^2(t) + \lambda^{CV}(t)\frac{ZAP(t)}{\pi}[\frac{1}{2\sqrt{h(t)}(2Rh(t)-h^2(t))} - \frac{2\sqrt{h(t)}(R-h(t))}{(2Rh(t)-h^2(t))^2}]\end{aligned} \quad (21b)$$

$$\dot{h}(t) = \frac{-ZAP(t)\sqrt{h(t)}}{\pi(2Rh(t) - h^2(t))} \quad (21c)$$

From Equation 21a, if $h(t) \neq 0$,

$$\lambda^{CV}(t) = [pq - \alpha - 2\beta ZAP(t)\sqrt{h(t)}]\pi[2Rh(t) - h^2(t)]. \quad (21d)$$

Therefore, we will have

$$\begin{aligned}\dot{\lambda}^{CV}(t) = & -2\beta Z\dot{AP}(t)\sqrt{h(t)}\pi[2Rh(t) - h^2(t)] - \frac{2\beta ZAP(t)}{2\sqrt{h(t)}}\dot{h}(t)\pi[2Rh(t) - h^2(t)] \\ & +[pq - \alpha - 2\beta ZAP(t)\sqrt{h(t)}]\pi[2R - 2h(t)]\dot{h}(t)\end{aligned} \quad (21e)$$

Plug $\dot{h}(t)$ Equation 21c into $\dot{\lambda}(t)$ Equation 21e,

$$\begin{aligned}
\dot{\lambda}^{CV}(t) = \quad & -2\beta Z\dot{AP}(t)\sqrt{h(t)}\pi[2Rh(t)-h^2(t)] - \tfrac{2\beta ZAP(t)}{2\sqrt{h(t)}}\tfrac{-ZAP(t)\sqrt{h(t)}}{\pi(2Rh(t)-h^2(t))}\pi[2Rh(t)-h^2(t)] \\
& + [pq-\alpha-2\beta ZAP(t)\sqrt{h(t)}]\pi[2R-2h(t)]\tfrac{-ZAP(t)\sqrt{h(t)}}{\pi(2Rh(t)-h^2(t))} \\
= \quad & -2\beta Z\dot{AP}(t)\sqrt{h(t)}\pi[2Rh(t)-h^2(t)] + \beta Z^2 AP^2(t) \\
& -[pq-\alpha-2\beta ZAP(t)\sqrt{h(t)}][2R-2h(t)]\tfrac{ZAP(t)\sqrt{h(t)}}{2Rh(t)-h^2(t)}
\end{aligned} \tag{21f}$$

Plug $\lambda^{\dot{CV}}(t)$ Equation 21f and $\lambda^{CV}(t)$ Equation 21d into Equation 21b,

$$\begin{aligned}
\dot{\lambda}^{CV}(t) - r\lambda^{CV}(t) = \quad & -2\beta Z\dot{AP}(t)\sqrt{h(t)}\pi[2Rh(t)-h^2(t)] + \beta Z^2AP^2(t) - [pq-\alpha-2\beta ZAP(t)\sqrt{h(t)}][2R-2h(t)]\tfrac{ZAP(t)\sqrt{h(t)}}{2Rh(t)-h^2(t)} \\
& -r[pq-\alpha-2\beta ZAP(t)\sqrt{h(t)}]\pi[2Rh(t)-h^2(t)] \\
= \quad & -pq\tfrac{ZAP(t)}{2\sqrt{h(t)}} + \tfrac{\alpha ZAP(t)}{2\sqrt{h(t)}} + \beta Z^2AP^2(t) + [pq-\alpha-2\beta ZAP(t)\sqrt{h(t)}]\pi[2Rh(t)-h^2(t)]\tfrac{ZAP(t)}{\pi}[\tfrac{1}{2\sqrt{h(t)}(2Rh(t)-h^2(t))} - \tfrac{2\sqrt{h(t)}(R-h(t))}{(2Rh(t)-h^2(t))^2}]
\end{aligned} \tag{21g}$$

Rearrange Equation 21g,

$$\begin{aligned}
2\beta Z\sqrt{h(t)}\pi[2Rh(t)-h^2(t)]\dot{AP}(t) = \quad & \beta Z^2AP^2(t) - r[pq-\alpha-2\beta ZAP(t)\sqrt{h(t)}]\pi[2Rh(t)-h^2(t)] \\
\Rightarrow \dot{AP}(t) = \quad & \tfrac{ZAP^2(t)}{2\sqrt{h(t)}\pi[2Rh(t)-h^2(t)]} - \tfrac{r}{2\beta Z\sqrt{h(t)}}(pq-\alpha-2\beta ZAP(t)\sqrt{h(t)})
\end{aligned} \tag{21h}$$

if $h(t) \neq 0$.

