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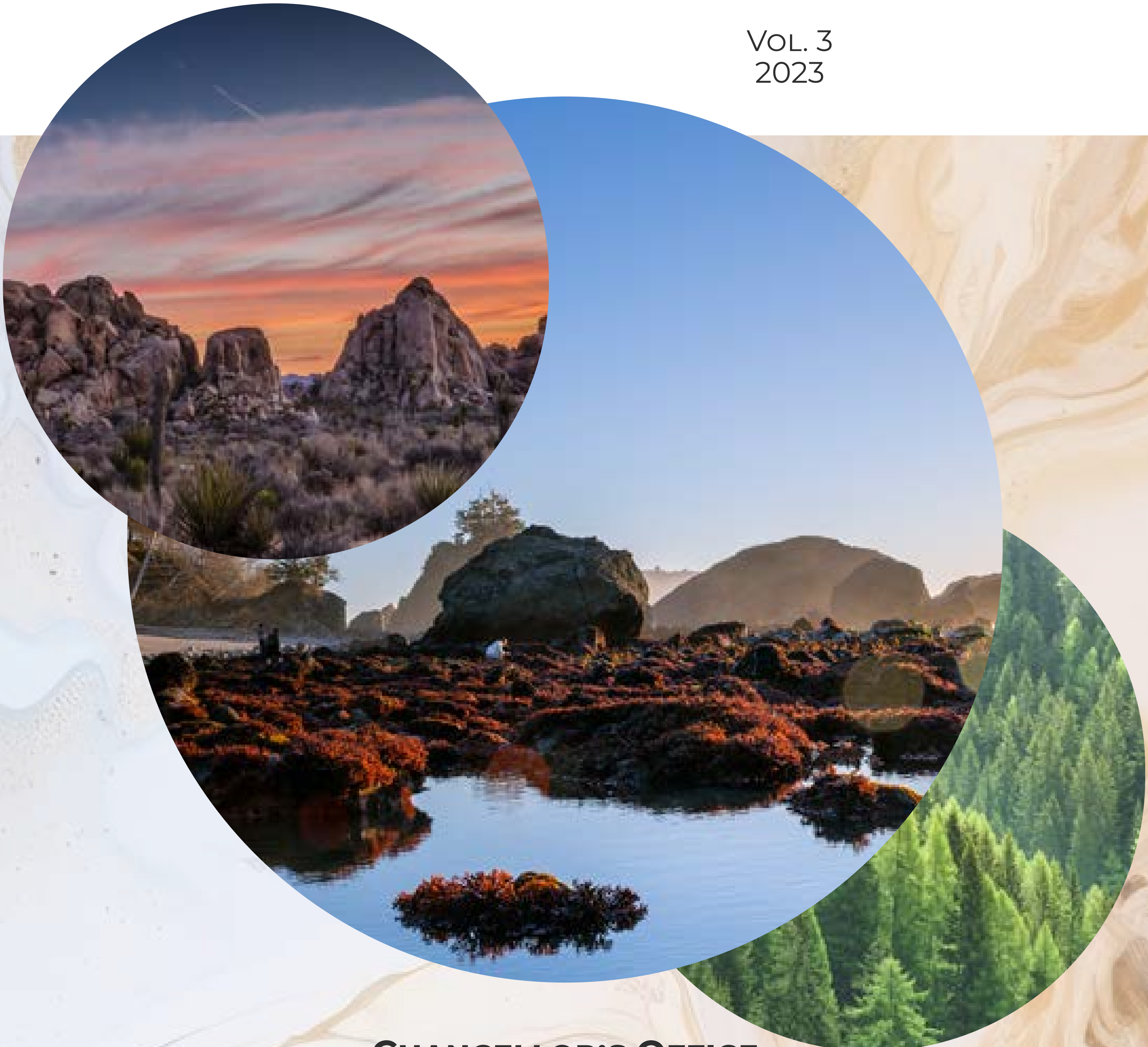

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Altering Attitudes on Climate Change: Testing the Effect of Time Orientation and Motivation Framing

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Climate change has become a defining issue of the 21st century. According to a Pew Research (2020) survey, for the first time in its two-decade history, a majority of Americans now believe that dealing with climate change should be a top priority for the President and Congress, which is a 14% rise from four years prior. Nonetheless, this rise is accompanied by a deep partisan divide amongst citizens of the United States (U.S.) and Republicans are far less likely to consider climate change a top public priority with a roughly 50% partisan gap on the issue (Popovich, 2020). Thus, this partisan gap raises an important question: what are the effects of political orientation, time orientation, and motivation orientation on climate change attitudes and behavioral intention? The goal of this research is to examine this question by testing the influence of these factors on eight outcome variables.

Related Research

Before discussing the study and its results, this paper provides background information that informs our experimental design. First, this review outlines a brief description of Agenda Setting and Framing as a lens that guides our study's manipulation. Following this review, we describe the independent variables tested: (1) political orientation; (2) time orientation; and (3) motivation orientation.

Agenda Setting and Framing

Agenda Setting Theory (AST) broadly claims that news media sources tell people what to think about (McCombs & Shaw, 1972). According to West and Turner (2018), when media sources show some news stories frequently and other stories are filtered out, people over time come to think that the stories shown frequently are the most important. This theory has also evolved to claim that not only do media sources tell viewers what to think about, but that media sources also inform how viewers evaluate people and objects within stories (Wilber, 2017). Guber and Bosso (2012) sought to connect issue framing and agenda setting in relation to environmental discourse. They found that the definition of "the environment" is critical to perceptions, and that in politics, whoever can define "the environment" has the advantage. Pralle (2009) used Kingdon's multiple streams model of AST to explore strategies for making climate change a political priority. Pralle found that raising climate change's salience with the public pressured policymakers to prioritize the issue and that it was important to frame solutions in ways that garnered maximum support.

Relatedly, Framing Theory also describes and explains how people may be influenced by media stories. Framing Theory claims that the information that is selected to be included in a message and the degree that different parts of that message are treated as "more or less" salient will impact the audience's understanding of that message (Entman, 1993). Therefore, Agenda Setting and Framing are related theories that both tell us how news media stories may impact attitudes and beliefs of audience members. Although, it is worth mentioning that while agenda setting effects are more likely to occur due to frequent exposure to a message, framing effects occur simply based on the perspective to which information is presented with less of an emphasis on the frequency to which a message is shown (Wilber, 2017).

Taken altogether, Agenda Setting and Framing both help us understand how a message is presented can influence viewers. Although an extensive review of both theories is beyond the scope of this paper, these theories provide a lens for the manipulation in our research. In this study, we change the framing of a message according to the "motivation" frame and the "time" frame of the message to see if this has any specific impact on attitudes related to climate change.

Political Orientation

One variable that can influence outcomes associated with climate change is a person's political orientation. Political orientation, or where an individual falls on a spectrum between conservative and liberal, has been identified by multiple studies as a factor that affects a person's likelihood to believe in and act against climate change. In this area, McCright and Dunlap (2011) analyzed 10 Gallup polls from 2001 to 2010 and demonstrated that liberals and Democrats were more likely to express beliefs consistent with scientific consensus (climate change is occurring and human-caused) while conservatives and Republicans were less likely.

In addition, Wolsko, Ariceaga, and Seiden (2016) conducted a series of three experiments to examine whether the framing of a climate change message impacted a person's perceptions toward conservation intentions, climate change attitudes, and donations when comparing liberal and conservative political affiliations. While liberals did not significantly differ across conditions, conservatives demonstrated significant shifts in the pro-environmental direction after exposure to a binding moral frame in which environmental protection was framed as a matter of obeying authority, defending the purity of nature, and demonstrating one's patriotism to the United States. In related research, Hart and Nisbet (2012) found that when participants read about public health threats to distal victims, Democrats demonstrated increased support for climate policy while this support decreased in Republicans. Gregersen et al. (2020) studied the role of climate change beliefs and political orientation in explaining worry about climate change across 23 countries. They found that right-leaning individuals expressed less worry in most countries, and while increased belief in climate change and its impacts was associated with increased worry across the political spectrum, this relationship was weaker among right-leaning individuals.

All three studies suggest that there are additional factors that may impact a person's likelihood to support climate policy than just political orientation alone. In other words, despite the partisan divide that exists when it comes to climate change related topics, one's political orientation is not the only factor that influences attitudes and beliefs. Given this information, we examine two more independent variables: time and motivation orientation.

Time Orientation

A second variable that may influence outcomes associated with climate change is time orientation. Multiple studies have identified differences in participants' behavior based on changes to time orientation, or what "time frame" is appealed to in a study. For example, Rickard, Yang, and Schuldt (2016) manipulated the "departure date," or the hypothetical year after which the climate in a given location would be warmer than anything experienced in the meteorological record. In this study, three timeframes were examined with participants seeing a departure date of 2020, 2047, or 2066. Spatial distance was also studied with participants seeing either New York City or Singapore. Results found that the highest climate change policy support was shown for the New York 2066 condition and that lowest climate change policy support was shown for the Singapore 2047 condition. While few other differences were identified based on time orientation alone, the study found that the influence of departure dates was moderated by participants' political orientation with some of the largest effects of the manipulation observed on conservatives in the U.S. This suggests that the framing of a message may play an important role on conservative's viewpoints about climate change.

Relatedly, Baldwin and Lammers (2016) performed six studies to examine whether conservatives' unwillingness to act against climate change was possibly due to fundamental differences in conservatives' and liberals' temporal focus (focus relating to time). Through these studies, they demonstrated that conservatives were positively impacted by past-focused environmental comparisons and not by future-focused comparisons. In fact, past-focused comparisons nearly eliminated the divide between liberal and conservative attitudes toward climate change with both groups in the study reporting to be almost equally likely to fight climate change. Essentially, conservatives were shown to find a message about climate more compelling when the message was framed as a problem that was already happening (in our past) rather than framing it as problem that might happen in the future.

Motivation Orientation

A third variable that may influence outcomes associated with climate change is a person's motivation orientation. A person may find a message more compelling if it happens to align in some way with their value system or personal preferences. Several studies examined the impact of individual values and motivations on a person's likelihood to believe in anthropogenic climate change and support climate policy. For example, Li and Su (2018) conducted a meta-analysis and reviewed experimental studies to examine the effects of value framing on one's public engagement with climate change. Results suggest that messages that emphasize the environmental, moral, and economic aspects of climate change had a positive impact on a person's reported engagement with climate change topics.

Similarly, Bloodhart, Swim, and Dicicco (2019) conducted three studies to examine whether the emotional tone of a message related to climate change played a role in how people responded. In their study, they compared messages that were framed with negative emotions (fear, sadness, and anger) to climate change messages that were framed without emotion. Overall, they found that participants preferred messages without emotion, but that women and Democrats were more likely to prefer emotional messages than men and Republicans. As such, people may find messages that align with their personal preferences to be more motivating.

Lastly, Wolsko, Ariceaga, and Seiden (2016) tested the impact of value framing on conservatives' likelihood to believe in and act against climate change. In their study, they tested messages that were framed to appeal to the ideals of "tradition and patriotism" or the ideals of "compassion and egalitarianism." Their findings showed that appeals to tradition and patriotism did indeed impact conservatives to report being more likely to engage in pro-environmental action while appeals to compassion and egalitarianism did not. Taken together, this research suggests that when a message is framed to align with someone's personal preferences or values, they may be more motivated to support climate change policies.

Hypotheses

This literature review describes past studies on political orientation, time orientation, and motivation orientation. The current study extends this research and tests these variables together to further examine which variables will be more likely to impact attitudes and behaviors related to climate change. Based on the findings of the studies discussed, the following three primary hypotheses (with eight sub-hypotheses) guide this study.

H_1: A person's **political orientation** influences outcomes related to climate change, such that **liberals** will indicate more:

a. Concern for climate change.
b. Support for climate change policies.
c. Belief in climate change.
d. Belief that humans cause climate change.
e. Value in stopping climate change.
f. Behavioral intention to stop climate change.
g. Impact of a climate change FB post.
h. Self-efficacy to respond.

H_2: **Time orientation** influences outcomes related to climate change **for non-liberals,** such that **a past-to-present** message will produce more:

a. Concern for climate change.
b. Support for climate change policies.
c. Belief in climate change.
d. Belief that humans cause climate change.
e. Value in stopping climate change.
f. Behavioral intention to stop climate change.
g. Impact of a climate change FB post.
h. Self-efficacy to respond.

H_3: **Motivation orientation** influences outcomes related to climate change **for non-liberals,** such that a **patriotic** message will produce more:

a. Concern for climate change.
b. Support for climate change policies.
c. Belief in climate change.
d. Belief that humans cause climate change.
e. Value in stopping climate change.
f. Behavioral intention to stop climate change.
g. Impact of a climate change FB post.
h. Self-efficacy to respond.

Method

This study utilized a posttest-only experimental design to manipulate the time orientation (past-present or present-future) and the motivation orientation (patriotism or compassion) displayed in a fabricated social media post on the topic of climate change. The goal was to examine whether altering the framing of a message would impact an individual's perceptions and their likelihood to take pro-climate action. Following the experiment, differences between groups were compared.

Participants

Two hundred and sixty-six participants were recruited from a large Western University and consisted of both students and parents. Some students were offered a nominal amount of extra credit as incentive. Participants reported their gender as 70.7% females, 27.4% males, and 1.9% preferred not to say with a mean age of 28.58 years (*SD* = 14.18). In terms of ethnicity, 72.2% identified as White, 9.4% as Asian or Pacific Islander, 6.8% as Hispanic/Latinx, 5.3% as Multiracial, 1.9% as Middle Eastern, and 4.5% preferred not to say.

To measure political-orientation, participants were asked "which of the following best matches your political ideology?" Participants responded as 1.1% very conservative, 10.9% conservative, 30.8% as neutral, 44% as liberal, and 12.8% as very liberal. Due to less conservatives participating in our study, we collapsed the categories of "very conservative, conservative, and neutral" into a category we are labeling as "not liberal" (42.9%) to compare them with liberal (56.8%) participants. This likely skewed the results to some degree, as "neutral" could have been included in either category, and "neutral" may take on very different meanings depending on geographic location. Although this was not the most ideal way to compare participants by political ideology, it provided a starting point to compare people who identify as more liberal and those who identify as less liberal.

Procedures

Participants were recruited using both convenience and volunteer sampling. The researchers posted the questionnaire on student and parent online group pages (e.g., Facebook and GroupMe) and asked university professors to share the link with students. Upon self-selecting to participate, respondents clicked on the link and were directed to an online Qualtrics questionnaire. The questionnaire began with a consent form notifying respondents that participation was voluntary and confidential.

Second, random assignment sorted respondents into one of four manipulated stimulus conditions in which participants viewed a fabricated social media post that contained an image with a comparison of the "past to the present" or the "present to the future" and a caption with an appeal to "patriotism" or an appeal to "compassion" (totaling four possible conditions). Following the manipulation, participants answered 28 questions to assess perceptions about climate change and behavioral intentions. Lastly, participants completed a measure of demographics.

Stimulus Materials

Participants were randomly assigned to view one of four possible social media posts. Depending on the condition, participants saw a post that either appealed to the values of patriotism (*n* = 145) or compassion (*n* = 121). For the appeal to patriotism or compassion, the social media post's caption was either directed at patriotism and related values (purity of the natural environment, tradition, respect) or compassion and related values (caring for the vulnerable environment, fairness, preventing suffering). These captions were drawn from a study on the effects of moral framing on climate change attitudes and conservation behaviors (Wolsko, Ariceaga, & Seiden, 2016; manipulation materials available upon request).

In addition, the post showed two pictures side-by-side. Picture 1 depicted a landscape of a full reservoir of water and picture 2 was a dried-up reservoir basin. These two pictures were either framed as past-to-present (*n* = 138) or present-to-future (*n* = 128). Both emphasized negative environmental damage over time; but the past-to-present frame depicted this issue as "already occurring" (it has happened in the past) and the present-to-future frame depicted this issue as something that might happen someday (it has not happened yet). These images were provided by researchers who successfully used them in related published work (Baldwin & Lammers, 2016). The four posts were identical in appearance, with only the changes to the captions and images differing between them.

Measures

Eight outcome variables were examined to test attitudes and behavioral intention in relation to climate change after exposure to the manipulation: (1) Concern about climate change; (2) Support for government intervention; (3) Belief that climate change is real; (4) Belief that climate change is human caused; (5) Value in the environment; (6) Behavioral intention to combat climate change; (7) Impact of the information from the post; and (8) Self-efficacy to make a positive environmental impact. For each outcome, composite measures were used (Likert scales from 1 – 7 indicating "strongly disagree to strongly agree") in which multiple questions were asked for each variable and the average of each measure was obtained (a full list of questions is available upon request). The reliability of each measure was acceptable (see table 1 for reliabilities).

Results

SPSS 26.0 was utilized to analyze experimental data. Given the hypotheses, statistical analyses were performed to examine the impact of political, motivation, and time orientation on the eight dependent variables. In order to have a large enough sample size, non-liberals were categorized as those who considered themselves very conservative, conservative, or neutral (*n* = 114) and liberals were those who considered themselves liberal or very liberal (*n* = 151). Results and conclusions are subsequently discussed.

Political Orientation

Hypothesis one predicted that political orientation would influence outcomes related to climate change. Independent t-tests were conducted for each outcome. Findings indicated that this hypothesis was generally correct as liberals tended to score significantly higher for each variable in comparison to non-liberals. The only variable that did not produce a significant difference between groups was "the impact of the Facebook post." Therefore, hypothesis one was mostly supported with this one exception. For a summary of the differences between groups reported for each outcome, see table 2.

Time Orientation

Hypothesis two predicted that time orientation would influence outcomes related to climate change for non-liberals. Independent t-tests were again conducted to examine difference between groups. Significant findings were found for three of the dependent variables: (1) belief that climate change is real; (2) belief that climate change is human caused; and (3) behavioral intention. For all three of the significant findings, non-liberal participants were more likely to favor pro-climate perspectives when shown the "past to present" comparison than the "present to future" comparison. For a summary of data for hypothesis two, see table 3.

Motivation Orientation

Hypothesis three predicted that motivation orientation would influence outcomes related to climate change for non-liberals. Independent t-tests were conducted once again to examine differences between groups. The differences did not yield significant results for any of the dependent variables tested under this hypothesis. Therefore, hypothesis three was not supported. For a summary of data for hypothesis three, see table 4.

