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Restoring Drying Lakes with Treated Agricultural Effluents under a Carbon-based Payments for Ecosystem Services Incentive

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Abstract

Wetlands store a significant proportion of terrestrial carbon, however, when degraded and dry, they can become net carbon emitters. Climatic stressors, such as rising temperature and reduced precipitation, further exacerbate carbon release risks. This study explores incentivizing adoption of constructed wetlands (CW) on agricultural farms for treating effluents and releasing into drying lakes. A payment for ecosystem services (PES) framework is developed to analyze land use allocation decisions of farmers towards adopting CWs on their private farms. Release of treated agricultural wastewater helps a drying lake remain wet under a warming climate preventing release of carbon stored in its soils. Results indicate that PES payments equaling 10,000 to 20,000 INR (150-300 US dollars) per mega litre (ML) can be effective in incentivizing adoption of CWs on farms in India, and their benefits to drying lakes can be significant. Specifically, life of lakes can be prolonged to more than 100 years under such PES based schemes besides resulting in substantial carbon storage in soils. Such PES schemes can be a cost-effective way to not only protect and conserve lakes for their biodiversity and livelihood benefits but also from a carbon mitigation perspective. Results further show that when a social planner allocates land between farming and CW, incorporating the carbon sequestration benefits of lakes and when facing a risk of abrupt and permanent drying of lakes, their adoption rate is higher compared to that of the farmers. When extrapolated, carbon benefits from such PES programs for the entire country could be nearly 15 trillion USD over the next 100 years.

Keywords: Drying lakes; constructed wetlands; carbon release; payments for ecosystem services; agricultural effluents; carbon sequestration

1. Introduction

Wetlands occupy about 12 million km² of global geographical area (Moomaw et al., 2018). They also store the most amount of carbon in the biosphere at nearly 30% of the total 15 Pg soil carbon (Nahlik and Fennessy, 2016). In the United States, there is about 10 times more carbon (at 9.6×10^{15} g C) stored in wetlands than in tidal saltwater sites (Braun et al., 2019). However, owing to anthropogenic pressures, the planet has been losing wetlands at a rapid pace. Since 1700 AD, we have lost 87% of the world's wetlands (Davidson, 2014). In the 20th century, coastal wetlands globally declined at a rate of 0.7-1.2% annually resulting in more than 60% loss to their total area. The loss in coastal wetlands has been highest in Asia at 1.1%, whereas in Europe it has been 0.99% and 0.51% in America (Lin and Yu, 2018). In China, wetlands are being lost at a rate of 10 km²/yr (Hu et al., 2019).

In India, more than a third of existing wetlands have been lost due to encroachment, urbanization, land use changes and warming temperatures. Wetlands in India occupy almost 5% of the country's geographical area. Currently India is losing wetlands at a rate of 2-3% per year (Prasher, 2018). Foote et al. (1996) identified 12 major causes of wetland loss in India, including agricultural conservation, deforestation, hydrological alteration, water quality degradation, wetland consolidation and groundwater extraction. More than 50,000 wetlands in India have been rendered dead from water pollution alone (Prasad et al., 2002). Owing to urban expansion and encroachment, in Mumbai, more than 70% of wetlands have been lost over the past four decades (Chauhan, 2020). Similarly, lake Shambhar in Rajasthan faces extinction threats due to encroachment and groundwater extraction (Rana, 2019). Whereas Karanji lake in Mysuru, India has completely dried up (Milton, 2019).

Warming temperatures are further projected to cause an increase in lake water evaporation rate over the course of this century (Wang et al., 2018). Based on IPCC's A1B scenario, climate change could cause significant drying of Montane wetlands in the US Pacific Northwest (Lee et al., 2015). Similarly, warming temperatures and reduced precipitation are expected to decrease wetlands in Canada by between 7 and 47% (Withey and van Kooten, 2011). Due to frequent drought conditions, Chad and Urmia lakes in Africa have shrunk by 80% and 65% (Smith, 2012). Warming temperatures also increase the risk of fires. The great Dismal Swamp sequesters significant amounts of carbon, however catastrophic fires can cause a release of 6.5 million tonnes of CO₂ and a net present value (NPV) of losses amounting to more than 200 million USD (Pindilli et al., 2017).

Climate change is also increasing the frequency of droughts, causing several wetlands to go dry temporarily and permanently. Dry wetlands can become net emitters of methane and carbon (Petrescu et al., 2015; Stirling et al., 2020). Degraded wetlands have been found to be net carbon emitters and their restoration can be 100 times more cost-effective as compared to alternative carbon mitigation options (Were et al., 2019). Restored wetlands in Illinois, USA sequestered between 25 and 45% more carbon compared to degraded ones after 3 years of restoration (Were et al., 2019). The difference in sequestration rate further improved to more than 50%, 10 years after degradation. Whereas a meta-analysis of more than 600 wetlands globally found that the sequestration rate in restored wetlands remained about 25% lower compared to undegraded wetlands (Moreno-Mateos et al., 2012). Further, restoration benefits only start to manifest after a certain point of time, resulting in time lag costs of forgone benefits to society. In Ohio, USA, the average time lag cost of restored wetlands has been estimated at about 16,000 USD per acre (Gutrich et al., 2004). Similarly, in Colorado, time-lag costs in terms of mitigation wetlands

reaching full floristic equivalency have been estimated at about 27,000 USD/acre (Gutrich et al., 2004). Therefore, it is important to prevent degradation of wetlands in order for society to maximize benefits from carbon mitigation efforts.

