Practical Paper

A multidisciplinary perspective to protect the quality of water in natural wetlands. A case study in Oaxaca, Mexico

Ignacio Sánchez-Cohen, Finlandia Barbosa-Moreno, Maritza Argelia Macias-Corral, Gabriel Díaz-Padilla and Rafael Alberto Guajardo-Panes

ABSTRACT

In Mexico, 142 sites covering almost nine million hectares are listed as Ramsar wetlands. Given the complaints of local inhabitants regarding water quality, and the interest of the federal government for setting up a plan for wetlands protection, we evaluated the ecological condition of a wetland in rural Oaxaca, Mexico. Existing water quality data were compiled and analyzed. Among the parameters of interest were temperature, pH, DO, N, P, and fecal contamination. Even though microbial contamination was a primary concern, a more important worry to local users was the presence of pesticides in water due to inadequate disposal of empty containers and runoff from upstream farmlands. Public meetings with water users, researchers, and local and federal personnel were held to get the opinion about strategies for protection of the wetlands. Outcomes of the decision meetings using a decision-support system highlighted that to preserve the wetlands, the implementation of riparian vegetation (buffer zone) and the management of surface water should be considered as conservation practices. Law enforcement would improve the watershed and wetlands’ health for preventing further deterioration. Because of the success in getting public participation and input, the approach will likely be replicated in other parts of the country.

Key words | coastal wetlands, multi-objective decision modeling software, Oaxaca Mexico, sensibility analysis, social implications

INTRODUCTION

Wetlands are essential in providing water for drinking and agriculture, cooling water for the energy sector and other services such as fisheries and tourism (Russi et al. 2015). They also provide regulating ecosystem services such as climate stabilization, water purification, mitigation of soil erosion, and they even have cultural functions such as spiritual, recreational, esthetic, and educational (Alam et al. 2017). The Ramsar Convention on Wetlands of International Importance, an intergovernmental treaty currently signed by 170 parties and protecting 2,334 sites, provides the framework for national action and international cooperation for the conservation and wise use of wetlands and their resources (Ramsar 2018). Mexico started its participation in the Ramsar Convention in 1986 and, at present, the country has 142 sites covering 8,657,057 ha listed as Wetlands of International Importance (Ramsar 2018).

Coastal wetlands show a strong relationship with the surrounding environment; consequently, they are fragile and particularly sensitive to alterations in water quality (Andreu et al. 2016) due to anthropogenic activities such as bathing and even as receiving waters of domestic effluents (wastewater). The anthropogenic release of chemicals from industry, agriculture, and the breakdown of consumer wastes constitute a major threat to water resources and...
Many wetland habitat assessments conducted by state, university, local, and citizens groups are often based on individual project goals and do not provide a compatible, consistent picture that can be used to assess conditions across broader spatial scales (Nestlerode et al. 2014). The use of multi-objective optimization models to provide decision-support tools for wetland restoration has been reported by some researchers (Schroder et al. 2018). Recently, Karanja et al. (2018) described the problems of public participation in conserving a Ramsar site in Kenya. They found that citizens were strongly interested in wetland resources conservation as long as their customary rights to governing resources were sufficiently recognized.

Ramsar wetlands in Mexico are protected by the highest level of laws. However, in practice, deterioration due to over-exploitation and lack of law enforcement for protection of water quality are a reality and a concern to many parties around the country. The Lagunas de Chacahua is a Ramsar coastal wetlands system in southern Mexico. Complaints of local water users regarding water quality issues in the wetlands (lagoons), and the interest of the National Water Commission for setting a plan to cope with this issue, called for a study with scientific meaning as the foundation for future local management plans. Therefore, the objectives of this study were: (1) to evaluate the condition of the wetlands based on strategic monitoring of water quality and public consultation, and (2) to propose conservation measures. The participation of local users and government officials to arrive at inclusive courses of action for preventing the deterioration of the ecosystem was a key part of the project. To our knowledge, this is the first attempt at using an open-source multi-objective optimization software to evaluate the current status of a Ramsar coastal wetland in Mexico and to take protective measures considering the participation of interested parties and input from regulatory agencies, research groups, and the local community (water users).

