A Hawaiian Fishpond as an Educational Interdisciplinary Nexus

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ABSTRACT

Loko iʻa, or traditional Hawaiian fishponds, backed by thousands of years of wisdom and knowledge of the kupuna (ancestors), were ecological treasures that thrived because of their harmonious connection with the surrounding land and water. Rather than imposing on the land, kupuna seek to understand the relationship between tidal flows from the ocean, the nutrients from the watershed, and the fish in the pond. As a result of this understanding, kupuna strategically choose locations for loko ʻia that amplify the abundance of the surrounding area. The end product is an expanse of the sustainable food production system from mauka (mountain) to makai (ocean). Sadly, most ancient fishponds have been destroyed or overrun by development. Various efforts are underway to restore the few that survive by integrating traditional knowledge and current technology.

An example of this effort is done in a fishpond on Mokauea Island, off the south shore of Oʻahu. Once a small holding pen for young fish (kiʻo pua), the fishpond was enlarged in the early 1980s to the size of a football field. Recently, temperature, dissolved oxygen, water level, and flow rate sensors were deployed to understand basic physical characteristics of the pond. Mathematical models were adapted to analyze the observed data, and used to understand climate change effects.

While the modeling and the computational aspects of this work is interesting, the emphasis of the work is on developing interdisciplinary projects and classroom materials drawn from real world applications. As an ecologically integrated food system, a fishpond is an excellent nexus for interdisciplinary projects. For example, the mathematical model for dissolved oxygen level necessitates the understanding, among others, the wind regime of the area, sediment oxygen demand, and surface and water oxygen saturation levels. At the heart of this work is preparing future generations by making a connection between ancient knowledge with current technology, data analysis, mathematical modeling. In this vein, an equitable relationship with the indigenous knowledge keeper and the land stakeholders is the key to the success of the project.

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1. INTRODUCTION

Keʻehi region is the area in the south shore of Oʻahu at the base of five ahupuaʻa (land divisions that stretch from mountain to sea): Kalihi, Kapalama, Moanalua, Kahauki, and Nuʻuanu. The nutrients brought down from the mountain accumulated at the mouth of the sea surrounding the Keʻehi region, making it a fertile and ideal place for aquaculture.

This concept of working with the ecosystem and the approach of encouraging the system to make room for fish growing was masterfully applied by the Hawaiian people, including those resides in this region, up to mid 1900s. The Keʻehi region was home to upward of 20 large fishponds, producing more than 300 kg/ha/year or more than a half million pounds of fish per year for this region [8]. All was done by establishing a deep understanding of the complex processes involved in an aquaculture connecting the surrounding ecosystems, and by optimizing natural elements that elevated sustainable fish production. In western terms, these natural elements would include solar energy to keep the temperature ideal, the wind to keep the oxygen dissolution churning, and primary production.

But westernization of the social structure and overdevelopment of the surrounding region have destroyed the aquaculture system in this area and across the Kingdom of Hawaii, and with it, the knowledge that come with that culture. Indeed, the ancient Hawaiian sustainable aquaculture is a complex process that warrant systematic and careful study, because the perpetuation of its knowledge might guide us in navigating sustainable food production in the future.

To study a complex model like the Hawaiian fishpond, one must understand the elements involved and how they interact in the system. Mathematical models are valuable tools in understanding a complex system. They organize or systematize assumptions while providing venues to incorporate quantitative measurements and any other available knowledge [9]. Grounding an interdisciplinary study on a sound mathematical model is in some sense imperative in trying to understand the interactions of the processes. Furthermore, a byproduct of a mathematical model is its projective capability, so the model could be useful for simulating possible events to come, and for understanding the effects of changing parameter regimes.

To illustrate this modeling concept, we show here the application of a mathematical model of dissolved oxygen level in an open body of water. All life forms use oxygen, and so dissolved oxygen is one of key health indicators, and therefore, one of the elements that must be constantly monitored. Beyond developing the content knowledge about the fishpond, the collaboration practice between academics (UHWO faculty Dr. Widiasih and students Mr. Garrido and Mr. Johnson) and community leader (Ms. Kupihea from Mauliola Ke'ehi) illustrates the concept of building relationships with land stakeholders as well as that of establishing mathematical context for the students.

2. MODELING DISSOLVED OXYGEN

A fishpond clearly is a complex system, with interconnected networks of activities. Therefore, determining its well-being could be difficult, but one reliable health indicator is the level of dissolved oxygen (DO). Oxygen is not only needed for fish respiration, but also needed by algae, benthic substrates, and other life forms. Beyond biological systems, dissolved oxygen also plays a role in the nitrogen and phosphorus transformation. A level of dissolved oxygen that falls below 5 mg.L $^{-1}$ negatively affected growth and metabolisms of fish and invertebrates, and when the oxygen level falls below 2 mg.L $^{-1}$ leads to mortality. A dissolved oxygen level that drops below 2.5 mg.L^{-1} could impede the formation of phosphor and nitrogen, and lead to anoxic water [1, 2].