There exists a significant body of work in the literature dealing with the determinants of wetland loss as well as analyzing the use of existing and new policy tools for their protection. Section 404 of the Clean Water Act in the United State mandates that for every wetland that is lost due to draining, a new wetland must be created to offset the services provided by the lost wetland (Ribaudou et al., 2009). As a result, there are currently more than 600 mitigation banks in the US that provide credits for wetland restoration which can be sold to developers who destroy wetlands. Similarly, the possibility of using environmental impact bonds for restoring wetlands in Louisiana has been explored by Herrera et al, (2019). Under this scheme, investors pay in advance for restoration projects however, their returns are guided by the degree of environmental outcome achieved. Carbon credits for conservation efforts have also been promoted. Nath and Lal (2016) explored the possibility of managing global wetlands towards rice output expansion while simultaneously promoting soil organic carbon conservation in the littoral zones. Further, society's valuation of wetlands could be capitalized towards investment in wetland preservation initiatives. Birol et al., (2006) performed choice experiments to assess the value of Cheimaditida wetland in Greece through willingness to pay (WTP) of respondents. They found that the aggregate net benefit of attaining wetland restoration (respondents' WTP minus the costs of restoration program) was about 3 million euros.

Agricultural expansion is one of the key stressors of wetlands globally. Farmers' perceptions related to the value of wetlands may differ significantly from other stakeholders such as the government, fishermen and wetland non-users. In the Rushebey-Kanyabaha wetland of

southwest Uganda, farmers perceived agricultural expansion in the wetland area to be beneficial for their livelihoods whereas wetland non-users expressed a strong preference towards wetland conservation (Bosma et al., 2017). Whereas in a Swedish catchment-based wetland creation program, farmers expressed their willingness to voluntarily participate for private profit as well public environmental benefits related reasons (Soderqvist, 2003). Similarly, in China, creating better awareness about the ecological benefits of wetlands amongst farmers reduced the required compensation payments and overall restoration costs (Wei et al., 2021). A meta-analysis of 78 studies revealed that participation in PES programs increased with ownership of capital assets such as land endowments and financial wealth (Jones et al., 2020).

Given that agriculture directly and indirectly poses a significant threat to wetlands, the solution to their conservation must also be explored within that sector. For instance, farmers could be incentivized to reduce effluent loadings into streams that end up in wetlands. Heberling et al. (2010) explore the use of wetlands in reducing nutrients in water streams through water quality trading-based incentives in the United States. Wetlands also sequester large amounts of carbon, which could be further promoted through payments for ecosystem services (PES) incentives. Several studies have explored carbon mitigation value of wetlands. The Wetland Reserve Program (WRP) in the Mississippi Alluvial Valley generates an annual carbon mitigation value of between 177 and 222 USD/ha through restoration of degraded wetlands (Jenkins et al., 2010). Wetlands in Nova Scotia have been estimated to sequester on average of 4.99 tons/ha/yr of carbon, yielding a value of \$124-373/ha/yr or a total value of 10 billion Canadian dollars (Gallant et al., 2020). Apart from carbon benefits, flood protection services of wetlands can also be substantial (Calder et al., 2019).

While carbon mitigation potential of wetlands has been widely recognized, there are few programs that incentivize farmers to adopt best management practices on farms that could result in higher carbon sequestration in wetlands. The use of constructed wetlands (CWs) is increasingly being promoted for treating agricultural effluents and industrial wastewater (National Research Council, 2012; Wang et al., 2018; Garcia et al., 2020). In coastal catchments of Stockholm Sweden, 30% of surveyed farmers in a choice experiment study were willing to create wetlands on their farms to mitigate eutrophication of waterbodies (Franzen et al., 2016). However, their use for protecting natural lakes from drying and preventing release of carbon under future warming scenarios remains unexplored thus far. Recognizing this gap, we propose a PES framework that could incentivize farmers to adopt CWs on their private lands and contribute towards lake conservation and carbon mitigation objectives while simultaneously augmenting livelihoods.