Discussion

The goal of this research was to test the influence of political orientation, time orientation, and motivation orientation on eight outcome variables associated with climate change attitudes and behavioral intention. Although aspects of our hypotheses and the literature review were not confirmed, the results indicate several findings worth highlighting. First, liberals were more likely to be in favor of believing in and working to stop human-caused climate change as they consistently scored higher on all outcome variables (except for the "influence of the Facebook post itself") in comparison to non-liberals. While this finding is not surprising, it is worth noting that the "non-liberals" in this study were largely made up of participants who described themselves as politically "neutral." In related research, such as that of McCright and

Table 1.
Outcome Measure Reliabilities

Dependent Variable	α	M
1. Concern	.90	5.60
2. Support for government intervention	.94	5.89
3. Believe climate change is real	.92	6.28
4. Believe climate change is human caused	.84	6.01
5. Values	.89	6.22
6. Behavioral intention	.82	5.55
7. Impact of post	.85	4.22
8. Self efficiacy	.78	5.61

Table 2.
Political Orientation t-tests

Depedendent	P.O.	M	SD	t	df	p
1. Concern	Not Liberal Liberal	4.92 6.11	1.40 .82	-8.61	263	.000***
2. Support for gov.	Not Liberal Liberal	5.15 6.45	1.50 .69	-9.45	263	.000***
3. Belief climate change	Not Liberal Liberal	5.83 6.62	1.25 .58	-6.81	263	.000***
4. Belief human-caused	Not Liberal Liberal	5.55 6.33	1.18 .72	-6.63	263	.000***
5. Values	Not Liberal Liberal	5.81 6.53	1.10 .69	-6.59	263	.000***
6. Behavioral intention	Not Liberal Liberal	4.93 6.02	1.38 .88	-7.84	263	.000***
7. Impact of post	Not Liberal Liberal	4.10 4.33	1.29 1.06	-1.56	263	.121
8. Self-efficiacy	Not Liberal Liberal	5.27 5.88	1.17 .90	-4.83	263	.000***

Note. *p < .05, **p < .01, ***p < .001

Table 3.
Time Orientation t-tests (Non-Liberals)

Depedendent	T.O.	M	SD	t	df	p
1. Concern	Present-Future Past-Present	4.71 5.14	1.50 1.25	-1.68	113	.096
2. Support for gov.	Present-Future Past-Present	4.92 5.37	1.62 1.33	-1.63	113	.105
3. Belief climate change	Present-Future Past-Present	5.52 6.15	1.46 0.92	-2.80	113	.006**
4. Belief human-caused	Present-Future Past-Present	5.29 5.83	1.38 0.91	-2.47	113	.015*
5. Values	Present-Future Past-Present	5.61 5.99	1.12 1.05	-1.85	113	.066
6. Behavioral intention	Present-Future Past-Present	4.60 5.23	1.45 1.25	-2.48	113	.014*
7. Impact of post	Present-Future Past-Present	3.99 4.18	1.42 1.17	-.79	113	.429
8. Self-efficiacy	Present-Future Past-Present	5.15 5.36	1.23 1.11	-.94	113	.346

Note. *p < .05, **p < .01, ***p < .001

Table 4.
Motivation Orientation t-tests (Non-Liberals)

Depedendent	M.O.	M	SD	t	df	p
1. Concern	Compassion Patriotism	4.93 4.93	1.43 1.37	.00	113	.999
2. Support for gov.	Compassion Patriotism	5.10 5.19	1.58 1.43	-.30	113	.765
3. Belief climate change	Compassion Patriotism	5.91 5.79	1.35 1.18	.53	113	.597
4. Belief human-caused	Compassion Patriotism	5.60 5.54	1.37 1.05	.26	113	.793
5. Values	Compassion Patriotism	5.74 5.85	1.10 1.10	-.52	113	.606
6. Behavioral intention	Compassion Patriotism	4.91 4.93	1.47 1.32	-.08	113	.937
7. Impact of post	Compassion Patriotism	4.03 4.12	1.35 1.27	-.36	113	.717
8. Self-efficiacy	Compassion Patriotism	5.31 5.22	1.20 1.15	-.40	113	.691

Note. *p < .05, **p < .01, ***p < .001

Dunlap (2011) and Hart and Nisbet (2012), self-proclaimed neutral groups are a population that is not commonly studied, as research instead tends to focus on those who fall strongly on either side of the political spectrum.

Still, in most measures in our study, these politically "neutral" participants were considered significantly less likely to demonstrate pro-climate attitudes and behavioral intentions. This suggests that climate change research must more clearly examine groups that are politically neutral as this population may be less likely to favor pro-environmental attitudes in relation to climate change. In other words, it is not simply a matter of liberals versus conservatives; groups that are more neutral in political affiliation also tend to be less likely to support fighting against climate change.

Second, switching the motivation orientation between appeals to compassion and patriotism yielded no significant results. Our results did not confirm the findings of Wolsko, Ariceaga, and Seiden (2016), who found significant shifts in conservative attitudes toward climate change when given a patriotic binding moral frame. The goal of changing the motivation orientation of the post was to observe how it might influence non-liberal participants' perspectives toward climate change, but the lack of significant differences suggest that it did little to sway their climate change opinions. Given the divisiveness surrounding the topic (Popovich, 2020), this is to be expected. Therefore, it will likely take more than a few carefully framed social media posts to impact people's attitudes toward climate change; at least when it comes to comparing the values of compassion to patriotism.

Third, for time orientation, although this variable did not have an impact on the majority of outcomes, our data show that the past-to-present frame (i.e., climate change effects have already been happening in the past) was more likely to influence non-liberals on three outcome variables: (1) belief that climate change is real; (2) belief that climate change is human-caused; and (3) behavioral intention. However, this is still a promising result, as it suggests that the framing of a message can indeed encourage non-liberals to demonstrate pro-environmental attitudes to some degree considering there was an effect on these variables.

This result fits within the context of past literature as Baldwin and Lammers (2016) also found that conservatives were more positively impacted by past-focused environmental comparisons and not by future-focused comparisons. This may be because priming non-liberals to think about the past could be an approach that aligns with conservative values. As such, the past-to-present framing may be a more successful route to pursue when considering how to design persuasive messages for non-liberals.

Another possible explanation for this finding is that in the past-to-present condition, the change in the picture may be perceived as already occurring, while in the present-to-future condition, the change is merely expected. Participants may have been more persuaded by an event that has already occurred rather than one which cannot be guaranteed. This is a common problem in climate change communication: it is difficult to make people care about something that has not yet happened and which they do not perceive as guaranteed to happen. Overall, our results suggest that influencing climate change perceptions is a challenging endeavor and that climate change communicators should find ways to focus on the impacts of climate change we have already witnessed rather than those we have yet to experience in the future.

Limitations

This research had three main limitations. First, this study was demographically skewed. The sample was drawn from a predominantly White (72.2%) Western University. In addition, most participants were female (70.7%), which may have influenced results as women and people from diverse racial groupings may hold different climate change orientations. Furthermore, conducting this research on a CSU campus has implications on the results. California tremendously differs politically from other states. People who identify as "neutral" in California may be seen as "liberal" in other states. A demographic that was more representative of the U.S. would be more likely to contribute to data with higher external validity.

Second, participant motivation and survey length may have skewed results. While the amount of extra credit offered to some students was nominal, this does not mean it had no impact. The survey took seven to ten minutes to complete, which means the length of the survey may have selected for full participation by more engaged participants.

Third, the nature of a social media post as the manipulation presents several potential limitations. Some of the participants may not use social media and therefore could be less likely to be influenced by a social media post. Participants also may have overlooked the content of the post and simply responded to the measures. Additionally, the ability of a social media post to portray a message is limited and therefore some of the persuasive potential of time and motivation orientation may have gone untested. Therefore, more research is needed to verify the internal validity of these results.

Directions for Future Research

The current study sought to add to our existing body of research on climate change messaging. Future research should examine those who identify as politically "neutral." As was stated, this is an understudied population and results from this study indicate that it is equally necessary for climate activists to focus on this group. Rather than categorizing this group as "non-liberal," a future study should test conservatives, neutrals, and liberals separately to understand how they differ. Additionally, this study should test these factors in different parts of the country in order to get a more representative sample.

In summary, this research tested the impact of political orientation, time orientation, and motivation orientation through two shifts in the framing of a climate change message to examine the influence on attitudes and behavioral intentions. Although results showed that the motivation frame did not influence attitudes, changing the framing of a message to focus on a past-to-present orientation seemed to be the most effective framing technique that researchers should continue exploring in future studies.

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A Framework for Creating Virtual Reality Models for More Effective Coastal Flood Risk Communication

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Coastal cities are exposed to increasing risks of flooding from sea-level rise. Climate change is expected to double the frequency of coastal flooding within the next decade, and some areas could experience floods of a magnitude 100 times higher than currently (Vitousek et al., 2017). People living in at-risk areas often ignore the impact of climate change on flood intensity and frequency. Immersive visual storytelling techniques proved promising and powerful tools to engage with and raise awareness of flood hazards. Here, we are introducing a framework to use Virtual Reality (VR) to reach better people living in coastal cities and help them understand the impact of climate change on their community. We developed a virtual experience in which people can be immersed in a coastal flood and experience its intensity. We used a combination of UAV imagery and digital photogrammetric techniques to create a virtual environment in which people can recognize real locations in their neighborhood and used GIS flood data to apply a water texture in Unity3D to create the flood levels.

1. Introduction

Coastal cities are exposed to a wide range of hazards. Among them, flooding is being magnified by global warming and its related effects, such as rising sea levels and changes in extreme precipitation events (Cheng et al., 2014). Coastal flooding often results from combined events, such as high precipitation, storm surge, high tide, and sea-level anomalies. This, alongside increased urban development in affected areas, means the number of coastal residents at risk for flooding is expected to increase. Currently, 200,000 people live in low-lying coastal areas in California (Crowell et al., 2010), and an additional 204,000 people are projected to be at risk by 2050 (McGranahan et al., 2007). Despite this increased risk being well documented in academic literature, climate change is not yet considered a direct and personal threat to many people living in these areas. A 2020 survey from the Yale Program on Climate Change Communication shows that while a large majority of Americans believe that climate change is happening (72% National, 77% California) and changing the weather (64% National, 69% California), it is still considered a far and future issue (71% National, 76% California). Only 43% of Americans think they will be personally impacted by climate change (50% California) (Desssler et al., 2016; Leiserowitz et al., 2015; Mcdoughall et al., 2011; Howe et al., 2015). Despite the frequent and stronger droughts, wildfires, floods, and heatwaves, most of California does not feel impacted directly and immediately by climate change (Fig-1).

The disconnect between the public's flood risk perception and the flooding's relationship to climate change has been extensively studied. For instance, it has been observed that flood risk communications in Europe were not accompanied by personal preparedness (O'Sullivan et al., 2012) or knowledge of the local flood risk (Bubeck et al., 2012). The feeling of helplessness, or inability to manage the uncontrollable, has been attributed as one of the causes of such dissonance (Paton & Johnston, 2001). The high trust in centralized governmental agencies managing hazards might also cause this lack of interest (Cannon et al., 2021). Moreover, the psychological distance between the

Figure 1.
Percentage of people who think climate change will impact them during their lifetime. Visualization of the data from the Yale Climate Opinion 2020 using Tableau's software.

public and climate change is extremely high: the long-term projections used by climate scientists or policymakers (such as 2035, 2050, or 2100) or the apparent small-scale climatic changes (objective of 1.5oC degree warming, current global sea-level rise of 3–4 mm/yr) gives the wrong impression to people that climate change is a slowly emerging issue only for future generations (Spence et al., 2015; Loy et al., 2020). Finally, terminology such as centennial flood or return period is not understood and has little to no meaning for people (Burningham et al., 2008; Chowdhury et al., 2011; Taylor et al., 2014). Research in individuals' risk perceptions has gained interest in improving risk communication strategies (Baan & Klijn, 2004; Siegrist & Gutscher, 2006; Plattner et al., 2006). Traditional visualization tools to inform people of coastal flood risk suffer from different flaws, such as assuming that people will process the information analytically (Marx et al., 2007). However, it was shown that the human brain prioritizes personal experiences over gathered analysis or statistical information (Marx et al., 2007). For instance, it has been shown that people who previously experienced a flood are more likely to be concerned about climate change (Whitmarsh, 2008). Consequently, many flood communication tools have failed to inform people about their risk, and there is a need to deliver risk information in a way that allows users to develop an informed judgment of their risk (Rollason et al., 2018).

Experts have been researching the best ways to reduce flood losses for years. Like other risk domains, flood risk management has increased interest in risk perception and communication research. Immersive Virtual Environments (IVE) have proved to be an effective tool in communicating flood risk in the past. Realistically 3D virtual environments can add drama to the scenarios while adhering to the representation of accurate scientific information (Olsen et al., 2016;). It provides a direct-to-user hands-on experience of the subject matter within the environment of interest. By being fully immersive and located in a place they know, we aim to make people more emotionally connected to the issue they are experiencing. The information interactively provided will also give them valuable information on why and how these floods are happening and changing in intensity. Pairing a persuasive message with a personal experience is potentially a valid and

Figure 2.
Left: area surveyed by the drone, view from the Drone Deploy Application. Right: ground view of the study area.

more effective technique to raise climate change awareness (Gustafson et al., 2020). By creating both affective (emotional) and cognitive (analytical) responses (Bostrom, 2003), VR is seen as a promising multifaceted tool to communicate climate change risk. By showing simulated flood scenarios in a photorealistic 3D environment that closely resembles a real place, people may better understand the impact of those scenarios in the real world. 3D modeling can create extremely realistic environments but is limited to faithfully reproducing an existing location. There are two main techniques to create realistic 3D models: The first uses a 3D scanner, which can produce high-resolution models but doesn't perform well over water. In contrast, the second uses only RGB imagery from different angles (stereovision) to estimate the 3D coordinates of each point. This last technique, called photogrammetry-stereovision or stereophotogrammetry (Wesencraft et al. 2019), is used in this paper since it is focused on coastal areas. This technique allows multiple photos of real-world objects to author game-ready assets and can realistically and faithfully reproduce landmarks near the coast. Photogrammetry is the reconstruction of object properties (i.e., shape, orientation, size, relative position, textures) based on images. Considering those, we propose a framework to augment two-dimensional traditional flood maps into a three-dimensional photorealistic virtual and immersive environment.

Previous attempts have been to use such technology to improve communication, especially flood risk communication. For instance, VR was used to improve flash flood evacuation in Japan (Fujimi, 2020) and in the UK (Skinner, 2020). It was shown that users could better understand complex phenomena, such as flash floods. Research in Taiwan has shown that when compared to static maps or visual presentations, VR programming increased the communication efficiency between the public and the government on a flood diversion infrastructure (Lai et al., 2011). According to the Construal Level Theory (Trope & Liberman, 2010), the perceived or psychological distance is defined by four dimensions: the temporal distance, the physical distance, as well as the social distance, and the hypothetical distance. While the previous studies are focusing on closing the temporal and physical distance, they lack the social, and hypothetical distances. Social distance can be reduced by choosing a place familiar to the user rather than a generic building, for instance a famous monument or a local public place. Hypothetical distance can be reduced by allowing the user to choose a set of climate change scenarios rather than a fixed one.

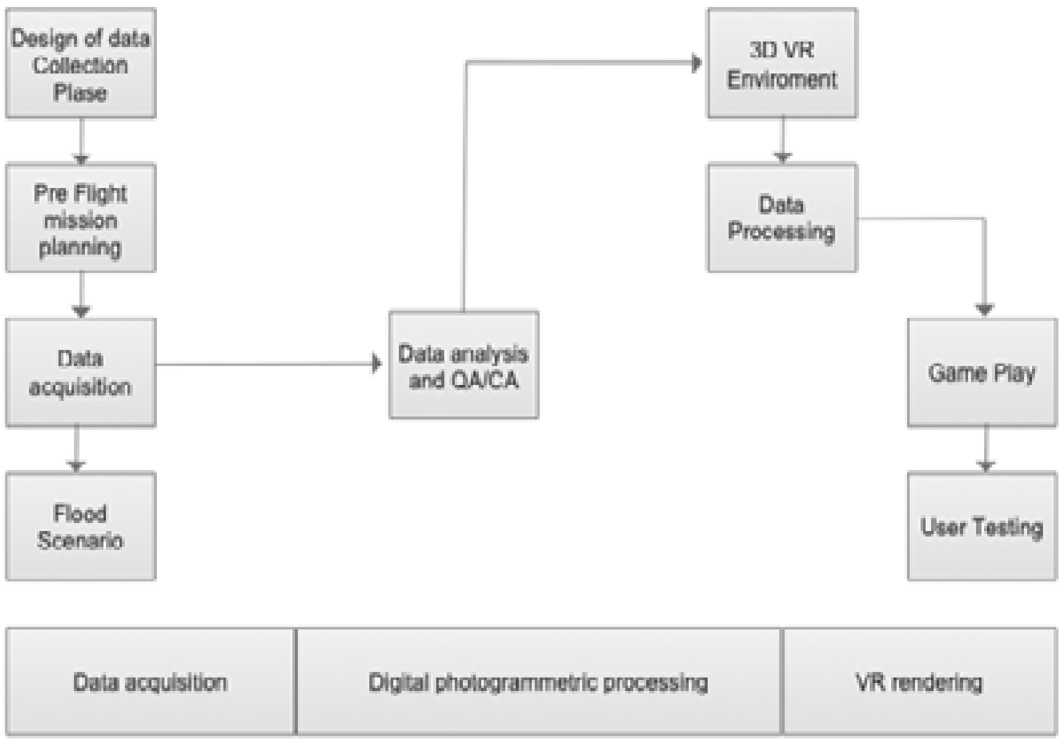
The goal of this paper is to introduce a framework to visualize flood scenarios in environments that resemble the real world, using drones as a tool to collect 3D data, and VR as a tool to create 3D immersive environments.

2. Data and methods

2.1. Study area

The study area is at the "Little Corona Del Mar" beach, located in Southern California. It has a total surface area of 10 acres, and the UAV covers 12 acres (see Figure 2). Residents of this coastal area experienced a relatively recent major flood (centennial) in January 2005, which impacted 355 properties (Gallien et al., 2011) and is still in people's memory. The area

Figure 3.
Framework developed for creating a photorealistic 3D and interactive environment.



exhibits several human constructions (staircase, lifeguard stands), several geological features (cave, sea stacks, cliffs), and it is a widely known beach among Orange County residents.

Due to its popularity, recent flood, and easy-to-recognized features, this location is a great choice to implement a flood VR experience, in which residents will be able to recognize local features, remember past flood experiences, and create a more personal and empathic connection with the environment. We will also be able to test the effectiveness of the VR experience as a risk communication tool for people familiar with relevant oceanic concepts (tide levels, wave patterns) otherwise unknown to more inland residents.

2.2. Overall workflow

The overall workflow consists of a data acquisition phase using an Unmanned Aerial Vehicle (UAV), data processing using digital photogrammetric techniques, flood data selection and rendering into an immersive virtual environment, the experience design to create an interactive environment, and finally user testing (pre and post survey) to identify learners' existing knowledge and whether the VR experience was effective in creating awareness about coastal flooding.

2.3. Data acquisition phase

The data acquisition phase has been divided into four interconnected phases: (1) design of the data collection phase, (2) Pre-flight mission planning, (3) data collection, and (4) data analysis and quality control.

The design of the data collection phase is the most critical step to ensuring a safe, data-producing flight. It is the role of the Pilot in Control (PIC) to assess the key parameters affecting the quality of the data produced, such as meteorological conditions, local topography, and sensor performance. It is also responsible for knowing current flight regulations, legislation, and safety protocols. Depending on the spatial and temporal resolution needed and the desired data precision, the PIC creates the mission plan while accounting for camera settings, flight paths, and battery management. The PIC also defines the optimal conditions for data collection using the UAV, such as low tide, to capture more rock structures at the beach, morning, and overcast days to minimize the shadows that can interfere with the digital photogrammetric process.

The pre-flight mission plan consists of the reconnaissance of the area that will be surveyed to identify potential hazards (e.g., powerlines) and problematic areas for the project's objectives (e.g., cave, benches, fire pits for our project will require a higher level of details and ground imagery). During this step, we identified all potential hazards, such as possible collisions with standing objects, structures that could alter the remote-control signal, and the presence of people or animals (birds) that could require attention. We also identified the objects or areas that require special attention when collecting imagery because of their shape or topography. Some areas were not accessible by UAV and will have to be surveyed using a DSLR camera.

The data collection phase involves flying the UAV on an automated path using the DJI Waypoint application. For this project, we set up a linear path for image acquisitions with Ground Control Points (GCP) to properly align and scale the study area. Aerial imagery was acquired by a DJI Mavic Pro 2 at 3 level altitudes (20m, 30m, and 50m). We used manual settings for the camera to avoid high ISO (camera's sensitivity to light) and noise and saved the images in RAW format. We set up a front overlap of 70%, a linear path, and a combination of nadir and oblique imagery to generate more accurate and realistic 3D reconstructions. DJI WayPoints were used to define the trajectory of the UAV, and all images were acquired automatically.