Numerous processes affect the level of dissolved oxygen in a fishpond. Some processes like photosynthesis add oxygen to the water and some others like respiration and sedimentation uses oxygen. When photosynthesis is involved, sunlight also plays a role, so the processes involved in determining DO level is diurnal. Clearly all these biogeochemical processes reside in multiple disciplines, and one needs a mathematical model to give a framework for the study.

Many DO models have been developed [3-6]. Here, we focus on the work by [3]. For completeness, the model of the oxygen exchange is presented and summarized as follows:

$$\frac{dx}{dt} = P + A - S - R \qquad \text{(Eq. 1)}$$

$x =$ oxygen concentration level in the water (in mg.L^{-1})
t = time (in hours),
P = Photosynthesis, A = Aeration,
S = Sedimentation, R=Respiration.

The *photosynthesis* process is represented by the function P where $P = P_c \times Chla$. Here P_c is the rate of oxygen production that depends on Chlorophyl-a ($Chla$). The rate Pc is proportional to the amount of PAR (photosynthetically active solar radiation) in the broadband solar radiation R_S.

The *aeration* process relies on the wind to accelerate oxygen dissolution and takes into account the effect of water temperature on the oxygen saturation level, and is represented by the function

$$A = \alpha_J \times K_L/H \times (C_{sat} - x).$$

Here, α_J is aeration adjustment coefficient, K_L is the oxygen transfer coefficient, H is the thickness of the surface layer, and C_{sat} is the oxygen saturation level of the surface layer. In this model, notice that the aeration process is the only term with dependence on the state variable x, and that the dependence results in negative feedback.

The *respiration* process, which is the opposite of photosynthesis, is also proportional to the amount of Chlorophyl-a, and is represented by the function

$$R = \alpha_R \times \theta^{(T-20)} \times Chla.$$

Here, the α_R is the respiration and θ_R is the temperature adjustment coefficients.

The final process, *sedimentation*, represents the demand of oxygen by organic matters at the bottom of the pond. This process depends on the water temperature and the characteristics of the bottom layer. The function representing this process is

$$S_{SOD} = S_{S20} \times \theta_S^{(T-20)}/Z,$$

where S_{20} is the sediment oxygen demand at 20^oC and Z the depth of the bottom sediment, and the parameter T is the water temperature. The details of the parameters, their units and the values used in the simulation is presented in **Table 1**.

While in [3] the model is treated as difference equation with an hourly time step, here we shall view it as a differential equation. Rewritten with the explicit dependence on the external forcing coming from the Chlorophyll-a concentration ($Chla$), water temperature (T), solar radiation (R_S) and wind speed (U), we have:

$$\frac{dx}{dt} = P(R_{S,}\, Chla) + A(U,x) - R(T) - S(T) \qquad \text{(Eq. 2)}$$

All four of the external forcing are time dependent, and in the model simulation, they will all come from interpolated observed data. Other parameter values either come from model fitting (calibration) or from literature. The model is run for 31 days, and the simulation results are shown in Figure 1.

3. USING XU & XU's DISSOLVED OXYGEN MODEL IN THE CLASSROOM

The DO model discussed in the previous section was shown to be a good representation of the observed DO in the fishpond, particularly for the purpose of predicting low level DO events (ie. < 5 mgL^{-1}). It also provides an excellent platform to connect a mathematical model, a collection of observable measurements, and basic scientific backgrounds.

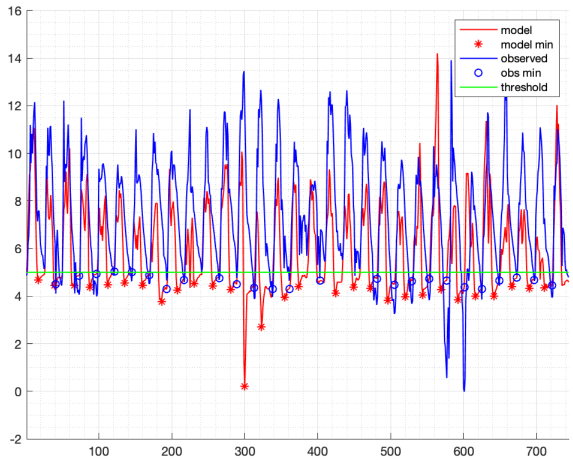

Figure 1 Mokauea fishpond Dissolved oxygen (DO in mgL^{-1}) simulation over 31 days (744 hours). The time dependent external forcing included in the simulation are water temperature, wind speed, solar radiation, and concentration of *Chlorophyll-a* in the pond. Visual inspection reveals that the simulation predicted all 26 events DO<5 mgL^{-1}.