Treated agricultural wastewater discharge from CWs to natural lakes can help improve water quality and volume, thereby reducing the risk of future drying and carbon loss. Release of treated agricultural effluents would ensure that the lake would have water even in drought years and would avoid irreversible degradation and loss. Landowners converting nutrient rich effluents into cleaner water could get paid carbon credits based on the volume of water discharged into the lake. If the lake became dry, it would turn into a net carbon emitter, resulting in long term societal damages. Further, a dry lake is more likely to get encroached upon or being temporarily used for growing crops. This could result in release of all carbon stored in the soil. When faced with such risks, the socially optimal water pollution abatement effort would be higher than what may be possible through water quality trading programs that are operational in some parts of world today.

In this study, a dynamic optimization model of CW adoption on agricultural farms is developed keeping in mind the long run benefits of releasing treated effluent water into the lake.

Water released into the lake from farms helps mitigate the effects of a warming climate, which is projected to cause increasing evapotranspiration rates over the course of the century. Optimal rate of CW adoption is compared from private farmers' and the social planner's perspective, where the latter also incorporates the risk of carbon release from a sudden drying of the lake. Implications on carbon sequestration and loss prevention are derived under several scenarios. This study contributes to the PES literature through demonstrating how financial incentives could be utilized to get farmers directly involved in carbon mitigation objectives while simultaneously benefiting wetland biodiversity and community livelihoods. It also adds to the literature dealing with the promotion of constructed wetlands through linking adoption of CWs on private farms to the protection of natural wetlands.

2. Model

2.1. Background

Consider that farmers in a community adopt CW technology on their individual farms. Farmers are assumed homogenous with respect to their land size, quality and crop choices so that a representative farmer can make land use and CW adoption decisions for the entire community. CWs on individual farms are connected through a drainage canal to a main channel that empties into the natural lake. The irrigation water used for farming is treated in the CWs before being released into the canal. Assuming a water scarce world, farmers do not extract groundwater for irrigating their crops as groundwater levels are too low. It is further assumed that the groundwater aquifer is not linked to the wetland so that a reduction in the groundwater levels does not impact on lake water storage. Under a PES mechanism, the farmer is paid for carbon sequestered due to enhanced water availability in the wetland. Optimal CW investment is also derived from a social

planner's perspective. In addition to farmer's welfare, the social planner considers the possibility of carbon loss in case of future drying of like due to climate change or encroachment. Next, we set up the formal model.

2.2. Model

Agricultural output q_t , at time t , is given as:

$$(1) \quad q_t = q_0 \frac{(r_t (1-\varphi))^{\alpha_0}}{(r_t (1-\varphi))^{\alpha_0 + \alpha_1}}$$

where q_0 is the maximum possible output per unit area (say tons/ha) irrespective of the level of rainwater r_t applied. Parameter φ is the rainfall runoff and α_0 & $\alpha_1 > 0$ are parameters that determine a non-linear increase in crop output with water application. Total agricultural income π_t is determined as a function of crop output per ha:

$$(2) \quad \pi_t = \pi_0 q_t a_t$$

where π_0 is the net price of the crop per ton and a_t is the total area under farming at time t . Agricultural area shrinks from conversion to CWs given as:

$$(3) \quad \dot{a}_t = -i_t$$

where i_t is the investment in CW area at time t . Whereas cumulative CW area b_t improves with annual investment i_t given as:

$$(4) \quad \dot{b}_t = i_t$$

Cost m_t of CW adoption is non-linear in the area converted (Gkika, 2015), given as:

$$(5) \quad m_t = \beta_0 i_t^{\beta_1}$$

185 where, $\beta_0 > 0, \beta_1 > 0$ are parameters of the cost function which vary across regions. The volume
 186 of effluent e_t treated per period is a function of the total installed capacity (Juwarkar et al., 1995)
 187 given by the area b_t as:

$$188 \quad (6) \ e_t = \min (b_t \gamma, r_t \varphi a_t \varepsilon)$$

189 where γ is the treatment capacity per ha of CW plant and ε is a parameter converting daily rainfall
 190 on a ha of land into ML. Total volume of treated wastewater cannot exceed the maximum capacity
 191 of the CW plants, given by $b_t \gamma$. Whereas $r_t \varphi a_t \varepsilon$ is the actual runoff water available for treatment
 192 from the total area under farming. Therefore, in equation (6), the per period treatment possible
 193 from CW plants would be the minimum of the maximum treatment capacity and the actual
 194 wastewater available. In case there is excess wastewater compared to the treatment capacity in any
 195 period, it is prevented from entering the canal connecting to the lake.

196 The wastewater treated by CW plants is discharged into the lake through canals resulting in
 197 augmentation of lake water volume w_t as:

$$198 \quad (7) \ \dot{w}_t = e_t - \theta w_t - v_t \tau + r_t \delta g$$

199 where g is fixed lake area, $v > 0$ is the rate of evapotranspiration loss in each time t , $\tau >$
 200 0 is a parameter converting evaporation in mm per day per ha to ML per year, $1 > \theta > 0$ is
 201 the fraction of lake water that is lost due to overflow and groundwater seepage and $\delta > 0$ is a
 202 parameter converting rain falling on lake into water volume (in ML).