The data analysis and quality control phase are critical to ensure the project's success. Despite the growing trend for using UAVs to collect data, currently, there are no universal standards and procedures to ensure the data's quality. For this reason, we implemented the following methods to ensure data reliability: mapping all imageries to ensure that the UAVs correctly recorded the GPS coordinates; qualitatively assessing the luminosity and level of glare over the oceans, and in case of high levels, postponing the flying plan, and finally quantitatively assessing the blur of each image and removing the low-quality ones or rescheduling the flying plan. There are many different methods to detect blur in imagery (Pertuz et al., 2013). We implemented a method based on the variance of the Laplacian on detecting blur (Pacheco et al., 2000) using the cv2.Laplacian function from the OpenCV library in Python to detect blurry images and exclude them.

2.4. 3D processing and rendering.

The general workflow to obtain Digital Surface Model (DSM), Digital Terrain Model (DTM), or 3D Model from UAV imagery is: (1) creating a low-density point cloud using camera orientations and locations, (2) creating a high-density

Figure 4.
CoSMoS data visualization around the area of interests for two scenarios of Sea Level Rise.w

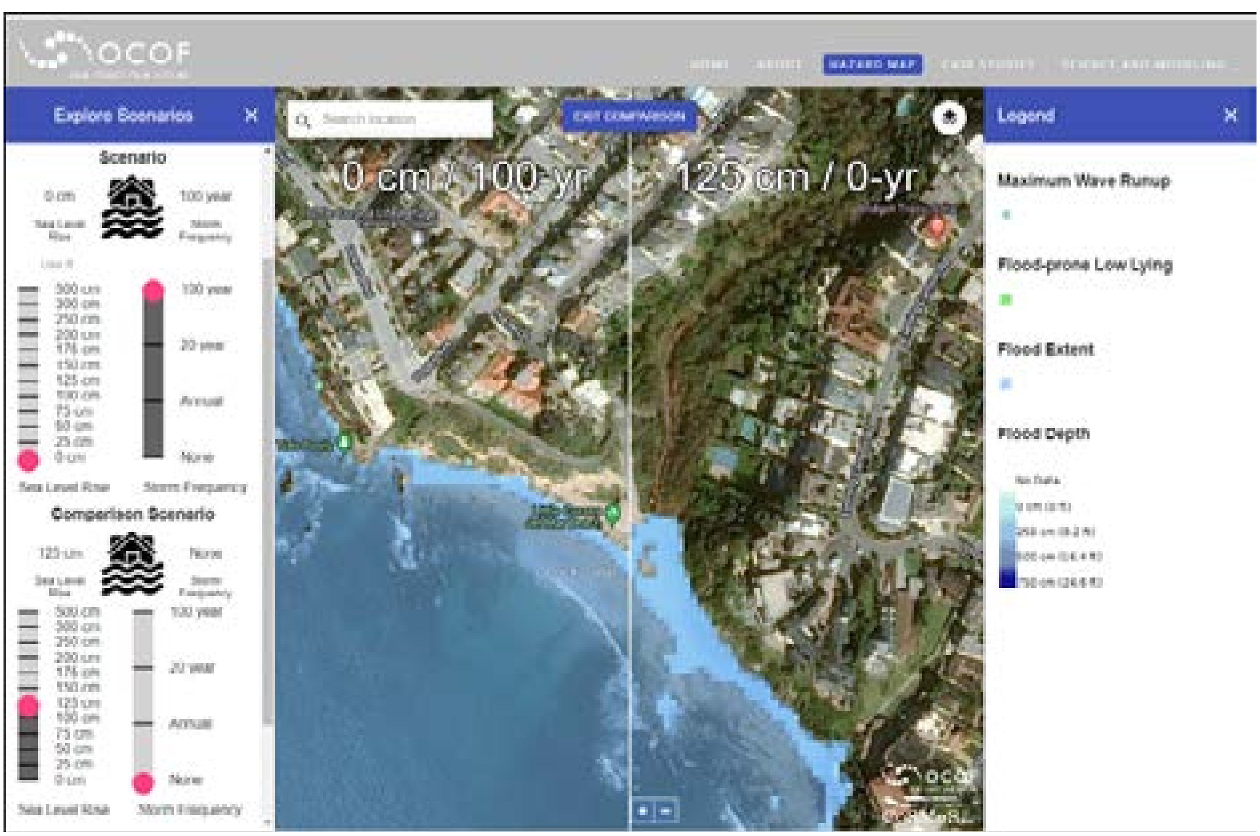


Table 1.
Scenario description for a non-expert user

Scenario	Sea Level Rise	Description for the use
S1	0 cm	Current world conditions, equivalent to the 2005 flood.
S2	50 cm	World where sea level rise has reached 50cm. This sea level rise is the most likely by the end of the century if global warming is contained to 2 to 3 Celsius (RCP 4.5) or by 2050 if global warming is around 4.5 Celsius (RCP 8.5)
S3	150 cm	World where sea level rise has reached 150cm. This sea level rise is the most likely by the end of the century if global warming reaches 4.5 Celsius (RCP 4.5) or by 2050 if global warming is around 4.5 Celsius (RCP 8.5)
S4	200 cm	World where sea level rise has reached 200cm. This sea level rise is the most likely by the end of the century if no action is taken (scenario H++)

point cloud, (3) generating a georeferenced mesh from the point clouds, and (4) applying the texture on the mesh. We used the commercial software Autodesk Reality Capture (ReCap) to generate a georeferenced 3D Model on the cloud with texture (colors) out of the UAV imagery. After scaling the model, we verified the quality of the output by comparing one virtual object's dimensions (a rock) on the model with its actual dimensions to ensure no wrapping or distortion of the 3D model. After validation of the DSM, we manually edited the 3D model using Maya 3D to smooth the object's surfaces and fill any holes in the model using ReCap's automated functions. The 3D objects generated by Autodesk ReCap were exported into Unity 3D, a virtual reality platform, along with the rest of this model's assets. Unity3D has been chosen due to its support for advanced physics (such as waves) which are essential for a realistic rendering.

Flood information were queried from the Coastal Storm Modeling System (CoSMoS) dataset (Barnard et al., 2018), which consists of detailed projections of storm-induced coastal flooding and erosion for both current and future sea-level rise (SLR) scenarios. The flood heights were extracted from the 100-years return period raster files using ESRI ArcGIS and summarized to water heights to feed the Unity3D software. We chose several scenarios of sea level rise and related them to several scenarios in California (Griggs et. Al., 2017).

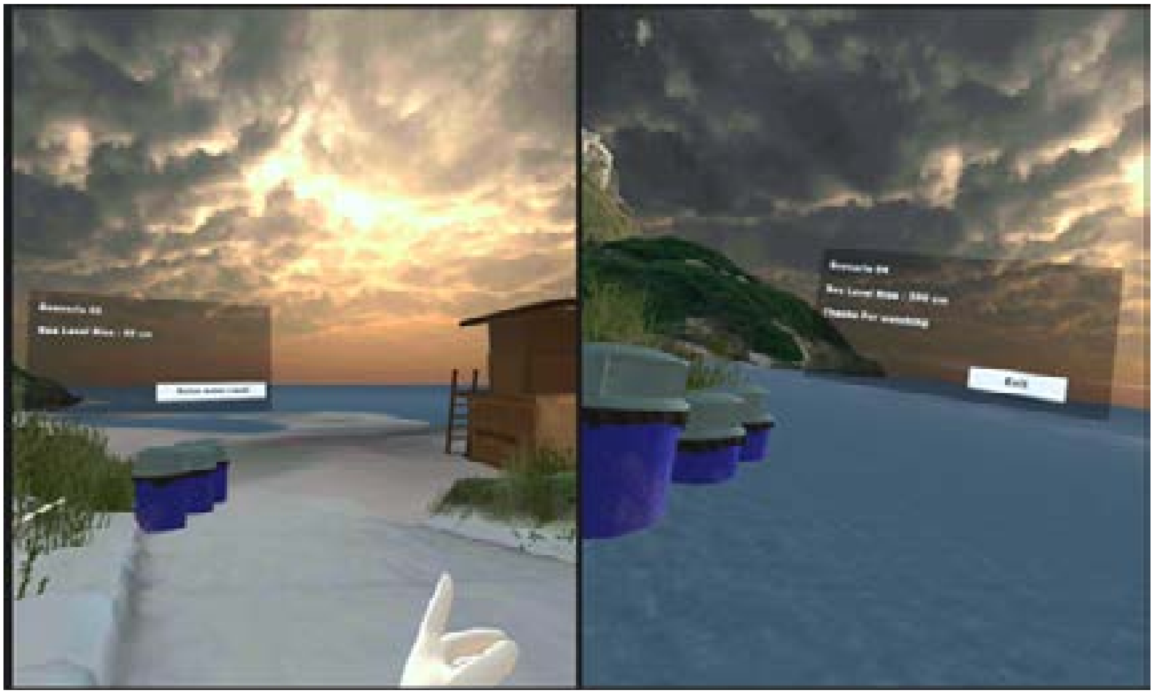
Finally, the application was implemented in C# on Unity3D and visualized using Oculus Rift virtual reality headset, as detailed in the results section.

2.5 Virtual Reality development

This phase formed the core of the whole research process; It included converting the images and videos obtained with

Figure 5.
Foliage modeling on the 3D model.

Figure 6
Final rendering of the VR environment



high-resolution cameras and drones to realistic 3D models in Reality-Capture software, 3D modeling smaller objects in Maya, using these 3D models in Unity to create a virtual environment that can be walked around freely like a virtual game, providing the audience with a six degree of freedom. The gamification involved coding the scene using the C# script to enable the audience's movement in a virtual environment. The scene enables the simulation of rising waves and tides at the beach, providing a first-hand experience to the audience to create awareness about the grim situation.

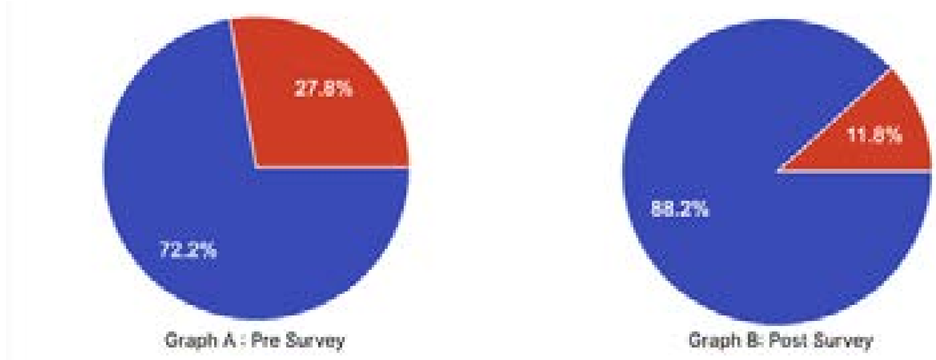
The next step involved creating realistic terrain from the Height/UV map using the Terrain to Object plugin in Unity. We created vegetation that resembled the one that Newport beach has. Finally, we used C# in the unity development environment to Gamify the environment where the audience could press the button to increase the water level and see the impact and hear the narration about different scenarios. The data about water rise was taken from the CoSMoS dataset. The audience is always provided with a narration in the background to give information about the flood rise in each scenario. We created a hype- realistic VR scene of the Newport beach, mapping the exact flora and fauna found on the beach. Although the 3D model from the Reality Capture gave us a high-quality UV map, it flattened all the foliage and high poly organic objects. As a result, we had to use some foliage from the Unity asset store and place them on the UV map. The foliage was placed on the UV map specifically selected based on the color, type of foliage, and its exact location, and motions were added to the leaves for realism.

3. Testing

We conducted a testing session with around seventeen participants; the main focus of our demography was young adults, who can play a pivotal role in creating awareness and achieving the goal of sustainable development. The

Figure 7.
Participants experiencing VR scene in Oculus headset

Figure 8.
The two graphs show an increase in the number of participants that feel concerned about increasing sea levels



participants were hired from San Jose State University and pursuing their undergrads.

We conducted surveys in two stages; the first stage helped us to understand the current level of understanding about the sea level rise and climate change and how it is affecting major decisions in the life of students. We found that almost 60% of participants felt that rising sea levels are not affecting their daily lives. This data showed us that very little awareness about the rising sea level directly or indirectly impacts our lives. On the contrary, almost 78% of participants agreed that they are affected by climate change. We need to make it obvious that climate change and Sea level rise are both issues that go hand in hand; very little effort is being put into making people aware of the consequences of rising sea levels.

The post-survey was aimed at getting insights into the VR application created and its effect on understanding the situation of sea level rise. About 88% of the participants found the application relevant in creating awareness about the rising sea level.

The experience got a positive response from the participants; all the participants found the experience informative and made them more aware of the consequences of rising sea levels. About 70% of participants did not encounter navigating the scenes. Our efforts to keep the effect of motion sickness to a minimum showed with 70% stating they did not face any dizziness or motion sickness.

4. Results

The 3D model was created using a combination of UAV and DSLR imagery with photogrammetry techniques. The image acquisition phase took 30 min using two sets of batteries. The imagery was taken in the morning when lighting conditions were ideal. One challenge of mapping the coastal environment is the surface roughness of the water layer created by the waves so that two images taken within one second would be dramatically different and create uncertainties in the digital photogrammetric process resulting in model errors. We took this into account by capturing images on a day with low tide, featuring as much of the landscape as possible while also minimizing potential problems caused by capturing the ocean. We obtained a total of 680 aerial photographs and removed 12 images with a high level of blur using the method mentioned in the previous section. We then processed the remaining images using photogrammetry software and obtained a high-resolution georeferenced 3D model (Figure 9). The processing time in the cloud (AutoDesk ReCap) took 3 hours for the 10 acres. Merging UAV and DSLR data were challenging, and we decided to process the two imagery sources separately. High-resolution DSLR ground imagery was processed to create separate 3D objects that were later integrated into the DSM.

The flood information has then been integrated into Unity so that the correct water level can be rendered. The hypothetical level under a sea-level rise in 2035 and 2050 has also been integrated. The final VR environment and flood scenario were implemented; we could virtually experience the 2005 flood under current and future climate conditions (Figure 10).

The combination of UAV and DSLR imagery created high-resolution surfaces with texture in most areas of interest, with some high-resolution objects when needed. All geological features (rocks, caves) and topographic features (sand dunes) were correctly captured by the UAV and rendered in Unity. The added water layer due to different sea-level and tide conditions has been rendered in Unity with visual effects, such as surface roughness and waves. We decided, however, not to include wave interactions with an object, people, and surfaces such as walls or cliffs. Such interaction (droplet projections) requires more data, such as current velocities, which were not directly available and would add another scenario level (high tide, low tide, wind conditions, etc.). However, adding flow conditions, such as velocities, and interactions with people, for instance, resistance to walking due to the wind or waves), would further improve the VR experience of the flood and the comprehension of the severity of the event. Vegetation was the most challenging as many small bushes and most small plants were either not fully captured in 3D or were captured as 2D assets. Capturing these 3D features would require adding an unnecessary and considerable amount of time and data. For these reasons, we decided to cut them out and add similar-looking vegetation features that were pre-modeled. Overall, using a ground based DSLR, it is necessary to model these complex features that cannot be fully captured by UAVs separately. These objects should be identified during the pre-flight mission steps so UAV and DSLR imagery is captured simultaneously and in similar lighting conditions.

Figure 9.
Overall view of the case study area (3D model).

Figure 10.
Details of the simulation: Left: High tide in 2005; Right: High tide with 50cm SLR

The results of the user testing are encouraging: the survey prior to the test revealed that only 60% of the participants (10 out of 17) felt that rising sea levels are not affecting their daily lives but 76% agreed that they are affected by climate change. Past the VR experience, about 88% of the participants found the application useful in raising awareness about sea level rise. All the participants agreed that the VR experience was informative and provided useful context to the data shown.

Finally, most (70%) of the participants stated having a positive experience, free of motion sickness or dizziness during the navigation and transition from one scenario to another one.

5. Discussion

This DSM was made possible by combining UAV and DSLR imagery, photogrammetric software, and 3D modeling to create a georeferenced, photorealistic model. Compared with their real-life counterparts, the objects depicted in this DSM are appropriately proportioned and accurately textured. VR has been used for experiential learning, as mentioned before; however, few can capitalize on a user's personal experiences and enhance the VR experience. By providing high-resolution details of a public place (beach) where users may have some sentimental attachment, we aim to personalize the VR experience to create a more immersive experience with emotional responses. Moreover, by using the georeferenced DSM into Unity and adding a layer of water with a parametric height, we can easily translate any flood scenario from a shapefile (ArcGIS, QGIS) into a 3D immersive experience.

These results provide several recommendations. One major challenge of climate change resilience is to increase local stakeholders' (local government, communities) participation in their risk mitigation strategies (Frazier et al., 2010). While a high-resolution local flood model exists, static or interactive web maps might not effectively engage most people. Visualizations, such as a preliminary model or an artistic mockup, have increased local stakeholders' engagement in infrastructure development (Assaf et al., 2002; Wang et al., 2019). In effect, however, much of this awareness media is often created by centralized governmental institutions or agencies, which may not account for the local community's specific environmental conditions or needs. The framework presented could help to engage the various local stakeholders by providing an accessible and provocative experience of the different flood scenarios (different return periods, sea wall heights proposed, or climate change scenarios), set in a location known to many within the community. It would furthermore create a space for two-way communication between local communities, which are knowledgeable on local environmental conditions, and centralized agencies, who provide a deeper understanding of the exogenous factors depicted by the framework. Several studies suggest that community-based adaptation measures can be more beneficial (Dumaru, 2010; McNamara et al., 2020). Another challenge is the multidisciplinary nature of flood risk mitigations, which makes it very challenging for the different stakeholders to understand the mechanism underlying coastal floods: sea-level rise, change in precipitation patterns, change in land use and runoff, green infrastructure, engineered infrastructure… The proposed framework is intended to help the different stakeholders better understand the impacts of each of these parameters by experiencing it.By using a consumer grade drone (less than $2000), and free software (Unity 3D, AutoDesk ReCap, free for small non-profit usages), the framework can be replicated in local communities without heavy investments on hardware and software.

We acknowledge that this study has several limitations. First, VR can induce dizziness in some users, so the experience should be calibrated to minimize this effect. Additionally, there is the risk that the program does not appeal to residents. For this reason, the VR experiment should be tested on a representative sample of the population of this paper's case study area, and a survey and robust analysis should be conducted to determine VR's real effectiveness in conveying awareness. Such analysis will be the object of a separate study as it will require testing several scenarios of climate changes and several technical and sensory features of the VR experience.

6. Conclusion

Climate change awareness does not always translate into personal risk awareness, especially in an age where climate-induced hazards are growing increasingly common. While more and more coastal residents understand the global changes in climate thanks to education and scientific outreach, too few are yet aware of the change in hazard frequency and severity at the local level. This paper presented a framework to augment a 2-dimensional flood map into a 3-dimensional photorealistic interactive environment. The framework developed successfully uses UAVs for imagery collection and processing and integrates different quality control and quality assurance steps. Currently, our project is limited to one type of scenario (Sea-Level Rise) over a small non-residential area. However, the framework is generic and can use any type of flood scenario saved in a 2D shapefile, such as sea-level rise, high tide, high precipitation, levee failure, seawall breach, or any combination. Adding a scenario will require no extra work to create the water layers but additional time and resources to create the narrative of the experience.

In future research and with appropriate flight authorizations, we plan to map a residential area protected by a sea wall and test the tool's effectiveness in communicating flood risks under different scenarios of sea-level rise and sea wall height. We will develop the VR Experience with an appropriate narrative in which the user will be able to visualize a historical flood and its projected level under a different scenario of climate change, levee failures, or infrastructure upgrade with the ultimate objective to better explain to people how the current change in climate will impact their local community.