Thus, given $h(t) \neq 0$, the Pontryagin conditions are

$$\dot{h}(t) = \frac{-ZAP(t)\sqrt{h(t)}}{\pi(2Rh(t)-h^2(t))} \tag{22a}$$

$$\dot{AP}(t) = \frac{ZAP^2(t)}{2\sqrt{h(t)}\pi[2Rh(t)-h^2(t)]} - \frac{r}{2\beta Z\sqrt{h(t)}}(pq-\alpha-2\beta ZAP(t)\sqrt{h(t)}) \tag{22b}$$

C.1.3 Boundary conditions

Boundary conditions are given T, given $h(0) = R$, $h(T) = \varepsilon$.

C.1.4 Numerical solution

1. Fixed T, $h(0) = R = 5$, $h(T) = \varepsilon = 0.3$. (See Figure 12a).

D Birds and tubers system

Table 3: Variable and parameter definitions with values and sources in birds and tubers system

State and Choice Variable	Label	Range	
	Variables continuous within year j		
$AP_j(t)$	size of aperture at t	$[\underline{AP}, \overline{AP}]$	
$h_j(t)$	water level at t	[0, R]	
$S_j(t)$	surface area under water at t	$[0, 2\pi R^2]$	
$C_j(t)$	accessible tubers per capita at t		
$E_j(t)$	energy reserve at t	$[0, \infty]$	
t	day	[1, T]	
	Variables continuous within year and discrete between year		
$B_j(t)$	number of cranes at time t year j		
	Variables discrete between year		
M_j	tuber stock at year j	10000	Guess
f_j	juvenile survival rate at year j	[0,1]	
Parameter	description	Value	Source
ρ	fraction of accessible tubers per capita that cranes forage	1	Guess
c	daily metabolic cost	0.1	Guess
ζ	wintering survival rate coefficient	0.1	Guess
p	juvenile survival rate coefficient	1	Guess
n	reproduction rate of the crane	10%	Johnsgard [
d	death rate of the crane	0.09	Guess
g	acceleration of gravity	$9.81\ m/s^2$	
C_v	velocity coefficient of water	0.97	
C_c	contraction coefficient (sharp edge aperture 0.62, well rounded aperture 0.97)	0.97	
$C_d = C_c \times C_v$	flow discharge coefficient	0.9409	
α	water discharge cost coefficient	0.1	Guess
β	water discharge cost coefficient	0.2	Guess
$E_j(0)$	initial energy reserve	5	Guess
$B_1(0)$	initial crane population	3000	Data
t_0^B	bird wintering season start	0(November 1st)	Data
T^B	bird wintering season length/end	150 (March 31st)	Data

E Joint model with insufficient tubers

With insufficient tuber, the within-year crane death is inevitable.

- fishery only: we see water releases stops on February 1st and crane decreases over year from the initial 3000 to 1793 (Figure 17).
- crane conservation only: water releases continuously from November 1st to March 31st. Yet, the crane population decreases from the initial 3000 to 1814 over five year (Figure 18).
- joint management:water release covers the whole wintering season with two sets of water flow

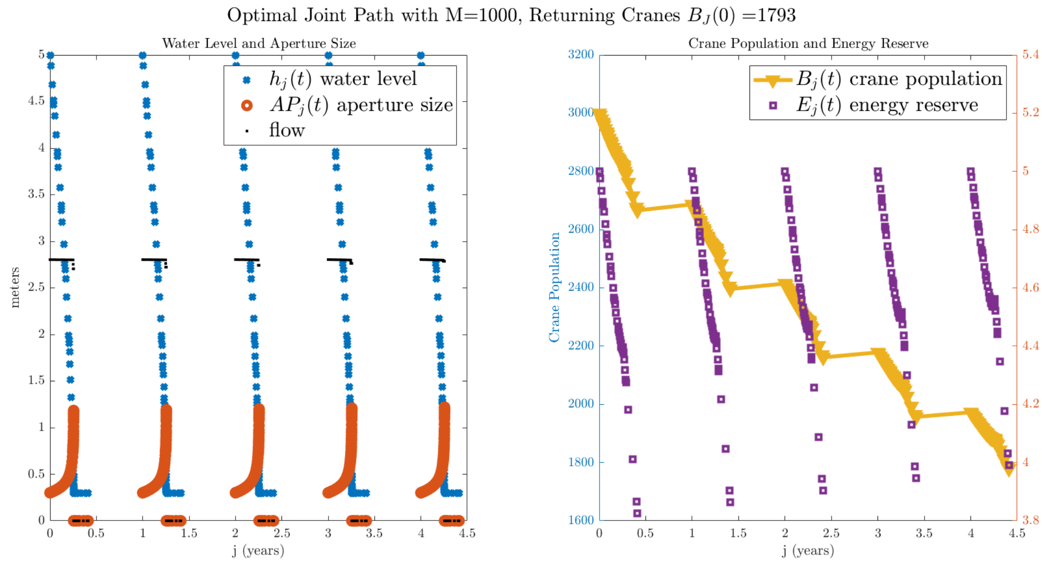


Figure 17: Insufficient tuber, No water release after Feb 1st, cranes 3000 ↓ 1793

and aperture sizes. The crane population decreases from the initial 3000 to 1814 (Figure 19).