203 The rate of evapotranspiration of the lake water is further given as:

$$204 \quad (8) \ v_t = v_0(1 + \mu t)g \tau$$

205 where μ is the annual percentage increase in evaporation rate (following Wang et al., 2018) and
 206 $v_0 > 0$ is a constant evaporation rate specific to the study area. This rate is determined by several
 207 factors including temperature, windspeed, vegetation and level of eutrophication in the lake, etc.
 208 (US EPA, 2008).

209 The representative farmer receives PES payments z_t based on total volume of effluents treated
 210 and discharged into the wetland stream in each time:

$$211 \quad (9) \quad z_t = e_t p_0$$

212 where $p_0 > 0$ is the PES payment per ML of treated agricultural effluent running off into the lake
 213 stream. The lake, as long as it is wet, will sequester carbon at a constant rate σ given as (Kangabam
 214 et al., 2016; Sankar and Das, 2020):

$$215 \quad (10) \quad \dot{c}_t = \sigma$$

216 where $\dot{c}_t$ is the rate of change of carbon stored in wetland soil. In a dry state, there is a constant
 217 rate of carbon loss, which is some fraction of the sequestration rate (Miao et al., 2013):

$$218 \quad (11) \quad \dot{c}_t = -\omega \sigma$$

219 where $\omega > 0$ is a parameter which could take on a value higher than 1 under extreme dry conditions.

220 The farmer's total income y_t comprises the sum of PES and crop incomes, given as:

$$221 \quad (12) \quad y_t = z_t + \pi_t$$

222 The optimal control problem for the framer involves maximizing:

$$223 \quad (13) \quad \max_{i_t} \int_0^{\infty} y_t \exp(-\rho t) dt$$

224 where ρ is their rate of time preference. Next, consider that a social planner maximizes the income
 225 of the farmer net of societal damages from carbon release in the state when the lake turns dry. The
 226 optimization problem of the planner is to maximize:

$$227 \quad (14) \quad \max_{i_t} \int_0^{\infty} y_t \exp(-\lambda_t) \exp(-\rho t) - \dot{\lambda} \exp(-\lambda_t) \exp(-\rho t) x_t dt$$

228 where $\dot{\lambda}$ is the instantaneous hazard rate of lake running dry, λ_t is the cumulative hazard, and x_t is
 229 the net present value of future damages to society from carbon released into the atmosphere in
 230 each year the lake is dry. The expected valuation of the pre- and post -dry states is derived using
 231 the methodology for exponential hazard functions as given in Reed and Heras (1992).

232 The lake will continue to release carbon until all stored carbon stock c_t has been released.
 233 Therefore, x_t is a function of c_t . The hazard rate of lake running dry is a function of the volume
 234 of water left in the lake. At a lower volume of water, the lake runs a higher chance of suddenly
 235 running dry. Apart from hydrological factors, the lake could also get drained by farmers or be used
 236 for aquaculture through creation of bunds. The chances of such illegal encroachments increase
 237 when the lake water level is low as it is less costly to drain the remaining water.

238 Lakes can abruptly turn from wet to dry state and vice versa (Shan et al., 2018). Once the lake
 239 runs dry, it flips into a degraded state where various chemical processes in the soil result in higher
 240 bacterial activity resulting in net carbon loss (Larsen and Alp, 2015). To incorporate a sudden
 241 change in lake state from wet to dry, the risk of lake drying is modeled as a non-linear function of
 242 the water volume remaining in the lake and is given as:

$$243 \quad (15) \quad \dot{\lambda} = \lambda_0 \left(1 - \frac{\left(\frac{w_t}{w_0} \right)^{\epsilon_0}}{\left(\frac{w_t}{w_0} \right)^{\epsilon_0} + \epsilon_1} \right)$$

where λ_0 is a constant hazard parameter, $\epsilon_0 > 0, \epsilon_1 > 0$ are parameters that determine a non-linear relationship between ratio of water volume at time t to maximum water volume w_0 and the hazard rate. The higher the ratio, the lower the hazard of lake drying.

The post-drying utility u_{post} from damages is based on the social cost of carbon s_0 and is solved through maximizing the below problem:

$$(16) \quad u_{post} = \int_0^{\infty} -s_0 \omega \sigma g \exp(-\rho t) dt$$

The post-drying value function is calibrated as a non-linear function of stock of carbon through fitting the various utilities u_{post} obtained for each starting stock of carbon in the lake at the time of drying, and is given as:

$$(16) \quad x_t = \phi_0 c_t^{\phi_1}$$

where $\phi_0 > 0, \phi_1 > 0$ are parameters of the non-linear damage function.

3. Numerical Application

A numerical application of the above model is presented in this section. A representative lake from the state of Uttar Pradesh in India is considered for parameter estimation. Relevant literature supporting estimation of parameter values is discussed in section 3.1 and results are presented in section 3.2.