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Spatial and Temporal Variations of Microplastics Within Humboldt Bay, CA

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This study aimed to quantify microplastic (MP) concentration and analyze the spatial and temporal variabilities of the concentrations during the tidal cycle in Humboldt Bay, California. To get an approximation of MP concentration, both water and sediment samples were taken at five different stations, twice during one tidal cycle. Sampling was conducted during two different cruises, on the 19th and 21st of September 2020. The samples were processed in the lab using a density separation procedure and filtration. MP concentrations in the different samples were determined using an average optical microscopy count. Comparison of the water column MP concentrations during ebb and flood tides shows higher concentrations during flood tide, 49.0 particles/L ± 32.37 (flood) vs 34.4 particles/L ± 16.32 (ebb), indicating that MPs are brought into Humboldt Bay from the ocean. The comparison of the MP concentrations during lower energy and higher energy conditions indicates that concentrations in the water column were elevated when there was greater tidal kinetic energy, approximated by the covariance of the measured velocity in North Bay Channel. This result was assumed to be caused by the strong tidal currents stirring up both sediments and the settled MPs into the water column. Due to lower tidal kinetic energy on the sediment sampling cruise day, we could not confirm that assumption. Water samples indicated that MPs are heterogeneously distributed in the bay, with higher concentrations found near the Entrance Channel and lower concentrations found further north in the bay. Sediment samples also indicate a heterogeneous distribution of MPs in the bay, with the lowest concentrations near the Entrance Channel, 15 particles/kg, where high tidal currents inhibit settling of particles.

Introduction

Plastics and Microplastics

In the past 65 years plastic pollution has risen dramatically. During that period, 6.3 billion metric tons of plastic have been produced (Dikareva & Simon, 2019). In 2016, the annual global production of plastic products was about 322 million tons (Li et al., 2018). About 60% of all plastic produced has accumulated in the environment (Dikareva & Simon, 2019). The multiple additives used to lengthen the life of plastics slow the degradation of plastic waste in the environment (Chamas et al., 2020). The duration of plastics make them an even greater concern in the marine environment. (Gall & Thompson, 2015).

Plastics are made from polymer-based materials and are processed with a range of chemical additives to make them usable, including inorganic fillers, pigments, plasticizers, and antioxidants (Lambert & Wagner, 2017). Plastic particles that are < 5 mm are considered microplastics (MPs) (NOAA Marine Debris Program, 2015). MPs are divided into two categories, primary and secondary MPs. Primary MPs are used as resin pellets to produce larger items or used directly in cosmetic products like facial scrubs and toothpastes. Secondary MPs are formed from the disintegration of larger plastic debris (Lambert & Wagner, 2017). These secondary MPs could originate from fishing nets, industrial resin pellets, discarded plastic debris, and emissions from wastewater treatment plants (Li et al., 2018) (Lambert & Wagner, 2017).

MPs have been found throughout the ocean in the water column and sediments in varying concentrations (Dikareva & Simon, 2019).

The variation in plastic composition leads to a heterogeneous spatial distribution of MPs in the marine environment (Wagner et al., 2014). MPs are not evenly distributed horizontally or vertically in the water column, and their abundance decreases at greater distances from their source (Mendoza & Balcer, 2019). Plastic debris can also be transported by winds and direct runoff after rain events, where it eventually reaches aquatic ecosystems and accumulates (Dris et al., 2015). Environments are likely exposed to different mixtures of micro- and nano- sized particles because of the composition of the plastic material.

MPs and other marine debris can have a detrimental impact on the marine environment. Bacteria can migrate on plastics, impacting the microbiome of areas not previously affected (McCormick et al., 2014). In addition, MPs can bioaccumulate in an organism's systems and cause digestive issues, tumors, or both (Li et al., 2018). Plastics have also been found embedded in rocks on shorelines, which could impact grazers and marine invertebrates (De-la-Torre et al., 2020). In order to curb the major effects of MPs on marine ecosystems, we need to better sample and quantify the distribution of microplastics in the marine environment.

Microplastics in Sediments

Van Cauwenberghe et al. (2015) estimated that millions of tons of plastic waste end up in the marine environment. Marine sediments are hypothesized to be major sinks of MPs. Plastics with a density greater than the average density of seawater (i.e. 1.027g/cm^3) will sink and accumulate in the sediment. Low density plastics will initially float at the sea surface or move down in the water column based on their density. Biofouling–the general accumulation of organisms on an object–causes even buoyant, lighter plastics to become denser and sink to the seafloor (Van Cauwenberghe et al., 2015).

MPs have been detected on the shorelines of all continents and the seafloor across the globe. Due to the large spatial variability of MP distribution in sediments, sediment samples must be collected from different locations in a region in order to correctly quantify the MP concentration in that region (Nuelle et al., 2014). The typical concentrations of MPs in sediments range from 1 to 100 items kg^{-1}. Wagner et al. (2014) found a maximum of 400 items kg^{-1} in coastal harbor sediments.

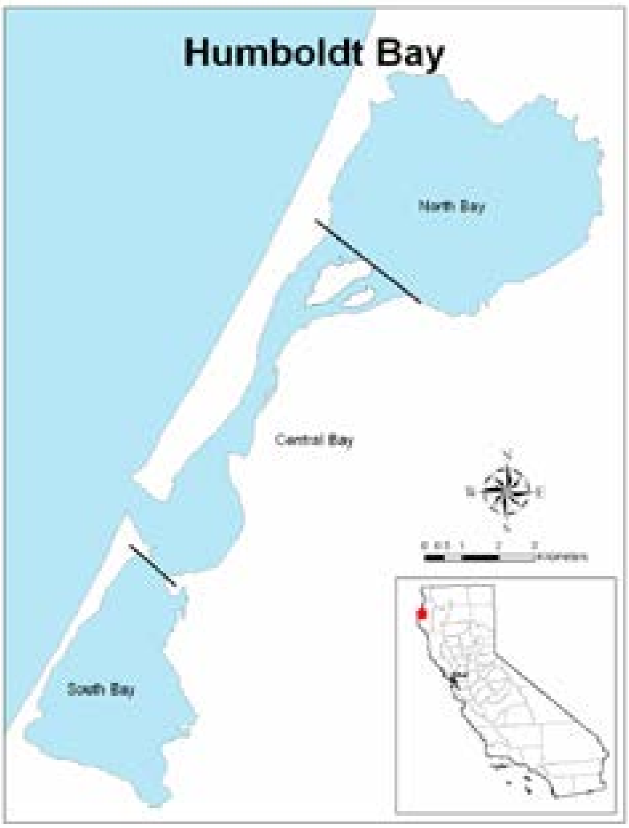
Transport of Microplastics

Estuarine river runoff is the primary source of MPs into the marine environment. The most abundant MP deposition into marine environments occurs during storm events directly at river and tributary mouths. After storm events in California, a six-fold increase in MP concentration is seen in surface waters of the ocean, and plastics are deposited farther from their original source (Lattin et al., 2004). The hydrodynamics of estuaries and bays affect MPs in a similar way to how sediments move in these environments when large volumes of water flow in or out due to tides or storm events (Zhang, 2017). In estuaries, MPs circulate and are distributed to the ocean through tidal mixing and currents. Once MPs have reached the open ocean, depending on their densities, they will either sink or float. The denser plastics will sink near their source, while the floating MPs will be transported by surface currents (Zhang, 2017). The floating MPs might experience biofouling during this transport, causing them to sink or become neutrally buoyant. During the sinking process, MPs will be circulated by deeper ocean currents. When the MPs become denser than the water column, they sink and settle in the sediment (Zhang, 2017). These particles can settle much farther from their source, depending on the duration of their suspension in the water column. Some MPs will never sink; they may remain floating or suspended in the water column. Ingestion by zooplankton, benthic organisms, and large marine animals is an additional source of sink for MPs in the ocean (Zhang, 2017). MP concentration in marine animals is directly correlated to the concentration of MPs in the seawater (Wright et al. 2013).

The goal of this study was to analyze the distribution of microplastics in Humboldt Bay, CA. Humboldt Bay, the second-largest estuary in California, is separated into three main sections: North Bay (NB), South Bay (SB) and Entrance Bay (EB) (figure 1).

There is a high degree of erosion and sediment transportation within EB, North Bay Channel, and Southport Channel. While the sediments deposited in the channels are predominantly sand, NB and SB are almost entirely composed of silty tidal mudflats (Costa, 1982). These tidal mudflats are extremely nutrient-rich and support an enormous variety of life, including major eelgrass habitats. Eelgrass beds increase deposition of sediment as the large leaves disrupt the flow of water, capturing sediments–and potentially plastic–within the water column (Schlosser and Eicher, 2012). The abundance of erosion causes sediment deposition at the mouth of the Entrance Channel, reducing the flux of water into and

Figure 1.
A map of Humboldt Bay, Eureka, CA. Three main sections of the bay are shown: North Bay, Central Bay, and South Bay (Pinnix et al., 2005). Inset depicts the state of California, with the red dot indicating the location of Humboldt Bay. Humboldt Bay's watershed spans an area of 557.6 km^2 (Barnhart et al., 1992). The bay is approximately 19 km long and 0.8 km–6.9 km wide, with a total surface area of 64.8 km^2 at high tide and 20.7 km^2 during low tide (Evenson, 1959). The average depth of the bay is 3.4 m, and the maximum depth is 12 m. Salt marshes make up 4% of NB and 1% of SB (Barnhart et al., 1992).



out of the bay. To maintain water flow, Humboldt Bay is dredged two miles south into SB and four miles up into EB, almost annually (Humboldt Bay Harbor District). Sediment distribution in Humboldt Bay suggests that dredging has increased the average grain size of sediment found within the bay (Stevens, 2002). Areas of Eureka and Samoa Channels become more sand dominated after dredging occurs (Stevens, 2002).

Freshwater Inputs

Plastic is a major constituent of riverine pollution (Lambert & Wagner, 2017). In their studies of MP transportation in freshwater systems, Luo et al. (2019) found that rivers provide MPs from land-based sources to estuaries and the ocean, and the researchers deemed the concentration of MP debris to be more detrimental to freshwater bodies than estuarine. Dikareva & Simon (2019) found that the total MP concentration in small streams varied between 17-303 items per cubic meter in the water column and 9-80 items per one kg of dry sediments, whereas Li et al (2018) found the average values of MPs in freshwater systems ranged from an undetectable concentration to almost a million pieces per cubic meter. The most abundant types of plastic found in the water column were fragments and fibers, making up 34% of all particles on average (Dikareva & Simon, 2019).

The freshwater sources of sediments are mainly the small creeks and rivers that empty into Humboldt Bay. These streams run through highly populated areas with around 65,000 residents, likely picking up contaminated runoff from streets, homes, and businesses. The major tributaries contributing to the bay are: Salmon Creek, which enters into SB; Elk River, entering into EB; and Freshwater Creek and Jacoby Creek, entering into NB (Barnhart et al., 1992). 62,532 metric tons/yr of sediments are supplied to the bay from its tributaries, the majority of which enter the bay after large winter storms, leading to heightened turbidity levels between 30–200 NTU (Houle, 2015). The biggest contributor is the Elk River, which transports sediments consisting mostly of silts intermixed with sands and clays eroded from the Wildcat Group of the Miocene-Pliocene age at a rate of 1200 Mg km^{-2} y^{-1} (Macdonald et al., 2016). This erosion rate is similar to those of other North Coast watersheds (Andrews and Antweiler, 2012).

Tides and Currents of Humboldt Bay

Humboldt Bay is a well-mixed marine estuary that is tidally driven by mixed semidiurnal tides, with a mean tide height ranging between 1.5 m and 2.1 m at the channel mouth (Anderson, 2015., Crawford and Claasen, 2004). Currents entering the bay from the northwest have the greatest impact on tidal fluxes, while currents coming in from the southwest have the highest contribution of wave energy (Crawford and Claasen, 2004). Overall current flow is generally in the northeast direction, resulting in the majority of water coming in from the channel mouth to be forced into NB (Gutierrez et al., 2005). Approximately 50% of the tidal prism travels into NB, with 30% of the tidal prism flowing into SB (Costa and Glatzel, 2002).

Maximum current velocities tested within the navigation channel can reach higher than 4.1 m/s, and wave heights can be as high as 7 m. In the Entrance Channel (EC), the average velocity of the currents during an ebbing tide is 1.9

m/s with an average of 2.1 m/s during a flooding tide (Costa and Glatzel, 2002). The velocities slow down as the depth decreases through the bay. The wave energy entering through EB tends to be the strongest, especially during flood tides, where it is deflected off of the south jetty towards NB Channel (Gutierrez et al., 2005). In addition to the high wave energies coming into the bay, the placement of the jetties and the positioning of the Humboldt Bay Bar both establish a huge means of sediment transport, erosion, and mixing within EC and into NB Channel (Costa and Glatzel, 2002; Gutierrez et al., 2005). The overall circulation in the bay varies daily and seasonally (Costa and Glatzel, 2002).

Human Impacts

Humboldt Bay is home to many industries, including local marine cargo, commercial fishing, mariculture, marine research, and recreational boating. There are two small commercial and recreational boat harbors in NB, located at Woodley Island Marina and Eureka Public Marina. The area surrounding the bay contains several sites of industrial operations: lumber mills, bulk oil storage, wrecking yards, and railroad yards which can contaminate local water sources with heavy metals, petroleum, and pentachlorophenol (PCPs). The Arcata Marsh and Wildlife Sanctuary, neighboring the top of NB, acts as a natural wastewater treatment plant for the city of Arcata and discharges the treated water into Humboldt Bay (Wastewater Treatment). Comparatively, Li et al. (2018) found that industrial wastewater treatment plants can release around 8 billion pieces of plastics per day.

Before 2013, there were sixty million single-use plastic bags used in Humboldt County and seven million or more were annually used within Arcata city limits (Ordinance No. 1434 of the City of Arcata Sec. 5476, 2013). The amount of local plastic deposited in Humboldt Bay and the ocean is still unknown. Another study found that an average of 415 pounds (188 kg) of plastics, including bottles, caps, and food packaging, washed up on North Jetty Beach annually (Plastic Pollution at Four Coastal Cali. Hotspots, 2020). Whether that plastic came from Humboldt Bay or was brought into the area from the ocean has not been determined.

This study aimed to quantify the MPs in Humboldt Bay and analyze concentration variability during a tidal cycle. To get an approximation of MP concentration, sampling was conducted of the water column and the sediments and compared during fluctuations in the tidal cycle. We also aimed to determine the directionality of plastic contribution between Humboldt Bay and the ocean, with a hypothesis that Humboldt Bay would be a net contributor of MPs to the Pacific Ocean. This prediction was founded on the presupposition that ebb and flood tides would result in sediment and MPs becoming suspended in Humboldt Bay, thereby increasing the concentration of MPs in the water column exiting the bay (G.P. Allen et al., 1980). We expected that sediment and MPs would resettle during slack tides, increasing the MP concentration in the sediment and decreasing MP concentration in the water column. We anticipated that surface sediment MP concentrations would be greater in the extremities of the bay, where there is less tidal influence, compared to the sediment MP concentration in the tidally driven mouth of the bay.

Methods

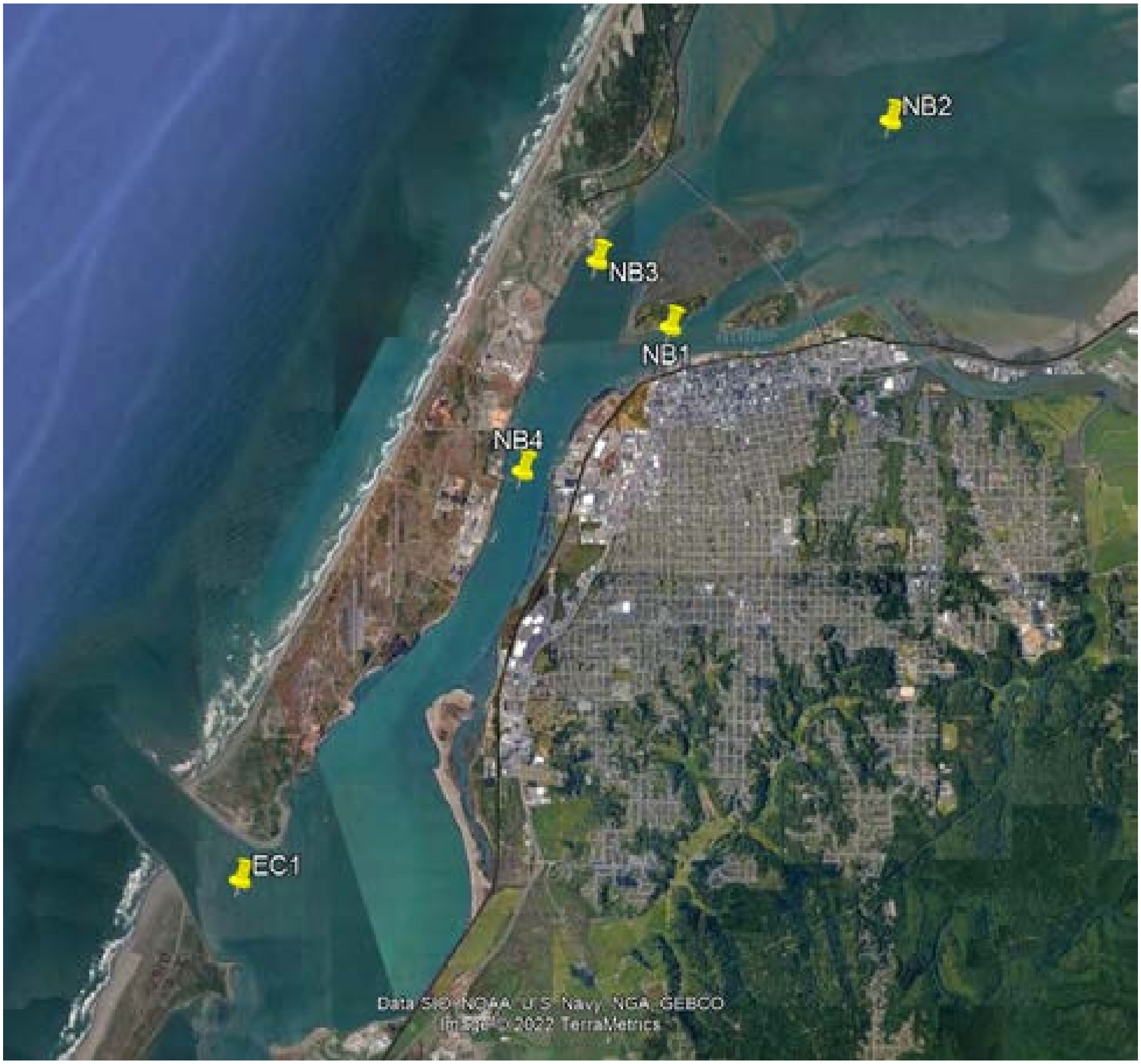
Sampling Sites

Samples were collected during two separate cruises aboard the R/V Coral Sea on September 19, 2020 and the Cal Poly Humboldt pontoon boat on September 21, 2020. Due to Covid-19 social distancing regulations aboard the vessels, two cruises were necessary. Humboldt Bay does not experience identical tides daily, so to minimize differences in sampling conditions, two days with similar tidal cycles were chosen for the separate cruises. Due to the time restraints on cruises at the time of sampling and the time necessary to complete the sampling, only flood/ebb tides were sampled for water data and only flood/slack tides were sampled for sediment data rather than sampling at all points of the tidal cycle. Samples were taken at five stations throughout Humboldt Bay (figure 2). These sites were chosen to sample distinct portions of Humboldt Bay that may experience pollution from their surroundings. For example, NB4 was near the convergence of the three main channels of Humboldt Bay, thus experiencing a variety of current direction and velocity. Ideally, stations in South Bay would have also been sampled, but due to the project's constraints around sampling protocol, this was not possible.