METHODS

Study site

Ramsar site No. 1819, Lagunas de Chacahua, is located in a rural coastal area of Oaxaca, Mexico (Ramsar 2018). This site was designated by Mexican authorities as a National Protected Area in 1957 and in 1986 the Chacahua Bay Beaches were designated as an area of importance for the protection of marine turtles. The wetland is connected to the lagoon known as Pastoria on a seasonal basis through a natural channel named El Corral. The site of study, also known as Chacahua-Pastoria Lagoon Complex (Figure 1), is located within the Priority Hydrological Region No. 20 Costa Chica-Río Verde in the Colotepec River basin and San Francisco sub-basin. The wetlands complex lies between 15°58' and 16°02'N and 97°33' and 97°47'W covering 3,525 ha at an elevation ranging from zero to 100 m above mean sea level. The climate is warm sub-humid with summer rains and a mean annual rainfall of about 2,719–3,737 mm and 16–35 °C average daily temperature. The rivers that flow into the lagoons are Chacalapa and San Francisco. The topography of the surrounding area includes an alluvial plain and two depressions, which are lagoons, and the deposits of waves and marine currents. The ecosystems present are high sub-evergreen jungle, pasture, dunes, mangrove, and low deciduous jungle.

Water uses

The wetlands serve as a wildlife refuge and fisheries for local rural communities. The watershed located to the north serves as the main water source for irrigation of small farms and drinking water for livestock. Water for agricultural use is 89.5%, urban public use 6.8%, services 3%, and domestic use 0.6%. Services use is the water used in two industrial facilities: a lemon oil processing plant and a water purification plant. Domestic consumption is intended for the particular use of people in households which can also include irrigation of gardens and trees and drinking water for domestic animals and cattle. Aquaculture use is also present in the lagoons for cultivation of different fish and mangrove species.

Water quality

An initial hypothesis regarding water quality of the wetlands was that it was dependent upon runoff from the watershed located to the north which discharges into them. Therefore, hydrologic monitoring of the system was performed in 2017...
and measurements of runoff and sediment loadings were included in the analyses. This situation called for a non-point source pollution approach within the watershed to identify the time and site variation of pollutants in order to propose adequate mitigation measures according to the type and level of contamination. A spatial distributed watershed model (SWAT) was calibrated. Model outcomes along with field observations indicated that water quality was not directly impacted by runoff because of the existence of a natural buffer zone within the proximity of the wetlands. Sediments were trapped or deposited there, thus they did not reach the wetlands. However, farming activities may be a source of contamination, mainly related to the inadequate disposal of containers for agrochemical use. Therefore, in order to evaluate the condition of the wetlands, water quality data were compiled from quarterly records from the National Water Commission (CONAGUA) from 2012 to 2017. The data covered sites at the two wetlands, Chacahua (seven sampling points) and Pastoria (six sampling points), as shown in Figure 1. The parameters measured included physicochemical (water transparency, color, turbidity, total suspended solids (TSS), temperature (water and ambient), pH, electroconductivity (EC), salinity, dissolved oxygen (DO), total organic carbon (TOC), total nitrogen (N), total phosphorus (P), orthophosphate, chlorophyll a) and microbial indicators (fecal coliform and fecal enterococci).

Public participation

When making decisions with a broad impact within communities, public participation of those individuals who will be impacted by the decisions is desirable (Sánchez-Cohen et al. 2011). In this study, several water users within the...
study region as well as watershed inhabitants were invited to participate in the decision-making process. Officials from the National Water Commission and state government (Ministry of the Environment and Natural Resources, National Institute of Ecology, and researchers of the University of Oaxaca) were also among the audience. The participants indicated their concerns about the status of water quality and highlighted the need of government participation to take back under control the disposal of pollutants which they thought was the main problem. In addition, the meeting organizers put forward for the audience’s consideration technical alternatives that could prevent, avoid, or ameliorate such concerns.