3.1. Model Parameters

Estimates over carbon sequestration rates in lakes vary considerably, ranging from 230 kg C/ha/yr (Moomaw et al., 2018) to 4000 kg C/ha/yr (Were et al., 2019). Lakes tend to sequester more carbon

264 as they age, whereas newly created lakes can be net emitters due to higher methane emissions. In
265 the natural wetland systems of Ohio and Costa Rica, C sequestration rate has been estimated
266 between 220-270 g C/m²/yr (Mitch et al., 2012). Carbon sequestration in wetlands is sensitive to
267 water levels, and dry wetlands or those converted into croplands can turn into significant net C
268 emitters (Petrescu et al., 2015). Restoration of degraded wetlands in China can sequester between
269 100 and 200 kg C/ha/yr resulting in an overall C storage of 0.014-0.028 Pg C/yr whereas
270 restoration of drained wetlands in Europe can result in even higher sequestration at 4000 kg C/ha/yr
271 (Were et al., 2002). Carbon release from wetland soils is sensitive to temperature changes and
272 precipitation (Miao et al., 2013). Carbon efflux in wetlands of Southeastern United States have
273 been noted to be higher during dry periods at almost 11 tons/ha/yr (Miao et al., 2013). Carbon loss
274 rate in soils doubles with every 10-degree Celsius increase in temperature (Kangabam et al., 2012).
275 In degraded arid wetlands of Australia, adding water to wetlands in the dry phase resulted in 28-
276 80% lower carbon and methane emissions (Limpert et al., 2020).

277 Average annual rainfall in India is 130 cm (Prasad et al., 2002). Average daily rainfall in
278 Saharanpur district of Uttar Pradesh is about 2.8 mm/day (Krishan et al., 2012). Evaporation rate
279 in the Sukhna lake of Uttar Pradesh varies between 2 and 10 mm/day between January and May
280 (Khobragade et al., 2016). Global lake evaporation rate, due to increasing climate warming, is
281 expected to increase by 16% by the end of the century (Wang et al., 2018). Carbon storage and
282 sequestration rates in lakes in India vary considerably. The loktak lake in Manipur, which is a
283 Ramsar site, has soil organic carbon storage of 51,800 kg/ha and annual carbon sequestration in
284 the lake is estimated at 8 tons/ha/yr (Kangabam et al., 2016). Whereas in Chatla lake of Assam,
285 stored carbon has been estimated at about 22 tons/ha (Sarkar and Das, 2020). Annual carbon
286 sequestration in the lake is estimated at 6.3 tons/ha/yr (Sarkar and Das, 2020).

Based on above observations, we assign parameter values for the numerical model. A representative region in the state of Uttar Pradesh is selected for analysis. Uttar Pradesh has large number of lakes, and many wetlands face extinction threats due to urbanization, agricultural encroachment and effluent loadings. A representative wetland, 100 ha area and depth 2 m, is selected for analysis. Daily rainfall in the representative lake's catchment and nearby farming region is assumed at 2.8 mm (Krishan et al., 2012), whereas daily evaporation rate is taken at 3 mm (Khobragade et al., 2016). Rate of carbon sequestration in the lake is taken at 4 tons/ha (following estimates for Indian lakes as in Kangabam et al., 2016; Sarkar and Das, 2020) which lies in the range of average sequestration rates in lakes in India and globally. Similarly, when dry, the lake is assumed to release 4 tons/ha of carbon annually. Starting level of carbon stored in the representative lake is taken at 50 tons/ha yr (Kangabam et al., 2016). A farming area of 100 ha is chosen, and farmers are assumed to grow rice, relying mostly on rain for irrigation. While groundwater can also be used for growing crops, we do not include it in the model to keep the analysis simple, and for the fact that the model is representing a warming climate due to which groundwater is significantly depleted. In the literature concerning CWs, the cost of setting up CWs varies with their capacity. For instance, a 200 m² CW wastewater treatment plant located at IIT Powai cost 1 million INR and had a capacity to treat 25 kld (Lukose, 2015). A CW unit with a combined area of 1 ha can treat 456.25 ML/yr of wastewater effluents. The rate of time preference of the farmer and the social planner is assumed at 6%. The complete list of parameter values is further presented in Table 1.

3.2.Results

The numerical example is solved using GAMS software and a time horizon of 150 years. Results are first derived for the base case which assumes no risk of sudden drying of lake. However, with

increasing evaporation, the lake could still run out of water in the long run. Several associated scenarios vary key parameters to explore their impact on optimal time paths of land use, CW adoption and carbon storage in the lake. Next, results are presented for scenarios where there exists a risk of the lake drying permanently. The risk-based scenarios are run from the perspective of the social planner, whereas the base case and its associated scenarios explore optimal investment in CW from the farmer's perspective.