Avoiding Contamination

Contamination has been a prominent issue for past studies on MPs in Humboldt Bay (Carlson et. al, 2018). To minimize possible contamination from our own clothing, attire guidelines were put into place and followed by all researchers. During all sample collecting and processing, researchers wore bright orange cotton jumpsuits, and any clothing made from polyester or other synthetic textiles was prohibited. The sampling and storage equipment was cleaned thoroughly prior to and following use, and equipment was

Figure 2.
Station map of cruise stops on the R/V Coral Sea and Cal Poly Humboldt pontoon boat in Humboldt Bay. The yellow pins indicate the five sampling sites: EC1, the only site in the Entrance Channel; NB1-NB4, various sites within North Bay.



stored in sealed bins to prevent ambient MP contamination during storage and transport of samples. Blanks were taken across the analytical procedures and on all equipment. The processing of blanks was essential in minimizing the effect of our inevitable contamination to our samples and procedural equipment.

DDI Water Blank Procedure

The DDI water collected from the Telonicher Marine Lab (TML) was used as an absolute blank and as a density separation procedural blank. 0.5L of DDI was filtered directly onto 20μm glass fiber filters. Filters were dried and weighed, and MP particle numbers were quantified using microscopy. This blank was used to quantify background MP concentration in DDI water. A separate set of 0.5L DDI aliquots was then run through the same density separation procedure as the actual water samples to quantify any possible MP contamination due to the procedure.

Freshwater Reserves aboard R/V Coral Sea

Freshwater from the hold of the R/V Coral Sea was collected in 2 L glass jars topped with aluminum foil and sealed with aluminum lids. These samples were taken back to the laboratory for blank analysis as described above for DDI.

The 0.5L aliquots were filtered directly onto combusted, 20μm glass fiber filters and were dried and weighed, and MP particle numbers were quantified using microscopy. This blank was used to quantify the background plastics that were introduced to the ship's freshwater from its collection pumps and storage facilities.

Hydrocast Sample Blanks

Freshwater from the R/V Coral Sea was poured directly into semi-open Niskin bottles while the rosette was on the stern of the vessel. This mimicked the environmental conditions of sampling as accurately as possible. This sample was then run through the hydrocast sample collection procedure, followed by the density separation procedure. Filters were dried and weighed, and MP particle numbers were then quantified using microscopy. This blank quantified MPs introduced by exposure of the sample to the PVC Niskin bottles and by the handling and manipulation of the sample during collection.

Sediment Blank Procedure

Blank samples were acquired by collecting sand from Trinidad beach due to the similar grain size of the sediment. The blanks were stored in a 2L glass jar topped with aluminum foil and sealed with an aluminum lid. These samples were placed in a muffle furnace and baked at 600°F for 1 hour to vaporize any potential MPs. Samples were then sieved in a 5.25 phi screen for 10 minutes. This sample was then mixed with 0.5 L of DDI water with 30% H_2O_2 and ran through the density separation procedure. This blank was used to quantify the introduced MPs from the sieving and density separation procedures.

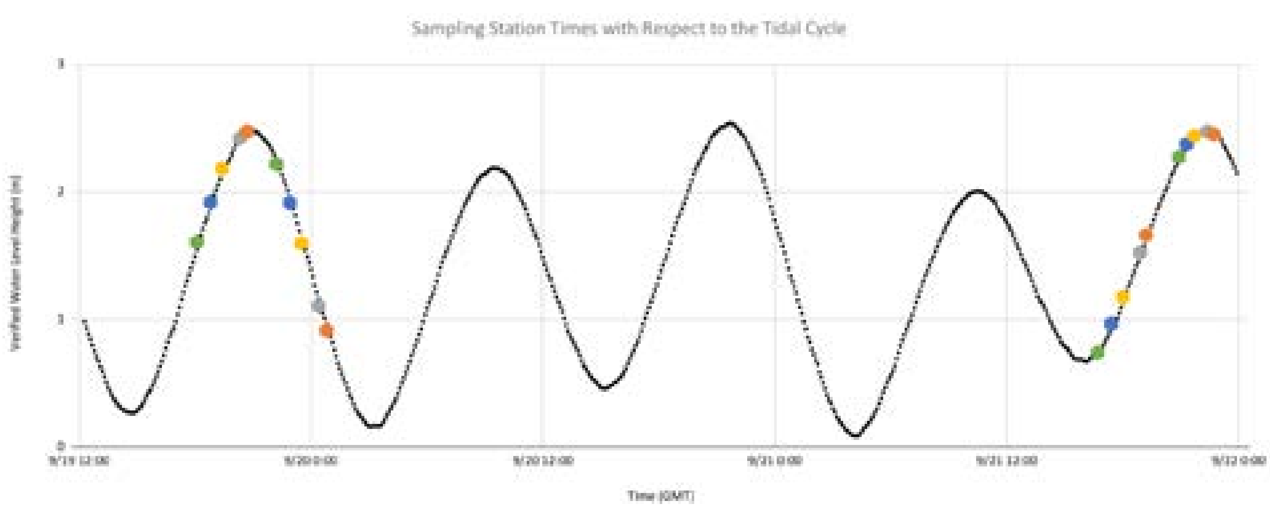
Niskin Bottle Water Sample Collection

Water samples were collected on September 19, 2020, aboard the R/V Coral Sea at 5 locations throughout Humboldt Bay, each of which was sampled twice during a single tidal cycle (figure 3). Water samples were taken using a rosette armed with three Niskin bottles to collect samples at specific depths in the water column. The rosette was deployed in conjunction with a SeaBird Electronics 19 plus SeaCat CTD which measured conductivity and temperature, as well as a transmissometer which measured turbidity. The Niskin bottles were set to fire at 3 different depths: 1 m from the surface, 1 m from the bottom, and mid-depth relative to each station. Samples were taken directly from the stopcock stream exiting the Niskin with no additional plastic tubing that is commonly used to direct the stream. The samples were stored in 2L glass jars topped with aluminum foil and sealed with aluminum screw down lids. For transporting to the laboratory for processing, the samples were placed in storage bins. A 30% hydrogen peroxide (H_2O_2) solution was added to remove any biological organisms that could interfere with later analysis.

Sediment Sample Collection

Prior to the cruise for sediment collection, all equipment

Figure 3.
Verified tidal cycle (m) at North Spit, Eureka, CA for September 19-21, 2020. The water sampling cruise aboard the R/V Coral Sea occurred on September 19th. The sediment sampling cruise aboard Cal Poly Humboldt's pontoon boat occurred on September 21st. Each color of data point represents each station: green=EC1, blue=NB4, yellow=NB3, gray=NB2, orange=NB1. Each station was sampled twice during each cruise. The station times were adjusted to plot where they were in the tidal cycle when they were plotted. The black data points represent the verified water levels taken at North Spit, Eureka, CA over the three-day study period.



pieces were cleaned with alconox and rinsed with DDI water. Sediment samples were collected on September 21, 2020, with a shipek grab aboard Cal Poly Humboldt's pontoon boat at 5 collection sites, each of which was sampled twice during a single tidal cycle (figure 3). The samples were stored in 2L mason jars topped with aluminum foil and sealed with aluminum lids. Samples were placed in storage bins for transportation to the laboratory. Sediments were collected once during flood tide and once during a high slack tide to compare the concentration of MPs during different points in the tidal cycle.

Water Sample Laboratory Analysis

To separate the MPs from the water samples, we used a density separation process adapted from Wenfeng Wang, et al. (2018). After adding 100 mL of 30% H_2O_2 to all water samples to remove organisms, the samples were left to settle for 48 hours. The full sample jar, minus the lid, was then weighed prior to pouring the sample into a separatory funnel. The empty sample jar was then weighed, and the mass of the jar subtracted from the total mass to determine the sample volume. The sample volume was then used to calculate the NaCl mass needed to saturate the sample to a density of 1.3 g/m³ (the ratio of salt to water ~360 g/L). The density of the saturated NaCl solution (1.202 g/cm³) allowed less dense MPs, such as polyethylene (0.917–0.965 g/cm³), polypropylene (0.85–0.94 g/cm³), and polystyrene (1.04–1.1 g/cm³) to be suspended in the supernatant after settling. The salt was then added to the funnel with the sample water, shaken vigorously, and then left to settle for 48 hours. The resulting supernatant was then re-mixed with additional saturated NaCl two more times. The final supernatant was then pumped through a 20 μm glass fiber filter. Filters were then dried and weighed, and MP particle numbers were quantified using microscopy. MP concentrations were determined by dividing the volumetric quantity of MP particles by the total aliquot volumes.

Sediment Sample Laboratory Analysis

The baking pans used for processing the sediment samples were cleaned with alconox and rinsed with DDI water. The wet sediment samples were then placed into the clean pans and dried at 105°C for 48 hours. The dry weight of the sediments was then taken prior to Ro-Tapping between -2 and 5.25 phi sieves. The sediments were then dried again for 10 minutes, and a post-Ro-Tap dry weight was taken. For each sample, 500g of sediment was placed into a 1L jar with 180g of NaCl, 500mL of DDI water, and 50 mL of 30% H_2O_2. Each jar was vigorously shaken and allowed to settle for a minimum of 48 hours. The resulting supernatant was then decanted into a separate 1L jar capped with aluminum and set aside for later filtration.

Filtration Process

Each sample was poured from their respective jar into a clean separatory funnel to begin the filtration process. The water and compacted salt were released from the spigot at the base of the separatory funnel until the volume in the funnel reached 200 mL. The excess was discarded. The remaining 200mL was then poured into the filtration setup to be filtered onto 20μm glass fiber filters by vacuum pump. Post filtration, the filters were placed in aluminum boats and allowed to dry in a sealed, unheated oven.

Filter Counts Procedure

To quantify the MPs on each filter, we began by pressing and sealing each filter between plastic graph paper. The filters were labeled with their respective filter numbers. Due to the limited number of people allowed in the lab following Covid-19 social distancing precautions, images of the filters were taken with a microscopy camera, to be counted offsite. Each image consisted of one 5 mm x 5 mm square of the filter. The images were then uploaded to a shared drive, with a total of 62 image files. At least three separate people counted

Figure 4.
Image of the upper left corner of Filter 15 taken with microscopy, showing a yellow fragment of hard plastic that is slightly larger than 1 mm.

particles on each filter, in an attempt to eliminate biases. MPs were identified in the images by first eliminating all particles exhibiting any cell-like organic structure. Identified MPs were then classified by size (<0.5 mm, 0.5-1.0 mm, 1.0-3.0 mm, 3.0-5.0 mm) and color (green, white/clear, red/orange, yellow, gray/black/blue) (example in figure 4). The counts were then averaged by filter and underwent a variety of statistics before producing the following plots in the results section.

Results

As displayed in figure 5, stations NB3, NB2, and NB1 when sampled on the flood all had fewer MP particles/L at the surface than at depth. This might have occurred by the particles being denser than the surrounding water, causing them to sink to the bottom. Overall, the number of MP particles/L is mostly consistent between the water samples taken on the flood and the ebb. It could be argued that this consistency is due to the energetic conditions experienced during both of the samplings. EC1 experienced a noticeable difference in concentration on the flood versus the ebb, which could mean the ocean is a provider of MPs to the bay. NB2, however, experienced higher concentrations on the ebb tide, possibly due to the water becoming quite shallow. NB4 exhibiting zero MP concentration at the surface on the ebb could have occurred by the particles sinking with the release of water from the bay, or they could have been transported elsewhere.

MP concentrations in the sediment were predicted to be at a maximum during the lowest current speed, during slack tide, as the relatively lower kinetic energy without the tides would potentially allow the microplastics to settle in the sediment. Our results show that the highest microplastic concentrations occur at stations NB4 during flood and NB3 during slack (figure 7). Overall, the sediment samples do not represent the expected changes in concentration with the variation in the tide. Aside from NB3, all stations saw higher concentrations of MPs during the second leg of the pontoon boat cruise. Unexpectedly, plastics had mostly higher concentrations during flood tide rather than settling during slack tides. This could be due to the tide bringing in MPs from the ocean and depositing them into the bay, or it could be due to the heterogeneous nature of MP distribution. The inconsistent values seen at each site are possibly due to natural variations in the concentration of MPs, the shipek grab deployment locations not being precise on site, and the tidal range being smaller than ideal for sampling.

Figure 5.
Water Column Microplastic Concentrations by Depth. The concentration of microplastics in the surface of the water column were noticeably the greatest at EC1 and NB2. These stations corresponded to the tidal change from flood to ebb and from ebb to flood, respectively. This data was collected by the Niskin bottle sampling of different depths in the water column procedures aboard the R/V Coral Sea on September 19, 2020. Total surface average concentration: 12.8 particles/L ± 9.70. Total mid depth average concentration: 12.6 particles/L ± 9.77. Total deep average concentration: 16.3 particles/L ± 8.88.

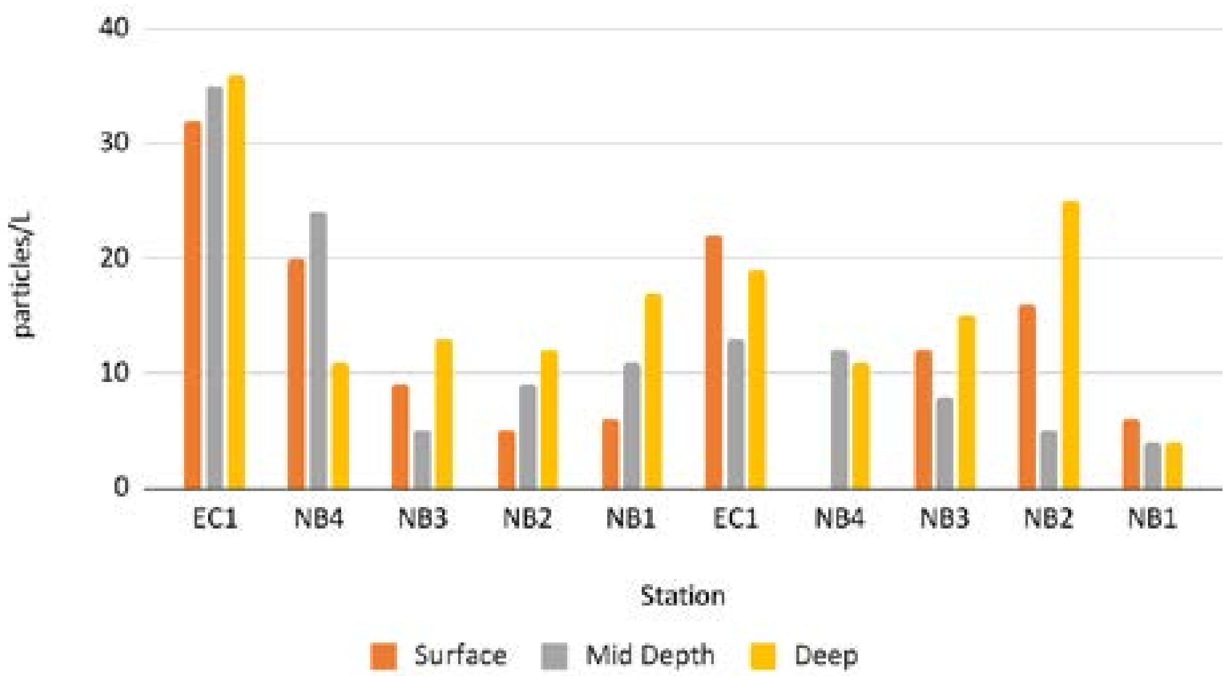


Figure 6.
Total MP concentration present in the water column per station on the flood versus the ebb of the tide. This data represents the sum of the MP concentrations represented in figure 5 from samples collected on September 19, 2020. Overall average concentration of 41.7 particles/L ± 25.36. The average of flood concentrations was 49.0 particles/L ± 32.37. The average of ebb concentrations was 34.4 particles/L ± 16.32.

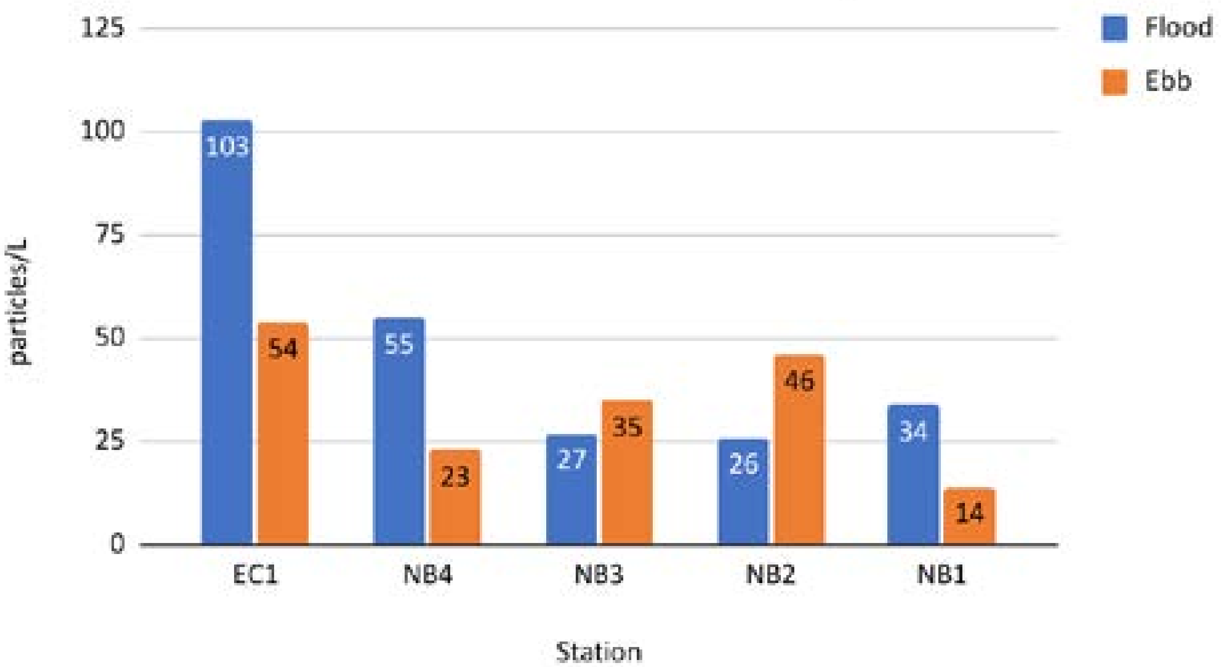


Figure 7.
Sediment MP concentrations in particles/kg, from the pontoon boat cruise in Humboldt Bay on September 21, 2020. The blue bars represent sampling taken during flood tide, and the orange bars represent sampling during slack tide. MP concentrations were found to be highest in the NB4 flood sample and the NB3 slack sample. The lowest concentration was seen at EC1 during the flood tide. A standard deviation of σ = ± 41.44 particles/kg was calculated based on this data and an average of 64.6 particles/kg. Average on the flood was found to be 61.4 particles/kg ± 49.38. On the slack, the average concentration for all stations was 67.8 particles/kg ± 37.40.