**Decision-making process**

By using a multi-objective decision support software (MODSS: ‘Facilitator’), the network problems of watershed deterioration and the wetlands water quality were analyzed. The history and description of this open source software is detailed in the work of Heilman et al. (2005) and Lawrence et al. (2000). The main assumption of the Facilitator is that the problem to be solved can be represented in a matrix in which the decision criteria and the selection of options are represented in its axis. To calculate an overall value, \( V \), as the sum of the products of a weight, \( w \), associated with each decision variable, or criterion, the score, \( v \), for that and \( i \) decision variable, (Equation (1)) is used. Although conceptually simple, the approach can be difficult to apply in practice because decision-makers find it difficult to assign weights or ‘subjective’ values. The essential mathematical algorithm (Yakowitz et al. 1993) is as follows:

\[
\max (V_i) = \sum_{j=1}^{n} w_i v_{ij}
\]  

subject to:

\[
\sum_{i=1}^{n} w_i = 1
\]

\[
w_1 \geq w_2 \geq w_n
\]

The first constraint (Equation (2)), normalizes the sum of weights to 1 while the second restriction requires that the solution be consistent with the importance order and restricts the weights to be non-negative. The solution of the two functions produces the complete range of all composite scores which fall between the best and worst score. In this study, the alternatives and criteria used to evaluate them are presented in Table 1.

In a participative meeting, a group of farmers (local producers) and government officials analyzed the possible alternatives for wetlands’ protection and selection criteria to score them. The alternatives and decision criteria were grouped into a matrix-like layout. Then, the farmers commented on the values assigned according to the importance of criteria versus the alternatives. The range of scores were from \(-5.0\) (a strong negative impact of the alternative on the resource of concern) to \(+5.0\) (a strong positive impact of the alternative on the resource of concern). The results are presented in Table 1.

**Table 1 | Alternatives and quality criteria for evaluation in the building of a decision matrix**

| Alternatives | Criteria |
|--------------|----------|
| Structure for waste disposal | Heavy metals and other pollutants in surface water |
| Water use | Degradation of pathogens and chemicals in surface water |
| Vegetative barrier | Degradation of pathogens and chemicals in sub surface water |
| Shallow water management | Degradation of nutrients in surface water |
| Sediment basin | Degradation of nutrients in sub surface water |
| Riparian herbaceous cover | Inadequate habitat for wildlife related with food |
| Riparian forest buffer | Inadequate habitat for wildlife related with water |
| Waste management | Waste disposal lining |
| Sediment basin | Vegetation filter |
| Filter strip | Critical area planning |
| Access control | Wetland construction |

...
concern). Thereafter, it was possible to formulate the different stages and the ranking of possible solutions to these problems in graphical form (chart).

RESULTS AND DISCUSSION

Water quality

For the purpose of addressing the local users’ concerns, the parameters of interest were temperature, pH, DO, plant nutrients (N and P), and microbial contamination. Maximum, minimum, and average concentration for physicochemical parameters as well as nutrients and microbial pollution indicators are presented in Table 2.

The Chacahua–Pastoria wetlands system is very shallow (<2 m at most points), thus ambient temperature and water temperature are closely related. Average water temperature was 29.37 °C at Chacahua and 29.8 °C at Pastoria while ambient temperature during sampling was 31.97 °C and 31.67 °C, respectively. Average and maximum pH values were in all cases above the neutral value (7.00), reaching 8.70 and 9.58 as maximum. The minimum pH was 6.80 and 6.90 at Chacahua and Pastoria, respectively. DO may also be affected by shallow and stagnant water and temperature. Even though average and maximum DO concentrations are suitable for aquatic life (>5.0 mg/L), there was a concern about low concentrations (1.10 and 2.15 mg/L) as they may not be adequate to support aquatic life.

The maximum concentration for nitrogen was 22.07 mg/L and for phosphorus 3.06 mg/L, but because they were single events, they did not have a significant effect on average concentrations which were <1.0 mg/L N at both sites and 0.24 mg/L P at Chacahua and 0.35 mg/L P at Pastoria. However, the source of the high concentrations should be investigated to prevent potential contamination. Regarding the presence of fecal coliforms and enterococci, it should indeed be a concern due to the high concentrations detected at the Chacahua–Pastoria wetlands (Table 2). Fecal coliform average (651 and 982 MPN/100 mL at Chacahua and Pastoria, respectively) and maximum (11,000 and 24,000 MPN/100 mL at Chacahua and Pastoria, respectively) were exceptionally high. Similarly, fecal enterococci also showed very high