In the base case, CW adoption gradually increases, taking 10 years to reach an area of roughly 0.66 ha (fig 1). Further adoption is not necessary given the water supply side constraints as the amount of rainfall limits the total drainage runoff. In the base case scenario, lake water volume declines for the first 7 years due to the effect of high evaporation (fig 2). Evaporation rate is also assumed to increase at a rate of 0.2% each year (or 16% over the next 80 years), which would further exacerbate water loss rate from the lake (fig 3). However, adoption of CWs begins to show its effect after 7 years when sufficient capacity is accumulated in treating effluents. Lake volume declines from 2000 ML in the first year to 781 ML by year 7 and then improves to 980 ML by year 17. However, due to increasing climate stress from warming temperatures, there is a gradual decline in the lake's water in the very long run as the lake completely dries out in 100 years. When CW area reaches 0.66 ha, there is about 300 ML of treated effluents that is released into the lake, whereas annual evaporation rate is roughly 1,100 ML from the lake in the initial years but increases to 1,300 ML by year 100. However, as the lake also receives rainfall directly, the combined effect of treated wastewater and rainwater helps improve water levels for the first 17 years, beyond which time there is a net decline. The base case also assumes that the catchment area of the lake has been encroached due to human activities and there is no additional inflow into the lake from those regions. In order to see the effects of a more severe warming effect, we increase

the rate of change of annual evaporation to 0.4%. Under this scenario, lake water improves to a lesser extent from CW intervention, and the long run decline in water volume is faster as the lake runs dry in just 60 years. Therefore, faster evaporation under a warming climate poses significant threats to lakes that receive limited annual replenishment of water. The 0.4% annual evaporation rate increase scenario does not have a reduced rate of CW adoption compared to the base case as the farmer receives the same PES (10,000 INR/ML) under the two scenarios.

In a scenario where there is no PES payment made, there is no incentive for the farmers to adopt CW. In fact, a smaller PES of 1000 INR/ML is also not good enough to incentivize adoption as it does not cover the costs of CW technology. Therefore, under the 1000 INR/ML scenario, we observe a sharp drop in the lake water volume in the lake as it dries up in just 9 years. The difference between this scenario and the base case scenario highlights the role of PES incentives in prolonging lake's life. As PES payments are increased from 10,000 to 20,000 and then to 200,000 INR/ML, time to full adoption (of 0.66 ha) reduces from 10 years to 6 years and then to 3 years. This suggests that PES can be effective in providing immediate respite to lakes that are at a higher risk of evaporation and drying. However, a higher PES can only expedite CW adoption rate. When water supply is limited and CW adoption cannot happen beyond a certain point, long run sustainability of the lake cannot be guaranteed. This is evident in comparing lake water volume under low and high PES scenarios. For the first 20 years, a higher PES results in better lake volume levels compared to a lower PES, however beyond that point the effect of higher evaporation takes over and the lake dries out in the long run under all scenarios. The base case assumes a low rainfall of 2.8 mm/day. An improvement in the rainfall to 4 mm/day can make a significant difference to the long run sustainability of the lake. Under this new scenario, lake water reaches a peak volume of about 3,800 ML by year 25 and starts to decline from then onwards, however, even at the end

of the time horizon (which is 150 years in our model), the lake volume is still at about 2500 ML. In another scenario, where rainfall is 1.8mm/day, the lake survives for only 4 years. This suggests that CW adoption needs to be promoted keeping in mind the shortfall in the long run rainfall experienced by a particular region.

We next consider two scenarios from the farmer's land size and agricultural opportunity costs perspective. When the farmer owns a lower land area (of 50 ha), adoption rate is delayed as the opportunity cost of enrolling land is higher, but more importantly, because revenues generated through farming fall short of the requirements for making faster investments into CW technology. When farm size is lower, agricultural income is also lower, which means that the farmer has to wait longer to reach the maximum CW capacity. This has an adverse impact on lake water volume as there is a sharp decline in its levels compared to the base case. In fact, the lake survives only 40 years under this scenario. Another scenario, where income from farming is 50,000 INR/ha (as compared to base case income of 100,000 INR/ha), there is a reduction in adoption rate. However, under a lower income scenario, even though it reduces the rate of adoption, complete CW adoption is reached in the long run. From fig 4, depicting the time path of agricultural incomes, it is clear that these two scenarios result in one of the lowest agricultural incomes to the farmer, which explains the low adoption rate. Also, compare PES based incomes, in fig 5, for the various scenarios. For the base case, PES income is lower compared to long run agricultural income. Whereas the highest PES scenario of 200,000 INR/ML far exceeds the agricultural income, which explains the fastest adoption rate under this scenario.