F Sub-lake Information

There are 102 sublakes in Lake Poyang basin area including 9 sublakes in the Poyang Lake Nature Reserve and 33 sublakes in the Nanjishan Nature Reserve. The sublakes differ in shape, size, and elevation.

Sublakes	Lakeshore Elevation†				Lake Bottom Elevation	Drainage Gate Bottom Elevation	Water Area (km^2)	Volume ($10^8 m^3$)	Water Depth (m)
	Hills or Permanent Dikes		Short Dikes						
	Minimum	Maximum	Minimum	Maximum					
Dahuchi	19.02	22.31	14.37	17.59	11.82	10.36	29.45	0.679	15.0
Shahu	16.13	17.03	14.02	16.05	12.22	11.05	10.31	0.103	13.5
Banghu	19.64	21.1	12.12	18.09	10.82	9.77	43.66	0.309	12.0
Zhushihu	16.65	23.42	14.44	16.30	11.92	11.55	2.15	0.027	14.5
Changhuchi	17.45	21.84	12.38	15.94	12.12	11.41	2.91	0.038	13.5
Zhonghuchi	18.73	21.14	13.96	15.30	12.42	11.26	4.744	0.051	14.0
Meixihu	16.92	27.54	14.24	16.48	12.52	11.22	2.039	0.028	14.5
Xianghu	20.63	21.18	13.9	15.94	12.92	11.57	2.686	0.024	14.5
Dachahu‡	15.32	21.05	13.7	14.94	10.32	11.20	48.95	0.23	10.9

- †: Sublakes are generally connected to rivers. The dikes/levees between the sublake and the river are naturally formed and artificially enhanced. The remaining sections of the lake shore are generally hills or permanent dikes. In the photo of the dry Dahuchi in 2004 Figure 20a, upper left is the hillside of Dingshan Hill while the upper right is the short dike next to Xiu River.
- ‡: Dachahu is a marsh. The drainage gate is the drainage ditch.

Table 4: Geographic Information of 9 Sublakes in Poyang Lake Nature Reserve (Yellow Sea Elevation) (Source: Hu [2020])

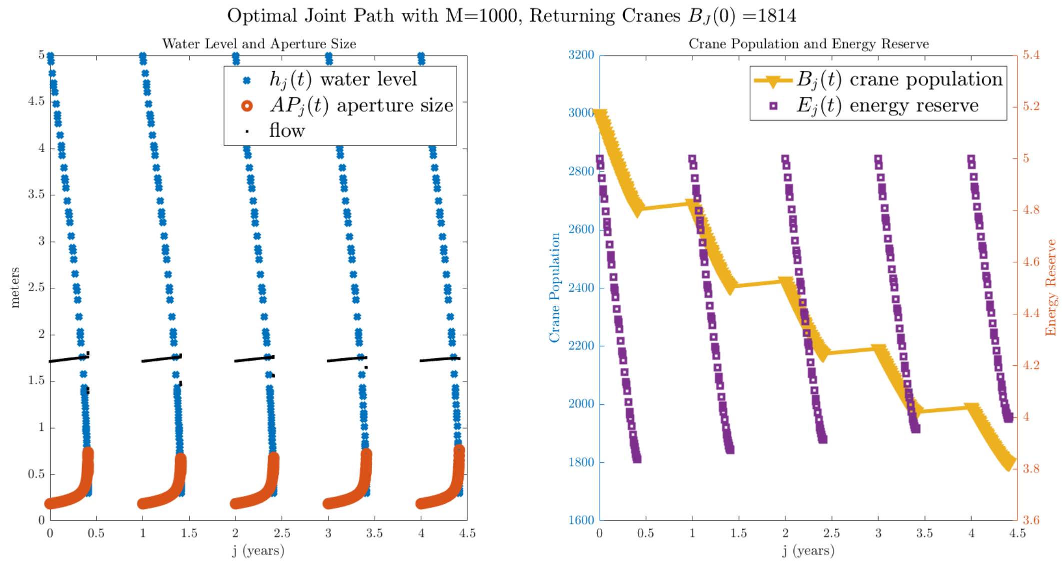


Figure 18: Insufficient tuber, Water release till March 31st, cranes 3000 $\downarrow$ 1814($>$ 1793)