| Parameter | Laguna Chacahua | | Laguna Pastoria | |
|-----------|-----------------|------------|-----------------|------------|
|           | Max  | Min  | Avg  | Max  | Min  | Avg  |
| Water temperature (°C) | 33.10 | 21.30 | 29.37 | 33.70 | 21.50 | 29.76 |
| Ambient temperature (°C) | 39.60 | 22.80 | 31.97 | 36.00 | 23.50 | 31.67 |
| pH | 8.70 | 6.80 | 8.01 | 9.58 | 6.90 | 8.12 |
| Turbidity (NTU) | 148 | 1 | 15 | 83 | 1 | 8 |
| TSS (mg/L) | 233 | 7 | 49 | 128 | 7 | 40 |
| EC (μS/cm) | 65,345 | 20 | 46,111 | 64,176 | 1,592 | 40,356 |
| Salinity | 38.83 | 0.04 | 29.08 | 38.82 | 0.10 | 25.09 |
| DO (mg/L) | 7.90 | 1.10 | 5.07 | 8.78 | 2.15 | 5.25 |
| TOC (mg/L) | 42.32 | 0.43 | 7.35 | 291.61 | 0.60 | 14.33 |
| N_NH3 (mg/L) | 0.96 | 0.02 | 0.15 | 3.52 | 0.02 | 0.23 |
| Total nitrogen (mg/L) | 22.07 | 0.00 | 0.63 | 7.62 | 0.00 | 0.82 |
| Total phosphorus (mg/L) | 3.00 | 0.01 | 0.24 | 3.06 | 0.01 | 0.35 |
| Chlorophyll a (mg/L) | 68.15 | 0.14 | 2.64 | 49.56 | 0.27 | 4.09 |
| Fecal coliform (MPN/100 mL) | 11,000 | 3 | 651 | 24,000 | 3 | 982 |
| Fecal enterococci (MPN/100 mL) | 24,196 | 1 | 1,380 | 12,997 | 1 | 730 |
concentrations (average 1,380 and 730 MPN/100 mL; maximum 24,196 and 12,997 MPN/100 mL at Chacahua and Pastoria, respectively). The source of microbial (fecal) contamination must be identified and controlled as soon as possible to prevent adverse effects on public health.

Monitoring of water quality is common practice in many countries, but there are significant differences among them. For instance, in the evaluation of a wetland system in Bangladesh (Alam et al. 2017), the parameters measured were pH, turbidity, EC, salinity, temperature, chemical oxygen demand (COD), biochemical oxygen demand (BOD), DO, heavy metals (Ni, Pb, Cr, Cd, Zn), and anions and cations, among others. In Spain, Andreu et al. (2016) investigated emerging pollutants of concern such as pharmaceuticals and heavy metals in coastal wetlands. A multi-level coastal wetland assessment for wetlands in the northern Gulf of Mexico even included the analyses of soil and pore water (Nestlerode et al. 2014). Wetlands provide aquatic environments with optimal conditions for the survival or proliferation of certain microorganisms which may cause disease through water consumption or direct contact (Anthonj et al. 2016), thus microbial, particularly fecal contamination, should be another parameter of interest.

Currently, there is no specific regulation applicable to wetlands’ protection in terms of water quality in Mexico. Therefore, it is very complicated to determine whether the water of the Chacahua–Pastoria system meets the criteria for coastal or protected natural wetlands. Furthermore, on a regular basis, only three parameters are monitored to determine surface water quality: BOD, COD, and TSS. An interactive map of Mexico’s surface water quality is available at http://sina.conagua.gob.mx/sina/tema.php?tema=calidadAgua.

For the site of study, the importance of the slightly acidic pH values is that local users were worried about a potential discharge from the lemon oil processing plant located upstream, which may have been reaching the wetlands and may have had the effect of acidification of the water. However, based on the water quality results, and an existing buffer zone, it appears unlikely. The presence of N and P was another concern because they can result in an increase in algae blooms that cause deterioration of water quality. Average concentrations for both parameters were low, but there were some high concentrations which need to be investigated. Hypothetically, sources of N and P could be non-point runoff from farmlands due to excessive use of fertilizers, or discharge of raw or partially treated sewage. The domestic use of water extracted from wetlands, for drinking and agricultural irrigation among other uses, has been identified as being potentially harmful to human health as a source of typhoid fever and diarrheal diseases (Anthonj et al. 2018). This type of contamination may be related to the discharge of raw or partially treated wastewater from surrounding communities into the wetland system. As shown in Figure 1, there are several small communities nearby the wetlands, thus an investigation into the disposal of domestic sewage is recommended to identify potential sources for the extremely high values for microbial contamination and the sporadic high N and P concentrations recorded at the site.