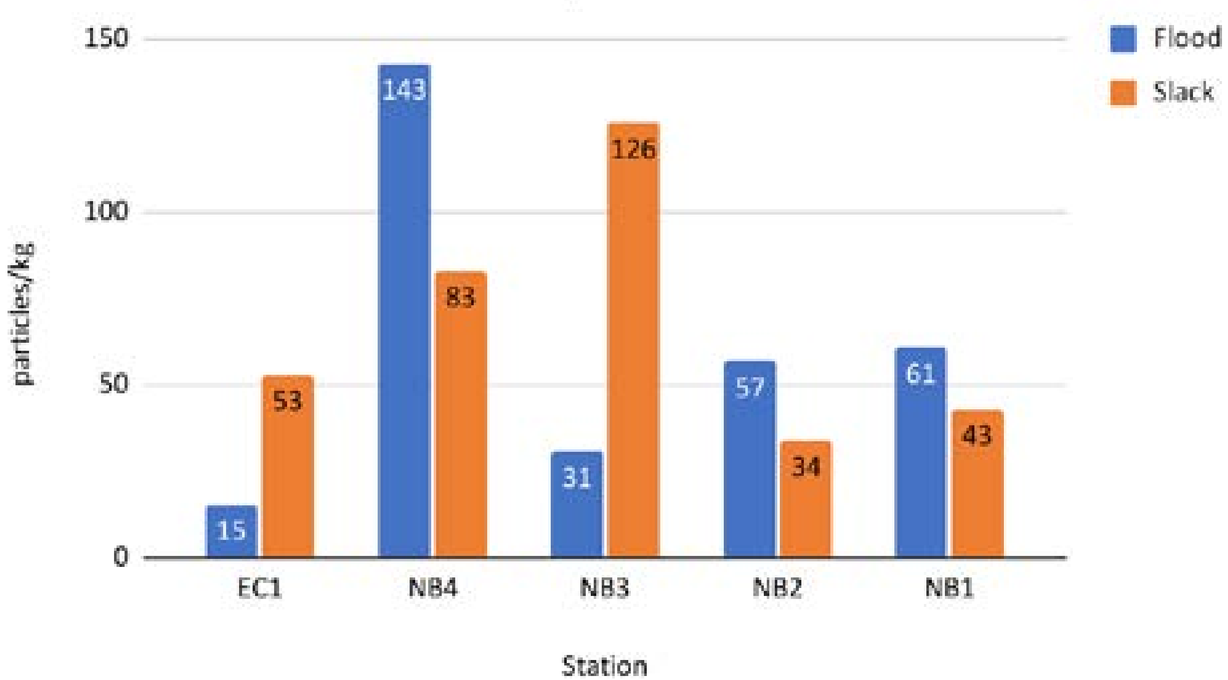


Figure 8.
Study station map of Humboldt Bay with transposed approximate 5-minute cotidal lines (seen in red) based on the time of the high tide in the NOAA tidal prediction model at various stations around Humboldt Bay ("Tide Predictions - NOAA Tides and Currents").

We hypothesized that sediment MP concentrations in the extremities of the bay would have a larger MP concentration. EC1 saw the lowest MP concentration of any station, which lines up with our hypothesis. NB2, however, was the farthest station from the mouth of the bay, yet it saw the second lowest total concentration of the 5 stations, possibly due to the site being in the center of NB and farther from terrigenous sources. MP concentrations were found to be highest overall at NB4, which is located at a point of convergence of the three main channels in the bay.

The concentrations of MPs found in sediments were lower than the maximum of 400 particles/kg mentioned by Wagner et al. (2014), with our two highest concentrations at 143 particles/kg (NB4 flood), and 126 particles/kg (NB3 slack). The overall average sediment MP concentration was 64.6 particles/kg with a standard deviation of σ = ± 41.44 particles/kg, making Humboldt Bay sediment relatively plastic-free; however, the evidence of MPs might allude to higher concentrations existing in places that were not sampled during this study.

The kinetic energy associated with the tidal cycle was expected to affect MP concentrations in the sediments and in the water column. To quantify the kinetic energy, we calculated the velocity covariance, which is directly proportional to the kinetic energy. To determine the velocity covariance (v^2), current velocity (cm/s) data was obtained from the NOAA Physical Oceanographic Real-Time System (PORTS) station at Chevron Pier in Humboldt Bay for the respective sampling times at each station ("CO-OPS Current Station Data"). To account for the noticeable delay in the dispersion of Humboldt Bay's tide, cotidal lines of approximately every five minutes were determined from the NOAA Tide Predictions historic data from the eight stations north of the Entrance Channel in Humboldt Bay (figure 8).

The respective velocities were then squared to find the velocity covariance and plotted against the MP concentrations of both the water column and the sediment samples, as seen in figures 9 and 10. The expectation was that when the covariance was high, the microplastics on the seafloor would be resuspended in the water column. Thus, when the covariance was higher at a given station, the microplastic concentration in the sediments would be lower and the microplastic concentration in the water column would be higher. The covariance values on the water sampling cruise were nearly an order of magnitude greater than the covariance values from the sediment sampling cruise. This difference was expected due to the difference in the tidal range between the two sampling days. The water sampling cruise occurred during an ideal tidal range to test our hypothesis, with a higher high and a lower low tide leading to greater tidal velocities. The sediment sampling cruise occurred on a day with less ideal conditions: a smaller tidal range and smaller tidal velocities.

The velocity covariance and the MP concentration in the water column for each station follows the expected pattern of higher covariance, higher MP concentration at all stations, except NB1 (figure 9). Site NB1 was located near both the Eureka Public Marina and the Woodley Island Marina, exposing it to high amounts of boat traffic. The increased human activity at this station could have affected both the concentration of MPs in the area and the mixing of the water column between sample collections.

Figure 9.
Velocity Covariance vs Concentration of MPs in the Water Column. Each color of data point represents each station: green=EC1, blue=NB4, yellow=NB3, gray=NB2, orange=NB1. Each station was sampled twice during the tidal cycle, as seen in figure 3. Velocity data obtained from the NOAA PORTS data for Chevron Pier in Humboldt Bay ("CO-OPS Current Station Data").

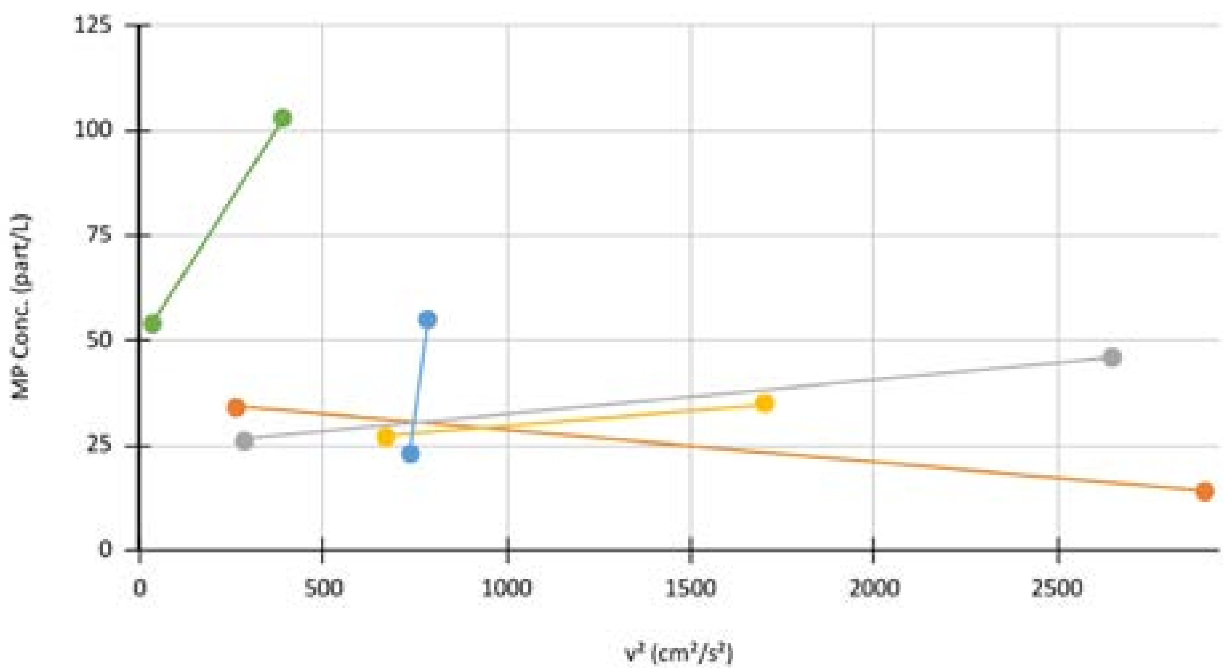
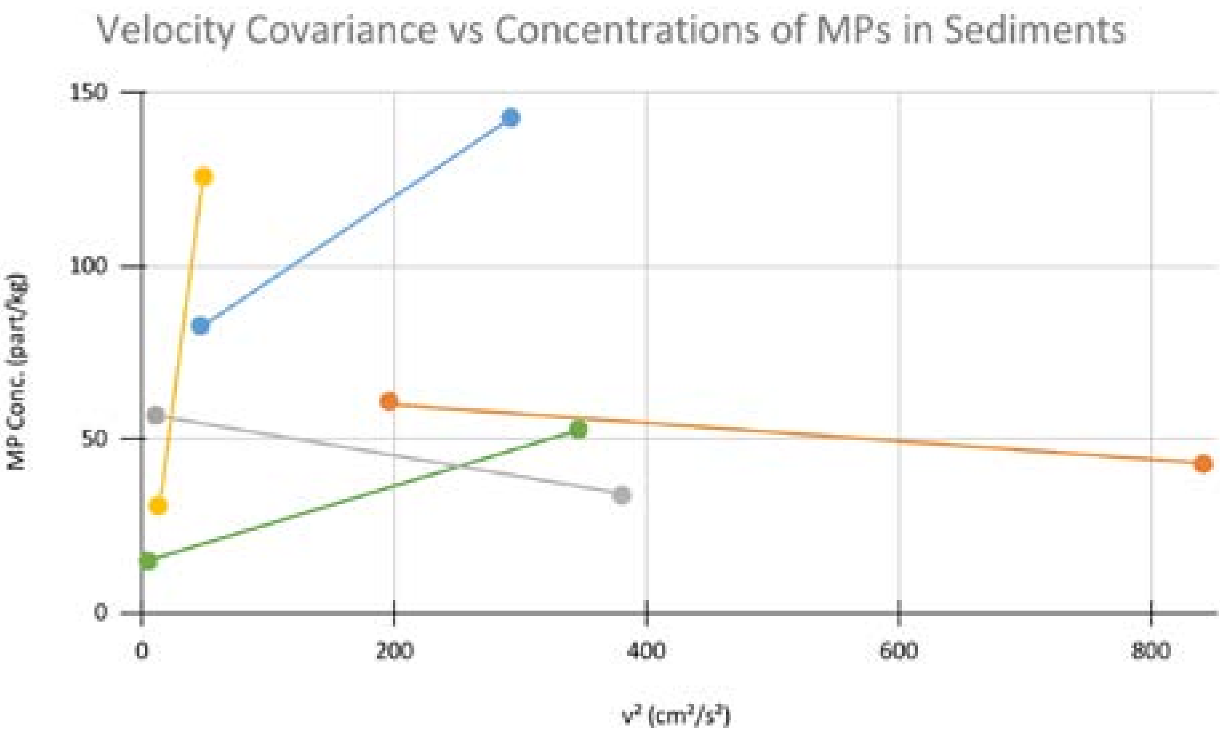


Figure 10.
Velocity Covariance vs Concentration of MPs in Sediment. Each color of data point represents a station: green=EC1, blue=NB4, yellow=NB3, gray=NB2, orange=NB1. Each station was sampled twice during the tidal cycle, as seen in figure 3. Velocity data obtained from the NOAA PORTS data for Chevron Pier in Humboldt Bay ("CO-OPS Current Station Data").



Discussion

Similar to the results found by Carlson et al. (2018), the sites with higher boat traffic had higher MP concentrations in the water column and sediments. However, EC1 concentrations contradict this pattern in the sediment data, likely because of the higher kinetic energy in the channel mouth that would not allow the MPs to settle fully into the sediment. It is also possible that MPs were present deeper down in the sediment at EC1, as well as at other sample sites, therefore they were not collected during the deployment of the shipek grab.

Future experiments would benefit by sampling on a singular cruise to fully utilize a greater tidal range, as bodies of water similar to Humboldt Bay can experience a broad range of conditions within a small time period. Unfortunately, due to Covid-19 boat time restrictions, obtaining more cyclical data was not possible with this study. In the future, to obtain a complete data set, samples should be collected on multiple days with various tidal ranges and conditions.

A possible cause for the three stations closest to the Entrance Channel experiencing a higher MP concentration on the floodtide is the MPs being supplied by the Pacific Ocean. The Pacific Ocean currently has two Great Pacific garbage patches, one of which is between California and Hawaii. This patch could act as the source of ambient plastics that can be transported along the western coast of N. America and throughout the Pacific Ocean. Local sources that deposit directly into the ocean, including Mad River and Eel River, could also contribute to the incoming MPs. Future studies could use a spectrometer for the identification of the MPs that could help pinpoint the source of pollution. In addition, this method would help minimize human error in identifying plastics and allow for more repetition within the study. These data could be used to help identify and reduce plastic pollution in Humboldt Bay and nearby bodies of water. As this was a preliminary study that could not yield as much data as desired, more sampling is necessary to comprehend how and where MPs move in Humboldt Bay.

The prevalence, distribution, and environmental impacts of MPs are not entirely understood, which is why baseline studies, like this one, are so important. The results from this study will hopefully improve the scientific community's understanding of the dynamics of MP distribution, helping to pave the way for further research into the cumulative and projected impacts of MP pollution in estuaries and elsewhere.

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Tidal, Geological, and Biological Impacts to Humboldt Bay's pH

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This research examines factors that control pH in Humboldt Bay – a shallow, tidally-driven estuary in northern California (USA) that supports shellfisheries which are economically important to the state. Time-series data from hydrographic sensors at two Central and Northern California Ocean Observing System (CenCOOS) stations, as well as sediment incubations, were used to understand the role of tides, biological productivity, and carbonate dissolution in controlling pH on various timescales. Differences in pH, dissolved oxygen, chlorophyll, and temperature between an in-bay sensor and a coastal sensor indicate that the tidal flux exerts a long-term, seasonal control on pH, but biological productivity substantially modifies carbon and oxygen, thereby controlling pH on daily and weekly timescales. Sediment samples were also collected from the bay in 2021 to study carbonate dissolution. Sediments were incubated for three days in both stirred and unstirred conditions (to mimic tidal mixing and no tidal mixing respectively) and DO, pH and alkalinity were monitored. For all stirred incubations, large increases in pH and alkalinity suggested considerable carbonate sediment dissolution. When scaled to the bay's in-situ suspended sediment concentrations, carbonate dissolution may exert a supplementary control on pH at similar time scales as biological productivity, but the magnitude of its effect is less.

Introduction

Ocean acidification occurs in response to increased anthropogenic emissions of carbon dioxide (CO2). Rising CO2 in the atmosphere increases dissolved CO2 in the ocean. This forms carbonic acid (Eqn 1) which then dissociates to bicarbonate and H+, lowering the pH (Eqn 2) (Feely et al., 2009). Data compiled since the 1980s at two Atlantic marine stations confirm that ocean pH has dropped by 0.02 every decade in response to increased atmospheric CO2 (Doney et al., 2009; Feely et al., 2009; Gattuso & Hansson, 2011).

Eqn. 1) CO_2 (atm) + H_2O ⍰ H_2CO_3 (aq)
Eqn. 2) H_2CO_3 ⍰ H+ + HCO_3- ⍰ 2H+ + $CO^{2}{}_{3}^{-}$

More dissolved CO2 shifts the equilibrium toward bicarbonate from both directions in Eqn 2. So a related consequence of high-CO2 in the ocean is the resulting reduction in carbonate ion (CO32-). Many marine organisms rely on CO32- for building calcium carbonate shells, and will struggle to build shells in a high-CO2 environment. In upwelling regions, conditions are particularly challenging since calcifying organisms must contend with higher atmospheric CO2 from "above" and the already high-CO2 water which naturally upwells from "below". During upwelling, many calcifying heterotrophs are already facing undersaturated conditions with respect to aragonite, a common form of calcium carbonate found in a number of important zooplankton and juvenile shellfish like oysters, red sea urchins and crab (Fabry et al., 2008; Feely et al., 2009; Rassmann et al., 2018). Even calcifying primary producers, which can initially benefit from additional CO2 that promotes increased photosynthesis and thus more energy to form shells, will struggle to build shells once dissolved CO2 reaches high enough levels (Ries, 2011). Thus, increasing CO2 in the ocean raises important concerns for the commercial cultivation of shellfish, including oysters and clams (Lim et al., 2021).

Many estuarine ecosystems support ecologically and commercially important shellfish, and already face adverse impacts from ocean acidification (Fabry et al., 2008). Understanding the factors that control pH in estuarine environments is key to mitigate future impacts. But these factors are complicated and vary considerably from one region to another. For example, Feely et al. (2008) observed low aragonite saturation state in surface waters along the entire U.S. west coast, with the lowest values just off the coast of northern California, which they attributed to a combined effect of upwelling and anthropogenic CO2. Further north in Puget Sound, WA, Feely et al. (2010) found that low pH was controlled by several factors including: the tidal input of acidified coastal waters, restricted circulation within the sound, and local respiration of organic matter. They estimated the tidal input of coastal waters was responsible for 24 - 49% of the acidified waters in the sound. Another factor found to control pH in bays and inlets along the west coast is eelgrass, which was found to significantly mitigate ocean acidification (Ricart et al., 2021; Werblow & Cobo y Gonzales, 2020). Ricart et al. (2021) found most eelgrass meadows contribute to at least a +0.1 increase in pH (equivalent to a 30% reduction in H+), but the increase was stronger in higher latitude meadows than in lower latitudes. Additionally, carbonate sediments have been found to control pH in estuarine environments. In both field (Su et al., 2020) and modeling studies (Shen et al., 2019) calcium carbonate dissolution from suspended sediments was found to mitigate the acidifying impacts of aerobic respiration and anthropogenic CO2 dissolution in Chesapeake Bay.

Ultimately the control of pH within a given estuary will depend on its physical, biological and geological characteristics. In this study, we examine pH and other related factors in Humboldt Bay, CA (HB). As a semi-enclosed, shallow bay, whose circulation is strongly controlled by the tides (Barnhart et al., 1992), HB provides an opportunity to assess tidal inputs as the primary control on pH. In addition, the bay is home to a thriving eelgrass community which contributes substantially to primary productivity, and provides habitat and detritus for a broad host of heterotrophic zooplankton and commercially important shellfish like oysters and crab (Schlosser & Eicher, 2012). Finally, the bay has a small load of carbonate sediments which can be resuspended by tidal mixing and alter pH through the carbonate equilibrium in seawater.

Since the tides, sediments, and biology have been shown to have competing and complementary impacts on the pH of other estuaries, our goal in this study was to determine which of these processes are most critical in controlling the pH in HB. In particular we address the following hypotheses:

1) Humboldt Bay's pH is driven by the tidal influx from coastal waters. This influx is the forcing for the pH in the bay that is brought in with each tidal cycle and is modified only as the nearshore waters change.
2) Humboldt Bay's pH is driven by carbonate sediment dissolution. Resuspension of carbonate sediments will promote dissolution of carbonate, which will raise pH as the released carbonate reacts with H^+.
3) Humboldt Bay's pH is driven by biological productivity and respiration. The prevalence of eelgrass beds and phytoplankton will raise the pH above the tidal forcing during periods of photosynthesis; while heterotrophic respiration or shell-building by marine calcifiers will lower the pH below the tidal forcing.