Next, we consider scenarios where a social planner maximizes incomes from farming while simultaneously accounting for the social costs of carbon released from drying of the lake. The risk of lake drying is a function of the water level, and when the water level (or volume) falls below

1000 ML, this risk increases significantly. We consider a base case risk scenario where the risk of lake drying is low. Compared to the no-risk case, the presence of risk results in higher rate of CW adoption by the planner (fig 6). This helps improve lake volume in the short term (fig 7). However, in the long run there is decline similar to no-risk case, given the water supply constraints. When the hazard rate of drying increases to 0.1 (from 0.06), there is a further increase in CW adoption rate by the planner in order to prevent the risk from increasing through keeping the lake volume higher. However, the fastest adoption happens when the planner ignores farm income in the utility function and is only concerned about social costs of carbon emissions. Under this scenario, full CW adoption occurs right in the first year. The impact of this early adoption on lake water volume (as depicted in the figure) is higher, however, given the low rainfall scenario it is not enough to protect the lake in the long run. Figure 8 depicts survival probabilities under the drying risk scenarios. Given that survival probabilities are endogenous, there is a higher rate of CW adoption to keep water level higher and prevent the lake from drying.

4. Discussion

Results from the numerical application of the model generate several important insights. From the findings, it is clear that PES mechanism can be an attractive option to induce CW adoption on private farms. PES payments of 20,000 INR/ML and 200,000 INR/ML can ensure maximum capacity installation in just 6 and 3 years. However, when there is less effluent water to treat, the long run sustainability of lakes cannot be ensured. This is especially true under a warming scenario where lake water evaporates rapidly. Under such as scenario, despite the CW based intervention, it is not possible to prolong a lake's life beyond 60 years. Similarly, when farmers' crop incomes are lower or there is less land available for farming, the high financial capital necessary for CW

installation can result in delayed adoption. Finally, when faced with risk of lake drying permanently due to a depletion in water levels, the social planner undertakes a faster rate of CW adoption as compared to the farmer. When the social planner only accounts for the social costs of carbon from carbon release in the post-drying state (that is, excludes farm incomes), the rate of CW adoption increases even further.

The value of the PES mechanism in terms of carbon mitigation benefits to society can be judged from the fact that in absence of PES incentives the lake dries up in just 9 years, whereas under PES it lasts 110 years. Therefore, under the PES initiative there is an additional carbon sequestration for about 100 years, which at a rate of 4 tons/ha/yr would result in 40,000 tons of extra carbon sequestration (given the lake area of 100 ha). In addition, damages from release of carbon for the next 100 years are also avoided. Assuming a carbon release rate of 4 tons/ha from dry lakes, another 40,000 tons of release is prevented. At a social cost of carbon of \$34/ton, total value of the PES benefits in terms of carbon sequestered and avoided release would be 2.72 million USD. Further assuming that a third of India's lakes (5.45 million ha in total area) may go dry in the next 10 years, one can extrapolate the carbon benefits of such a PES program at nearly 15 trillion USD over the next 100 years. Our findings add to the existing literature on valuation of stored carbon through developing innovative mechanisms for their protection. While our model indicates that farmers would benefit from such PES programs promoting carbon preservation, other studies have found that the impact of carbon storage may be poverty alleviating or exacerbating depending upon various circumstances (Ferraro et al., 2015).

There are a few limitations of the modeling approach of this study which are worth mentioning. The role of groundwater withdrawal on wetland water dynamics is not explicitly modeled. When farming areas encroach on wetland catchments, water withdrawals and diversion for agriculture

can adversely impact on wetland water levels. The model also ignores climate change induced decrease in precipitation in the long term which could further aggravate the drying effect. The role of additional stressors on the wetland environment, such as through fishing related encroachment and draining of water for private aquaculture or irrigation have not been included. Similarly, the supply of treated water to wetlands could generate substantial biodiversity values through supporting fish and bird species. This would mean that the value of environmental services generated by the CW adopting farmers would be higher than what has been modeled in this study. There could be multiple sources through which effluents may end up in large lakes. Therefore, for such a PES mechanism to work in large lakes, multiple arrangements would be required with several parties, which may increase the regulatory and monitoring burden of key stakeholders. CW adoption in this study is limited due to reliance upon rainfall as the main source of irrigation. However, there is also possibility of using municipal wastewater effluents in CW units and utilizing it on farms or releasing for the wetlands. Such an arrangement can further enhance the effectiveness of PES schemes. Finally, CW units also release carbon and methane, which was not accounted for in the model due to the reason that most of the carbon contained in nutrient rich effluents would get released into the atmosphere in absence of CW treatment.

5. Conclusion

The planet is losing wetlands at an alarming rate. Drying wetlands pose major challenges to carbon mitigation objectives through releasing large amounts of carbon stored in their soils. In this study, a potential PES mechanism involving constructed wetlands was developed to help slow down the loss of natural lakes through involving private parties in their conservation. Specifically, a PES model derived optimal adoption rate of CWs on private farms by agricultural farmers for treating

farm effluents and releasing it into a lake. Results showed that such financial incentives could result in rapid adoption of CWs, helping mitigate risk of drying of lakes. Further, carbon benefits provided by such PES schemes, when implemented over a third of the country's total wetland area, would be nearly 15 trillion USD over the next 100 years.