Simulator main outcomes

Wetland restoration projects require the integration of multiple factors, including managerial, ecological, and economic factors (Schroder et al. 2018). In this exercise, the best alternative selection changes according to the hierarchical order of the criteria based on the restrictions shown in Equation (2). Thus, if the prevailing criterion is the effectiveness of removing heavy metals and other pollutants present in surface water, the best alternative would be wetland enhancement followed by forest buffer zone and vegetative filter, as illustrated in Figure 2. The width of the bars shown in this figure indicate the sensitivity of the alternative; the wider the bar, the more uncertainty on the place that the alternative will take under a change of the criteria used for qualifying it. After several changes in the ranking (i.e., changing the hierarchical order of the criteria), the prevailing alternative was wetland construction indicating that the alternative will be the best choice under the criteria imposed. It is worthwhile to mention that all the alternatives that were considered will perform better than the ‘business as usual’ (‘do nothing’) scenario. The ‘do nothing’ alternative would typically be chosen when the costs of all other alternatives, both financial and environmental, significantly outweigh the benefits. The ‘do nothing’ alternative does not mean that you actually do nothing; it just means that you carry on doing whatever you would do without this planning project (Goodrich 2019). From the perspective
of the users’ lack of resources to preserve the wetlands, the establishment of riparian vegetation (buffer zone) and the management of surface water should be considered priorities. The common approach among the users and the technical group and officials that participated in the decision group was that law enforcement would enhance the watershed and wetlands’ health for preventing further deterioration of the ecosystem.

CONCLUSIONS AND FUTURE WORK

In this study, the participants in public meetings revealed two primary concerns: (1) the possibility of a lemon oil processing plant discharging effluent into streams that reach the wetlands, and (2) the possibility of having pesticides in the water due to the inadequate disposal of empty containers used on farms. Based on existing water quality data, the first supposition was eliminated as the main indicator of water acidification (pH) was within normal ranges. However, the second concern remains as agrochemicals are currently not analyzed. Therefore, future water quality monitoring is crucial and the inclusion of additional parameters such as heavy metals (Ni, Pb, Cr, Cd, Zn, Hg), indicators of organic matter (BOD and COD) and organic pollutants (e.g., pesticides and other agrochemicals) should be included. Furthermore, the dissolved fraction of nitrogen and phosphorus is recommended to be analyzed for comparison purposes with the standards used for water quality in other countries. Local participation may incorporate the needs of water users and may lead to a comprehensive plan to protect the wetlands based on local experience and resilience capacity. In our study, this opinion is also shared by government officials who have expressed their intention to replicate the exercise described in this work at some other communities with Ramsar wetlands or sensitive water resources in Mexico. Because the software used, Facilitator, is open source (https://apps.tucson.ars.ag.gov/webfacilitator/faq.html), we believe that it could also be used at some other locations with similar situations for natural resources management planning.

ACKNOWLEDGEMENTS

The authors acknowledge funding from CONAGUA-CONACYT fund which made possible this study through the development of the project ‘Biophysical Characterization
and Hydrodynamic Study and Sediment Transport to Watershed Level of Chacahua-Pastoria Lagoon Complex’, Grant No. 266193. Thank you to the anonymous reviewers for their valuable comments. The authors have no conflicts of interest to declare.

REFERENCES

Alam, M. Z., Carpenter-Boggs, L., Rahman, A., Haque, M. M., Miah, M. R. U., Moniruzzaman, M., Qayum, M. A. & Abdullah, H. M. 2017 Water quality and resident perceptions of declining ecosystem services at Shitalakka wetland in Narayanganj city. *Sustainability of Water Quality and Ecology* **9**–**10**, 53–66. https://doi.org/10.1016/j.swaqe.2017.03.002.