Site Description

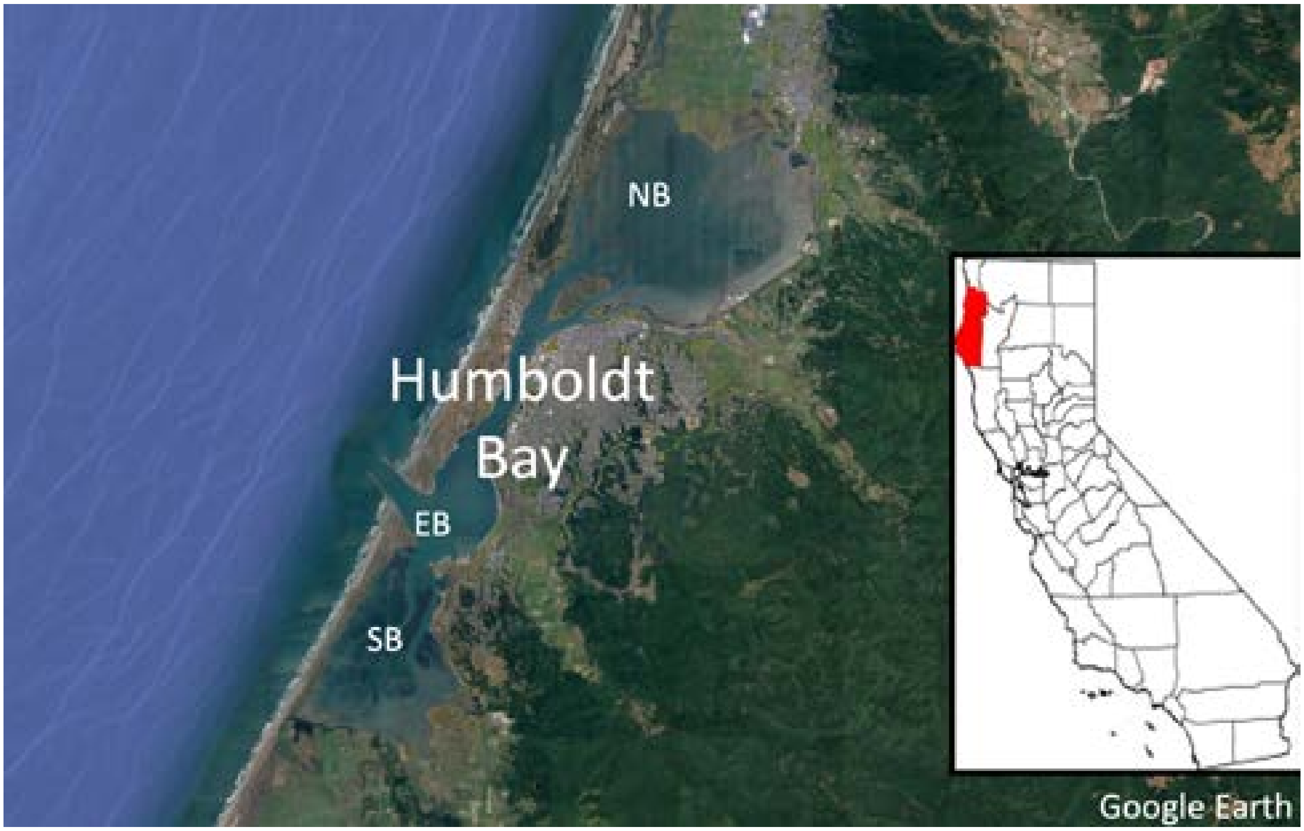
HB is located on northern California's coast in Humboldt County, CA (USA) (Figure 1). It is a semi-enclosed basin, connected to the Pacific Ocean by a narrow entrance channel. HB is 22.5 km long, up to 6.9 km wide, and spans 28.0 - 62.4 km^2 from mean low to mean high tide (Schlosser & Eicher, 2012). Mean volume is increasing slowly with time due to an estimated sea level rise of 47.2 cm/century (Sullivan et al., 2022). HB comprises three distinct basins: the northernmost known as North Bay (NB); the central channel known as Entrance Bay (EB); and the southernmost known as South Bay (SB) (Figure 1).

The climate in HB has two seasonal periods (Schlosser & Eicher, 2012). From October to April, the climate is mild and wet with frequent storms (Barnhart et al., 1992) and winds primarily out of the southwest (Claasen, 2003). From May to September, the climate is relatively cool and dry (Barnhart et al., 1992). Northerly winds cause intense upwelling starting in May and peaking in the summer, substantially altering the seawater that enters HB during flood tide.

HB circulation is strongly controlled by tides. HB has a large tidal prism, 44% in North Bay (NB), and 66% in South Bay (SB) (Schlosser & Eicher, 2012). Tidal currents are strongest in the channels, and decrease with distance from the entrance, while tidal amplitude increases with distance from the entrance (Schlosser & Eicher, 2012).

Tidal currents strongly influence the distribution of sediments in HB. Channels are dominated by sand; mudflats by silt & clay; marshes by peat (Schlosser & Eicher, 2012). Most of the sediments in HB come from the local drainage basin, which includes portions of the Klamath Mountains and the Coast Ranges (Barrett, 2004). Littoral sediments from coastal rivers to the north (Mad) and south (Eel) also enter HB during flood tide (Schlosser & Eicher, 2012). Although the mineralogy of the sediments is not well known, local field studies have found carbonate minerals present in NB and SB at weight percents from 0.5-1.0% (Bolster et al., 2015).

Figure 1.
A satellite image of Humboldt Bay (HB) in Humboldt County, CA (Google Earth, version 7.3.3.7786). The bay is nominally located at 40°46'N, 124°12'W and is composed of three distinct basins: North Bay (NB) sometimes referred to as Arcata Bay, Entrance Bay (EB), and South Bay (SB). Inset shows the location of Humboldt County in California.



A dominant biological feature of HB is eelgrass (*Zostera marina*), a marine plant mainly located in NB and SB, where water is retained in mudflats during low tide (Monroe et al., 1973). Satellite imagery indicates 22.85 km^2 of eelgrass across the entire bay, which is more than 30% of the coastal wetland habitat in HB (Schlosser & Eicher, 2012). Eelgrass affects the ecosystem extensively, including the sediment regime and infaunal distribution, (Barnhart et al., 1992; Moore et al., 2004)eelgrass (Zostera marina. It also alters dissolved oxygen (DO) and dissolved $CO_{2,}$ via photosynthesis, and turbidity and total dissolved solids via the production of organic matter and detritus (Gilkerson & Merkel, 2017).

Other major biological features in HB include phytoplankton and oysters. Phytoplankton are primarily advected with the tidal input and can then bloom within the bay. Like eelgrass, they are essential primary producers. Oysters are primarily cultured within the bay, with mariculture expanding from small areas in the 1950s (Monroe et al., 1973) to many acres of NB mudflats today. Oysters act as a source of dissolved CO_2 via their respiration and production of carbonate shells. They also provide a physical setting that acts as a sink, burying organic carbon, but also inorganic carbon, which in mudflats leads to a net venting of CO_2 (Fodrie et al., 2017).

Methods

To address our hypotheses, we utilized a combined data analysis and experimental approach. For hypotheses 1 and 3, we analyzed water quality data from two Central and Northern California Ocean Observing System (CenCOOS) stations: Chevron Dock in HB and Trinidad Pier about 15 miles north (Figure 2). We chose Chevron dock because it's centrally located in the bay, and Trinidad Pier because it monitors coastal waters similar to the waters entering HB on each flood tide.

CenCOOS sensors measure pH, temperature, depth, DO, turbidity, and chlorophyll-a (chl-a) at 15-minute intervals, with brief gaps of a few days for sensor calibration and maintenance. Data is quality controlled by CenCOOS technicians and faculty at Cal Poly Humboldt. We analyzed data from 2018 because it was the most recent year that had been fully quality controlled at the time of the study.

Data for each location was analyzed by comparing daily means and anomalies of pH to the other water quality parameters. Daily averages were first determined for all parameters. Monthly means were calculated from these daily averages, and anomalies were calculated by subtracting the monthly mean from each data point.

To address Hypothesis 2, bottom sediments were collected on 25 April 2021 at seven stations inside HB (Figure 3). A box corer or a Shipek grab was used to collect sediment, depending on the expected sediment type. Samples were collected at high slack tide, when the least amount of suspended sediment was expected, and the depth would allow the ship to access the sampling area.

Sediments were refrigerated in sealed Whirl-Pak bags for up to 2 weeks. They were then incubated at room temperature in Biological Oxygen Demand (BOD) bottles. For each incubation, 0.5 g of sediment was placed into 300 g of artificial seawater. Artificial seawater was prepared by adding sodium chloride to distilled deionized water to approximate HB's salinity of 33 ‰, and adding sodium bicarbonate and sodium carbonate to approximate 2000 μmol/kg of alkalinity. Samples were then incubated for three days under constant mixing using a magnetic stir plate (to mimic tidal mixing) or without stirring (to mimic no tidal mixing).

Incubations were periodically sampled for DO using a Hach optical DO probe, and for pH using a Hach glass electrode. Alkalinity was determined on replicate bottles by filtering 40 mL of incubation sample and analyzing using the Gran titration on a Metrohm 848 Titrino. A known mass of the sample was titrated with a standardized solution of dilute hydrochloric acid. pH was monitored after each addition of acid until a pH of 3.00 was reached. The measured pH versus volume was then graphically analyzed to identify the equivalence point and calculate the alkalinity. Only sediments from NB6, NB5, NB2, where eelgrass and oyster mariculture are most concentrated (Figure 4), and EB2, where tidal currents are greatest, were incubated (Figure 3).

Results

CeNCOOS Data Analysis

Daily average pH and temperature were strongly correlated at both Trinidad and HB. At Trinidad between April and November 2018, sharp decreases in temperature of 2-3°C were accompanied by sharp decreases in pH of 0.3-0.6 (Figure 5). Temperature and pH minima were followed by sharp increases on the same order of magnitude. Similar trends are observed in HB but of lesser magnitude. Temperature decreases in HB are 1-2°C between April and November, and the accompanying pH decreases are only 0.1-0.3. Temperature and pH were not as strongly correlated in July and August in HB.

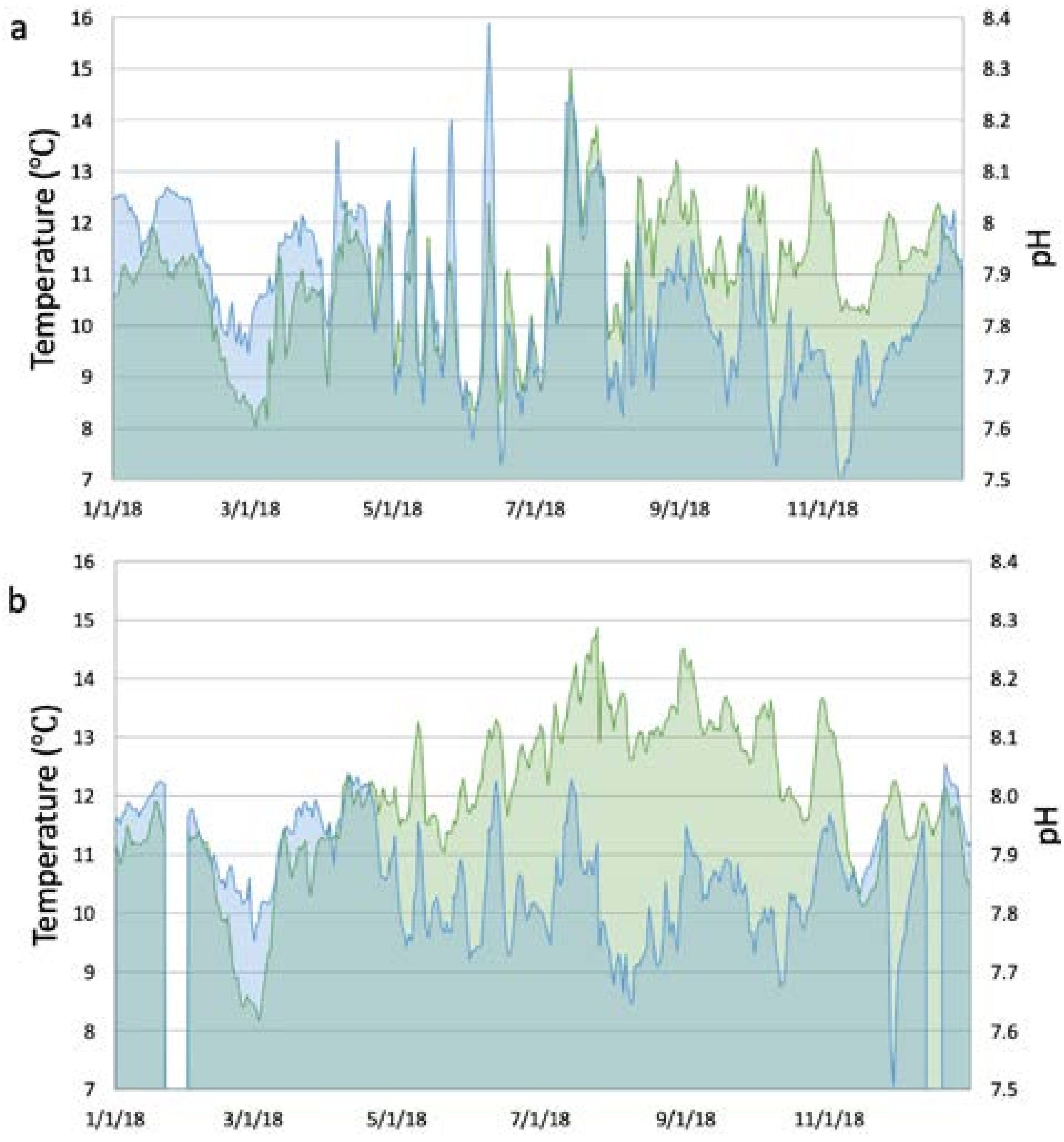
The rapid decreases in temperature at Trinidad are indicators of coastal upwelling that brings cooler, higher-CO_2, lower-pH, and more nutrient-rich water to the surface within a few days (Gilkerson & Merkel, 2017). The rapid increase in temperature and pH that ensues after these events

Figure 2.
Chevron dock sensor in Humboldt Bay at 40.7775N, 124.1965W (left). Trinidad pier sensor along the northern California coast at 41.0550N, 124.1470W (right). Images are from Google Earth (version 7.3.3.7786). Trinidad is situated along the coast about 15 miles north of the Entrance Channel of Humboldt Bay

Figure 3.
Sediment sampling locations for R/V Coral Sea cruise on 25 April 2021. This image was generated using Google Earth (version 7.3.3.7786). Note the proximity of Station EB1 to Chevron Dock (Figure 2).

Figure 4.
Historical water quality stations indicating eelgrass rich patches and oyster mariculture locations (Google Earth, v. 7.3.3.7786). Eelgrass is indicated by the darker of the mudflats between channels. Oyster beds are generally found on the periphery of these patches adjacent to channels. Stations with an 'e' are centrally located in eelgrass beds. Stations with an 'o' are near oyster beds.

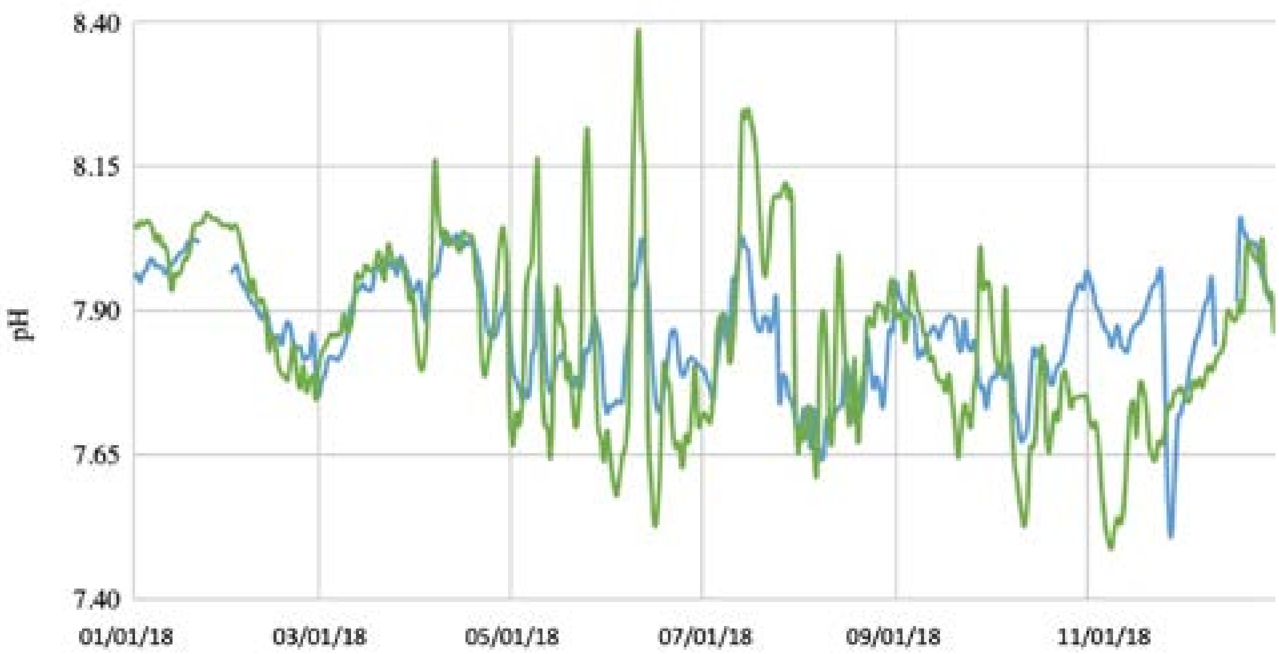
Figure 5.
pH (blue) and temperature (green) for 2018 at Chevron Dock in Humboldt Bay (a) and Trinidad pier (b). Individual points represent the mean of all 15-minute interval measurements collected during a day. Periods in late January (for both pH and temp) and in mid-December (for pH) reflect times when the sensor was not collecting data due to calibration and maintenance.



indicates relaxation periods: as the vertical circulation slows, the atmosphere warms the surface water, and phytoplankton accumulate, drawing down CO_2 and raising the pH.

Within HB the upwelling/relaxation cycle is also evident but the impact on pH is muted. Comparing pH at Trinidad and HB (Figure 6), we see that Trinidad pH minima are more frequent and of longer duration. Using a threshold pH of 7.8 – established by Feely et al. (2009) as a threshold for the saturation state of aragonite – Trinidad drops below the threshold 20 times during the year, for an average of 7 days per drop. In contrast, HB drops below the threshold only 15 times, for an average of 6 days per drop. This suggests that processes within HB may buffer the acidified coastal waters that enter with the tides. HB also exhibits less extreme

Figure 6.
pH in Humboldt Bay (blue) and at Trinidad (green) for 2018. Data were obtained from CenCOOS sensors which are continuously deployed at each site to collect pH and depth data every 15 minutes. Periods in late January and in mid-December reflect times when the sensor was not collecting data due to calibration and maintenance.



maxima than Trinidad. Trinidad exceeds the 7.8 threshold 19 times during the year, for an average of 8 days; while HB exceeds the threshold only 16 times, but stays above the threshold for an average of 13 days. Overall HB experiences more total days above the threshold during the year, but the maximum pH during these periods is lower than at Trinidad. This suggests that the relaxation period between upwelling events elicits a longer but less intense biological response within HB.