The challenge in the classroom is to lead students in gaining the skills to put together the model with the data from observations. The students' background makes a difference in the success of the project. This project might be best done with students having some math background, like one year of Calculus or more, and some science background, like Introduction to Biology and/ or General Chemistry. A computing experience is also helpful, though with some quick preparation, a motivated student can quickly pick up the skills. The project has been done as an independent project, and as an activity in a classroom setting.

The student skill building milestones starts with establishing the physical and historical context by connecting and listening in with the stake holder and the literature context by reading the literature on the subject. The work in [3] and citation therein provide excellent review and background literature on dissolved oxygen in a body of open water. From this interaction, some guiding questions are established, for examples: *Does the fishpond reach hypoxic or anoxic level? Could climate change affect the fishpond's DO concentration, and how? What information is needed to estimate the pond's dissolved oxygen level, if a sensor is not available? Is there a model that does a good job representing the fishpond's DO concentration?*

The next step is gathering and processing the data and incorporating them in the model. The data used were obtained from available nearby: wind speed from NOAA OOUH01 buoy, water temperature sensor installed for the purpose of this research (publicly available via smartcoastline.org), and the PAR/ Solar irradiance from remote monitoring weather station HOBO RX 3000. Processing of the data requires students to learn the skills to navigate the various file types as well as time stamps of the data (eg. UNIX or POSIX time vs. MMDDYYY version). Furthermore, since the time interval of the measurements are not uniform, the various data must be processed further using some interpolation technique. And finally, decisions must be made to deal with missing data. This type of data pre-processing is standard requirements in the professional world, and students in any field would benefit from the experience. Incorporating the observed data into the mathematical model will further enhance math and science students for numerous reasons. First, since the data come with geographical and temporal descriptions of what otherwise would simply be a set of parameters, then the observed data create a context for the model. Second, the data and the model time must be reconciled, and techniques like interpolation must be applied.

Once the computer model is executed, the simulation will serve as a *laboratory*. This is indeed the advantage of having an executable math model that mirror the real world. For example, while the effect of climate change on the global temperature is undeniable, it is not feasible to warm up the whole pond just to see what would happen to the DO level. But using the model, one can simulate the effect of increasing the water temperature. Increasing by 2ºC lower the average DO level by about 1 mgL^{-1}, while 4ºC increase lowers average DO level by about 3 mg^{-1}.

And last but not least of the milestones, students are tasked to go back to the stake holders to share the results. The results sharing is done at the end of the semester as part of the final presentation, or *ho'ike* (sharing of knowledge), for the activities done as a part of the course, or in the UHWO student research symposium, or in a one-to-one setting with the stakeholder. Through the modeling project, students have the opportunity to be the expert of their work. The *ho'ike* serves as a catalyst of that role transformation where the student becomes the expert in that particular area. Furthermore, inputs from the stake holder, other instructors, and from the peer also benefit the students' growth, as they provide diverse point of views of the subject.

The model has many outlets for future work. Exploring the effect of the wind regime to the model is an immediate step, though one might have to modify the dependence of oxygen dissolution on the wind regime. The modified model may be useful in predicting the effects of events like El Nino that causes sustained temperature elevation and weakening of the trade wind [7]. A study of parameter regimes in which hypoxia and fish kill event could happen will be useful for local communities.

Parameter	Description	Unit
x	DO concentration	Variable/ mgL^{-1}
t	Time	Variable/ hours (h)
P_c	O_2 production rate	mgO_2mg *Chl-a*$^{-1}h^{-1}$
Chla	*Chlorophyll-a* concentration	mgL^{-1}
α_J	Reaeration adjustment parameter	dimensionless
K_L	O_2 transfer coefficient	cmh^{-1}
H	Surface layer thickness	cm
α_R	Respiration adjustment coefficient	h^{-1}
θ_r	Respiration temperature adjustment coefficient	dimensionless
S_{20}	O_2 sediment demand at 20ºC	$mgO_2\,m^{-2}h^{-1}$
Csat	Surface layer saturated O_2 level	$mg\ O_2\ L^{-1}$

Table 1. Parameters used in the simulation. The actual values and the Matlab codes of the simulation can be found in the supplementary material folder https://osf.io/z2fh5/

4. CONCLUSION

In this paper, we illustrate interdisciplinary applications of Biology, Physics, Chemistry and Mathematics in understanding dissolved oxygen concentration in a Hawaiian fishpond in Mokauea island. Just like the ancient traditional Hawaiian fishponds that harmoniously connected the mountain and the sea and all the living things in them, the Mokauea fishpond has become the nexus that connects different fields of studies, including Biology, Physics, Chemistry, and Math. Much work must be done to uncover the ancient wisdom of the kupuna (ancestors) in establishing and encouraging the surrounding ecosystems to provide for them and to perpetuate that wisdom to the future generation. The work we present here is just the beginning.

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