Andreu, V., Gimeno-García, E., Pascual, J. A., Vazquez-Roig, P. & Picó, Y. 2016 Presence of pharmaceuticals and heavy metals in the waters of a Mediterranean coastal wetland: potential interactions and the influence of the environment. *Science of the Total Environment* **540**, 278–286. https://doi.org/10.1016/j.scitotenv.2015.08.007.

Anthonj, C., Rechenburg, A. & Kistemann, T. 2016 Water, sanitation and hygiene in wetlands. A case study from the Ewaso Narok Swamp, Kenya. *International Journal of Hygiene and Environmental Health* **219** (7), 606–616. https://doi.org/10.1016/j.ijheh.2016.06.006.

Anthonj, C., Diekkrüger, B., Borgemeister, C. & Kistemann, T. 2018 Health risk perceptions and local knowledge of water-related infectious disease exposure among Kenyan wetland communities. *International Journal of Hygiene and Environmental Health* **222**, 34–48. https://doi.org/10.1016/j.ijheh.2018.08.003.

Goodrich, D. C. 2019 Automated geospatial watershed assessment (AGWA) to aid in sustaining military mission and training. In: *Guidance Documents for AGWA Tool AGWA-Facilitator Export Tool Facilitator Decision Support Tool*. ESTCP Resource Conservation and Resiliency Program Project RC201308. USDA-ARS/Southwest Watershed Research Center, Tucson, AZ, USA.

Heilman, P., Davis, G., Lawrence, P., Hatfield, J. & Huddleston, J. 2005 The facilitator – an open source effort to support multi-objective decision making. *Proceeding 1st Biennial Meeting of the International Environmental Modelling and Software Society* **3**, 253–258.

Karanja, J., Matsui, K. & Saito, O. 2008 Problems of public participation in the Ramsar CEPA programme at the Tana Delta, Kenya. *Wetlands Ecology and Management* **26** (4), 525–535. https://doi.org/10.1007/s11273-017-9589-0.

Kearns, J. P., Bentley, M. J., Mohoki, P., Redmon, J. H. & Levine, K. 2019 Underrepresented groups in WaSH – the overlooked role of chemical toxicants in water and health. *Journal of Water, Sanitation and Hygiene for Development* **9** (4), 786–793.

Lawrence, P., Shaw, R., Lane, L. & Eisner, R. 2000 Participatory multiple objective decision making processes: emerging approaches with new challenges. In: *Watershed Management=and Operations Management Conference*, American Society for Civil Engineering, 20–24 June, Fort Collins, CO, USA.

Nestlerode, J. A., Hansen, V. D., Teague, A. & Harwell, M. C. 2014 Application of a three-tier framework to assess ecological condition of Gulf of Mexico coastal wetlands. *Environmental Monitoring and Assessment* **186**, 3477–3493. https://doi.org/10.1007/s10661-014-3631-y.

Ramsar 2018 *Ramsar Sites México*. Available from: www.ramsar.org/wetland/mexico (accessed 4 December 2018).

Russe, D., Brink, P., ten Farmer, A., Badura, T., Coates, D., Forster, J., Kumar, R. & Davidson, N. 2013 The Economics of Ecosystem and Biodiversity for Water and Wetlands. IEEP, London, UK and Brussels, Belgium; Ramsar Secretariat, Gland, Switzerland.

Sánchez-Cohen, I., Díaz Padilla, G., Guajardo Panes, R. & Macías Rodríguez, H. 2011 Decision making for sustainable development of natural resources. *Revista Mexicana de Ciencias Agrícolas* **1**, 57–68.

Schoeder, S., Lang, Z. & Rabotyagov, S. 2018 Forward-looking farmers owning multiple potential wetland restoration sites: implications for efficient restoration. *Environmental Management* **61**, 577–596. https://doi.org/10.1007/s00267-018-1002-0.

Yakowitz, D. S., Lane, L. J. & Szidarovsky, F. 1993 Multi-attribute decision making: dominance with respect to an importance order of attributes. *Applied Mathematics and Computation* **1** (August), 117–125. https://doi.org/10.1016/0096-3003(93)90057-L.

First received 28 December 2019; accepted in revised form 7 April 2020. Available online 16 May 2020.