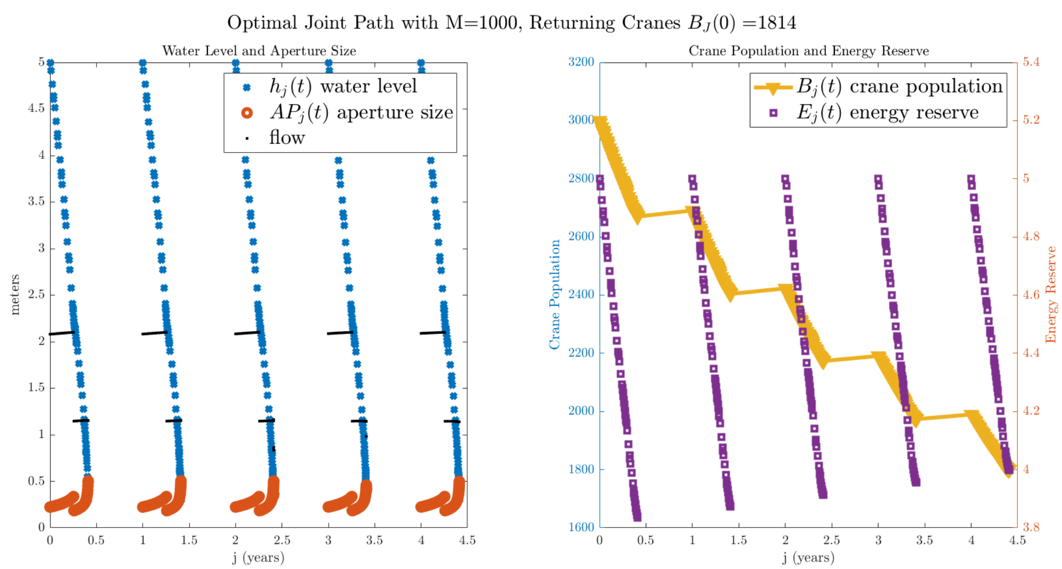
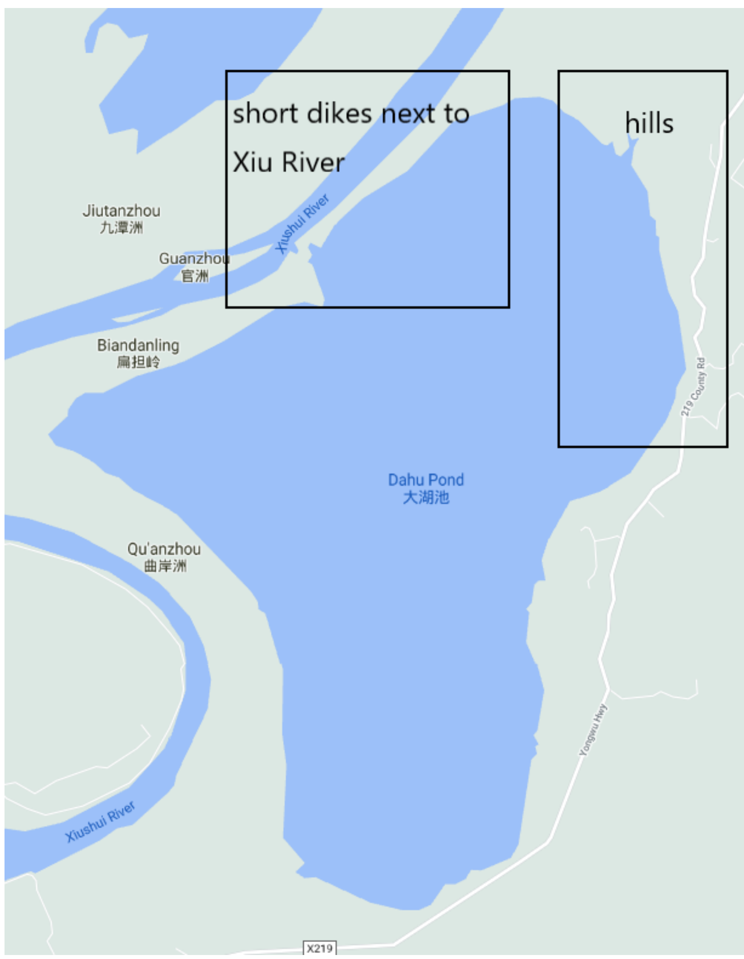


Figure 19: Insufficient tuber, By extending water release season, cranes 3000 $\downarrow$ 1814($>$ 1793)

(a) Dahuchi in 2004 (Source: Hu [2020]). Upper left is the hillside of Dingshan Hill while the upper right is the short dike next to Xiu River



(b) Map of Dahuchi

Figure 20: Sublake