In order for such PES mechanisms to be effectively implemented, regulatory, institutional and physical infrastructure may need to be strengthened. From a regulatory perspective, release of untreated effluents into water streams that end up in lakes would need to be made illegal. While many countries such as the USA and India already have such regulatory mechanisms in place, 100% compliance has not been achieved. Investment in physical infrastructure such as canals and creation of wetland boundaries would provide more incentives for farmers to invest in CWs as their returns from investment would then be guaranteed for a long time. Similarly, promoting collective participation in such programs would generate economies of scale through lowering the costs of adopting CWs. Finally, further research is needed to assess how farmers cooperate for adopting grey technologies that provide significant private and environmental benefits to society.

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465 **Funding** (Not applicable)

466 **Conflicts of interest/Competing interests** (the authors report no conflict of interest)

467 **Ethics approval** (Not applicable)

468 **Consent to participate** (Not applicable)

469 **Consent for publication** (Not applicable)

470 **Availability of data and material** (all data used in this research is contained within the
471 manuscript)

472 **Code availability** (available upon request)

473 **Authors' contributions** (Not applicable)

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579 Table 1: Parameter values used in the numerical model

Equations	Parameter Values
$q_t = q_0 \frac{(r_t.(1-\varphi))^{\alpha_0}}{(r_t.(1-\varphi))^{\alpha_0} + \alpha_1}$	$q_0 = 2 \text{ tons/ha}; r_t. = \frac{2.8mm}{day}; \varphi = 0.3; \alpha_1 = 10, \alpha_0=2$
$\pi_t = \pi_0 q_t a_t$	$\pi_0 = 100000 \text{ INR/ha}$
$m_t = \beta_0 i_t^{\beta_1}$	$\beta_0 = 1, \beta_1 = 37.5 \text{ M INR/ha}$
$e_t = \min(b_t \gamma, r_t \varphi a_t \varepsilon)$	$\gamma = 456.25 \text{ ML/ha}; \varepsilon = 0.01*365$
$\dot{w}_t = e_t - \theta w_t - v_t \tau + r_t \delta g$	$\theta = .2; \tau = 0.01; g = 100 \text{ ha}; \delta = 0.01 * 365$
$v_t = v_0(1 + \mu t)g \tau$	$v_0 = 3 \text{ mm/day}; \mu = 0.2\%$
$z_t = e_t p_0$	$p_0 = 10000 \text{ INR/ML}$
$\dot{c}_t = \sigma$	$\sigma = 4 \text{ tons/ha}$
$\dot{c}_t = -\omega \sigma$	$\omega = 1$
$\max_{i_t} \int_0^{\infty} y_t \exp(-\rho t) dt$	$\rho = 0.06$
$\dot{\lambda} = \lambda_0 \cdot (1 - \frac{(\frac{w_t}{w_0})^{\epsilon_0}}{(\frac{w_t}{w_0})^{\epsilon_0} + \epsilon_1})$	$\lambda_0 = 0.06; \epsilon_0=2; \epsilon_1 = 0.01$
$u_{post} = \int_0^{\infty} -s_0 \omega \sigma g \exp(-\rho t) dt$	$s_0 = 34 \text{ USD/ton or 2380 INR/ton}$
$x_t = \phi_0 c_t^{\phi_1}$	$\phi_0 = 1.9; \phi_1 = 0.79$

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Figure 1: Time paths of cumulative total area brought under constructed wetlands under no-risk scenarios

Figure 2: Time paths of cumulative total lake water volume under no-risk scenarios

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 590 Figure 3: Time paths of annual rate of lake water evaporation (ML) under 0.2% and 0.4% annual
 591 increase rates

Figure 4: Time paths of annual agricultural incomes compared for no-risk scenarios

Figure 5: Time paths of annual income derived through PES payments under no-risk scenarios

Figure 6: Time paths of cumulative total area brought under constructed wetlands under risk scenarios

Figure 7: Time paths of cumulative lake water volumes (ML) compared for risk scenarios

Figure 8: The probability that the lake will not turn dry until year t , depicted for lake drying risk scenarios

Figures

Figure 1

Time paths of cumulative total area brought under constructed wetlands under no-risk scenarios

Figure 2

Time paths of cumulative total lake water volume under no-risk scenarios

Figure 3

Time paths of annual rate of lake water evaporation (ML) under 0.2% and 0.4% annual increase rates

Figure 4

Time paths of annual agricultural incomes compared for no-risk scenarios

Figure 5

Time paths of annual income derived through PES payments under no-risk scenarios

Figure 6

Time paths of cumulative total area brought under constructed wetlands under risk scenarios

Figure 7

Time paths of cumulative lake water volumes (ML) compared for risk scenarios

Figure 8

The probability that the lake will not turn dry until year t , depicted for lake drying risk scenarios