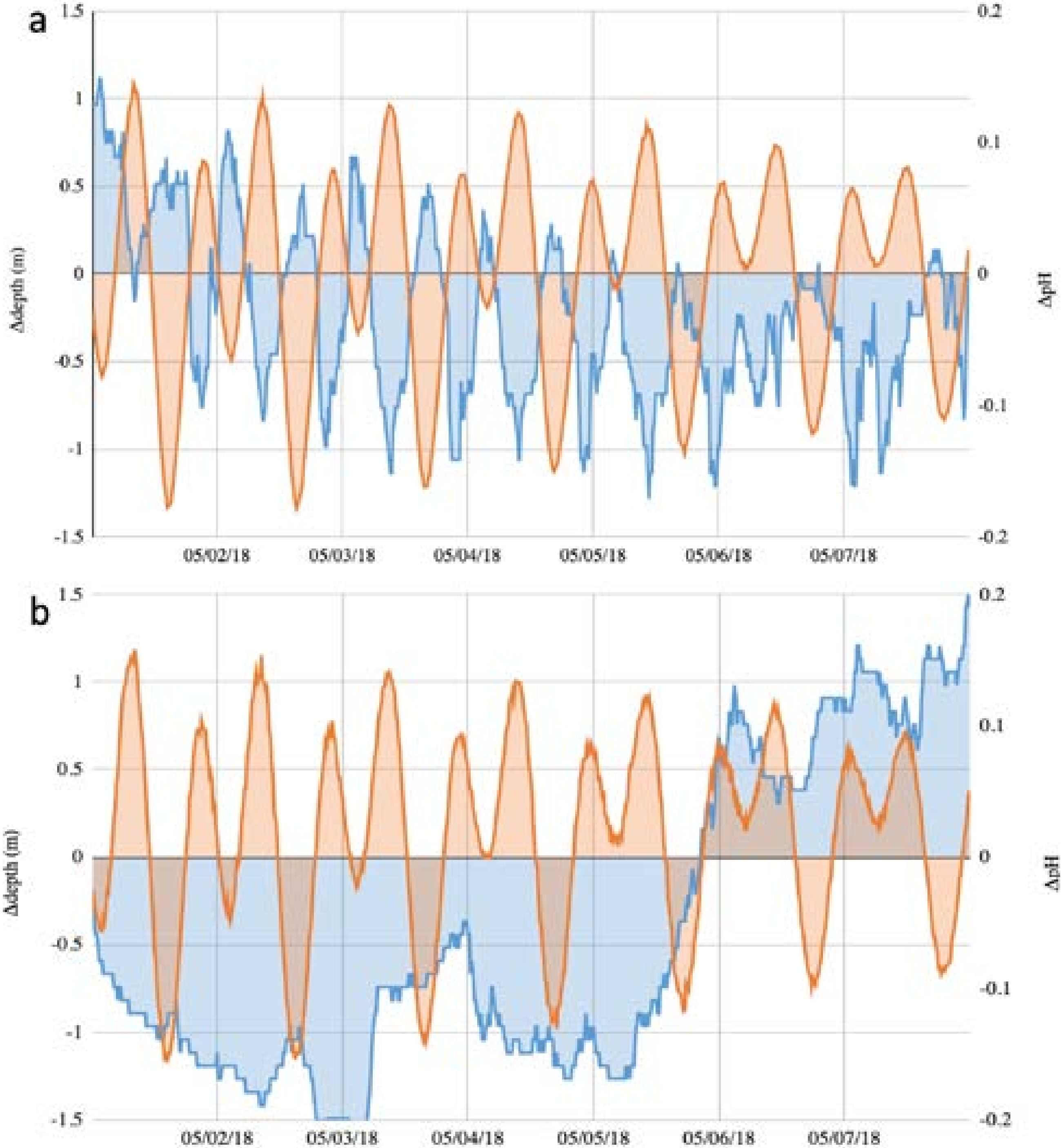
There is a clear correlation between the pH and depth anomalies within HB (Figure 7a). Generally, when the depth increases, indicating a flood tide, the pH decreases. When the depth decreases, indicating an ebb tide, the pH increases. Although this trend is true for most of the 2018 dataset, there are periods where the pH and depth increase and decrease synchronously (Figure 8). These periods show an inverse correlation between HB's pH and the tides. This pattern is determined by the relative pH of the coastal waters (indicated by Trinidad) and that of HB. When the pH in HB is greater than Trinidad, there is a decrease in pH with the incoming tide; when the pH in HB is less than Trinidad, there is an increase with the incoming tide (Figure 6).

The pattern at Trinidad demonstrates a pH which is not controlled by the tidal cycle (Figure 7b). The depth, an indicator of the tide, changes frequently without noticeable changes to the pH. The pH variation at Trinidad appears to be predominantly controlled by upwelling events, as indicated by the strong correlation with temperature (Figure 5b).

pH and DO demonstrate strong correlation in both HB and Trinidad (Figure 9). Examining one week in May where upwelling was prevalent at the start of the week, the pH anomalies in HB increase in accordance with the DO anomalies: reaching +0.1 when DO % saturation reaches +10%; and dropping to -0.1 when DO % saturation reaches -20%. At Trinidad, pH anomalies reach +0.2 when DO % saturation reaches +20%; -0.2 when DO % saturation reaches -20%. These correlations suggest a biological alteration of pH and DO. Positive anomalies imply increased primary productivity, which raises DO and reduces CO_2, raising pH. Negative anomalies imply increased respiration, which reduces DO and increases CO_2, lowering pH.

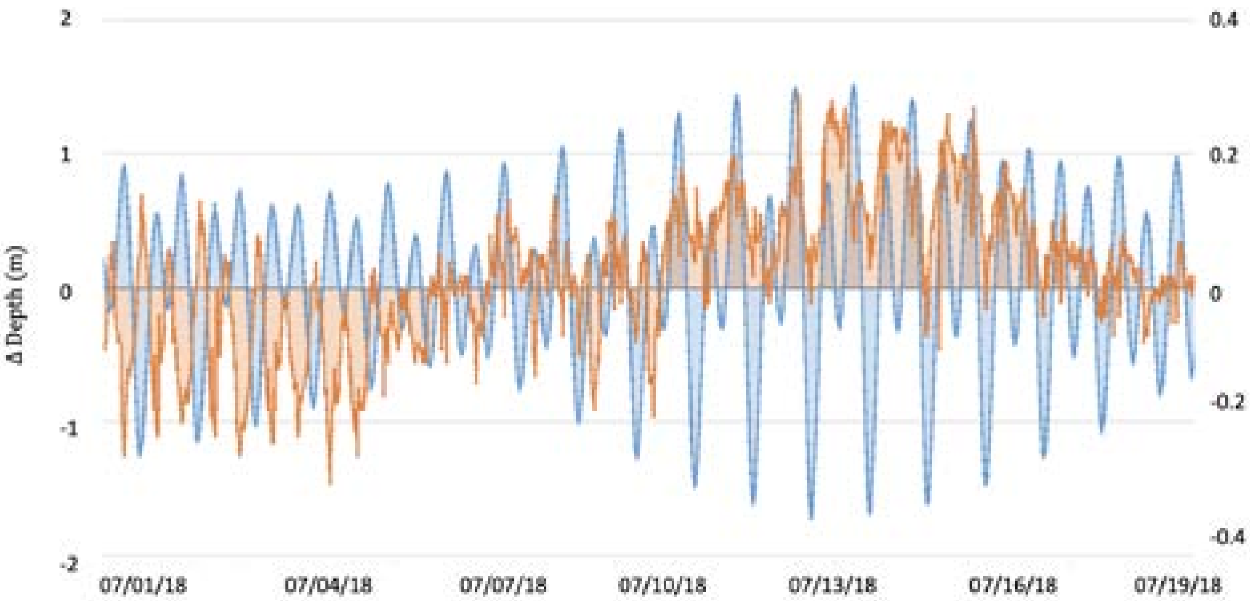
At Trinidad the negative DO and pH anomalies that lead off this week in May are indicators of upwelling. In contrast, during the same part of the week in HB, positive anomalies in pH and DO are observed. This implies that DO and pH are being elevated relative to the coastal water that enters HB during upwelling. Increased primary productivity is again the likely culprit: raising DO and pH as phytoplankton access the high-nutrient water that enters the bay. As upwelling continues in the first few days of May, DO and pH oscillate with each tidal cycle but edge toward the coastal water values observed at Trinidad. Then, as upwelling subsides in the last

Figure 7.
pH anomaly (blue) and depth anomaly (orange) (an indicator of tidal amplitude) from the first week of May 2018 at Chevron Dock in Humboldt Bay (a) and Trinidad Pier (b). Data were obtained from CenCOOS sensors which are continuously deployed at each site to collect pH and depth data every 15 minutes. Anomalies were calculated by subtracting the monthly mean from each value.



few days of the week, there is a large positive anomaly in both pH and DO at Trinidad, which is about twice as large as what was observed in HB earlier in the week. Conversely in HB at this time a negative anomaly in DO and pH is observed. This suggests that Trinidad's biological response to upwelled waters is stronger than the response in HB. It could also indicate that during periods of relaxation, primary production in HB shifts rapidly toward net respiration. This results in a lower pH and DO in HB when productivity in the coastal waters kicks into high gear. Over subsequent tidal cycles this coastal water signature will get progressively mixed into HB, but the magnitude of the signal is ultimately

Figure 8.
pH anomaly (blue) and depth anomaly (orange) (an indicator of tidal amplitude) from the first part of July 2018 at Chevron Dock in Humboldt Bay. Data were obtained from CenCOOS sensors which are continuously deployed at each site to collect pH and depth data every 15 minutes. Anomalies were calculated by subtracting the monthly mean from each value. Note that the first week was during an upwelling event, followed by a relaxation period.



controlled by the balance between primary productivity and respiration in HB.

The relationship between pH and chl-a at HB and Trinidad provide further support for the biological control of pH (Figure 10). Chl-a anomalies above 5 mg/m^3 generally indicate a phytoplankton bloom. At Trinidad two blooms are evident starting May 6th and 25th, with an additional bloom possibly on the 16th. (The May 6th bloom is coincident with the upwelling/relaxation pattern in Figures 7 & 9). pH generally rises with each bloom due to an increase in primary productivity, but the increase in pH precedes the May 6th bloom by a few days. This could be due to an initial increase in primary productivity per phytoplankton cell, which precedes the increase in cell numbers, or to enhanced grazing by zooplankton. It might also be due to continued upwelling during the bloom, advecting phytoplankton offshore by Ekman transport. These factors are not consistent, as pH and chl-a increase nearly synchronously during the May 25th bloom.

In HB the same three blooms are evident. and the chl-a has a similar variability as at Trinidad (Figure 10a). The anomalies oscillate with the tidal cycle, but generally maintain a timing consistent with Trinidad. The pH also increases with chl-a, as photosynthesis draws down CO_2 and raises pH. The correlation between pH and chl-a further emphasizes the control of biological processes on pH in HB.

Incubation Data Analysis

For each sediment incubation, DO decreased over time (Figure 11). Over the 3-day period, mixed incubations ranged from a 14.1 µmol/kg decrease at EB2 to a 36.7 µmol/kg decrease at NB2. Average decrease across all sites was 28.6 µmol/kg. Over the same period, unmixed incubations ranged from a 4.7 µmol/kg decrease at EB2 to a 24.0 µmol/kg decrease at NB5. Average decrease in DO across all sites was 13.6 µmol/kg for these unmixed incubations.

There was an average increase in pH of 0.62 for the mixed incubations from the initial day (0 hours) to the final day (72 hours) (Figure 11). The greatest increase in pH was 0.98 for station NB6. The smallest increase in pH was 0.31 for station NB5.

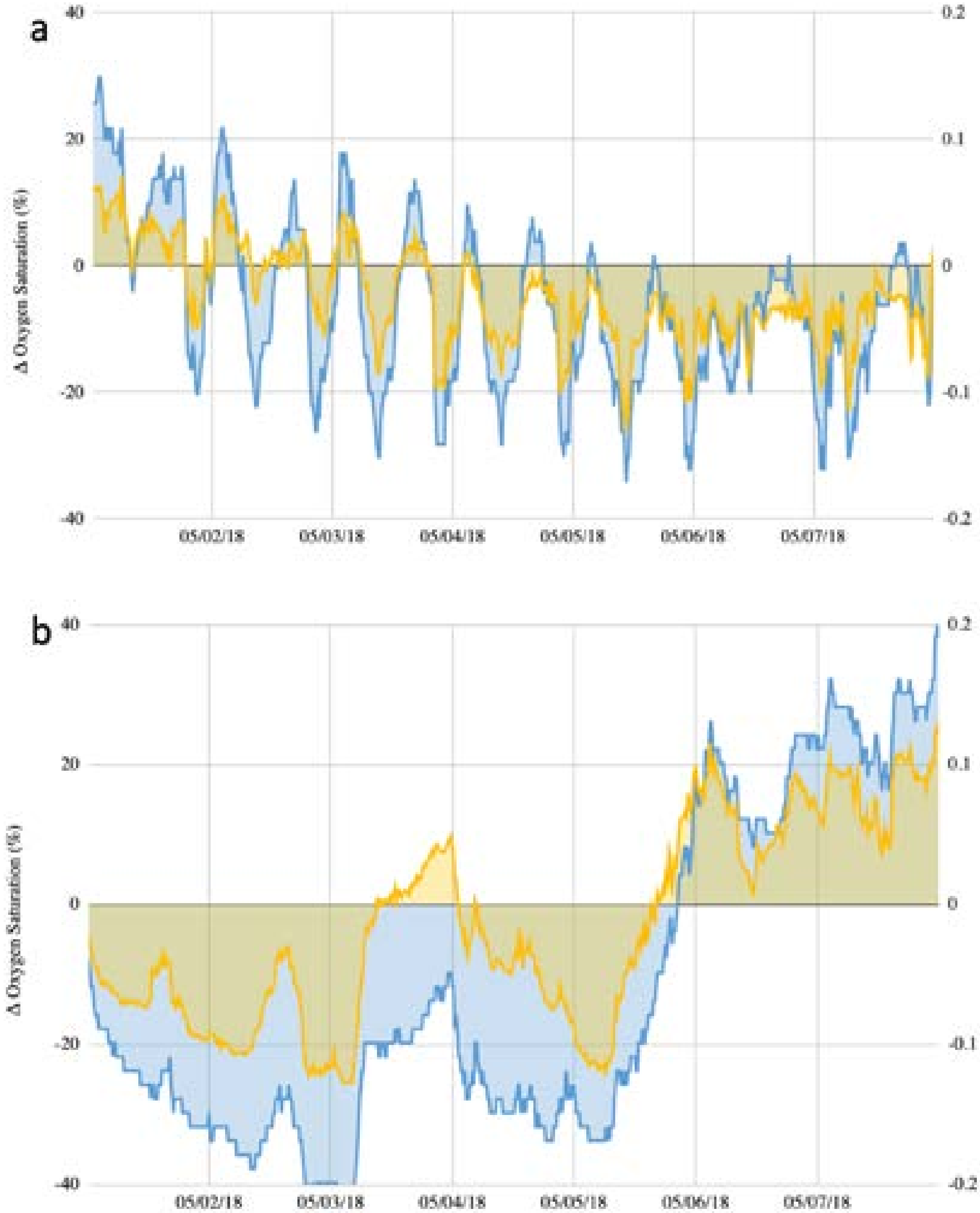
There was no clear trend in pH for the unmixed incubations. While the pH for station NB6 slightly increased by 0.06, there was an average decrease in pH of 0.06 for stations NB5 and NB2. Station EB2 did not experience any change in pH between the initial and final days.

The increasing trend in pH throughout all stations for the mixed incubations indicates that mixing enhanced the dissolution of calcium carbonate within the sediments. As the calcium carbonate dissolved, carbonate ions bonded with H^+ to produce bicarbonate (Eqn 2), raising the pH.

Three blank BOD bottles were measured on the initial day (0 hour) to obtain an average starting alkalinity of 1953 µmol/

Figure 9.

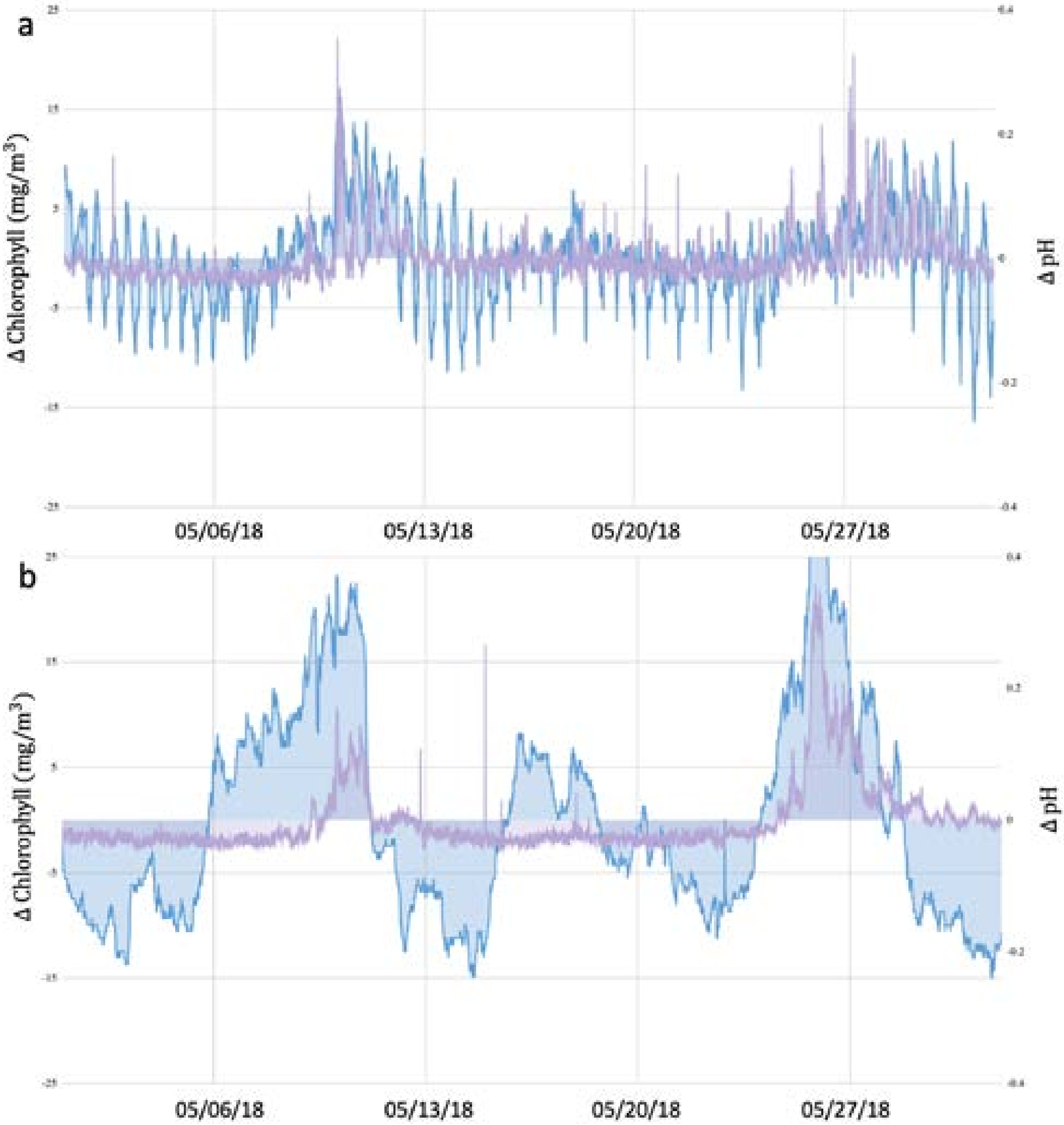
pH anomalies (blue) and oxygen saturation anomalies (yellow) from the first week of May 2018 at Chevron Dock in Humboldt Bay (a) and at Trinidad Pier (b). Data were obtained from CenCOOS sensors which are continuously deployed at each site collecting pH and DO every 15 minutes. Anomalies were calculated by subtracting the monthly mean from each measurement.



kg. There was an overall increase of ~320 µmol/kg between all stations from the initial day to the final day of the incubation for the mixed bottles (Figure 12). The mixed incubation station with the greatest increase in alkalinity was station NB6 with an increase of 736 µmol/kg and the smallest increase in alkalinity was station NB5 with an increase of 82 µmol/kg.

There was also an increasing alkalinity trend for unmixed incubations, with an average increase of ~34 µmol/kg. The unmixed incubation station with the greatest increase in alkalinity was station NB6, with an increase of 64 µmol/kg, and the smallest increase in alkalinity was station NB5, with an increase of 12 µmol/kg.

Figure 10.
pH anomalies (blue) and chlorophyll anomalies (purple) were collected during the month of May 2018 at Chevron Dock in Humboldt Bay (a) and at Trinidad Pier (b). Data were obtained from CenCOOS sensors which are continuously deployed at each site to collect pH and chlorophyll every 15 minutes. Anomalies were calculated by subtracting the monthly mean from each value.

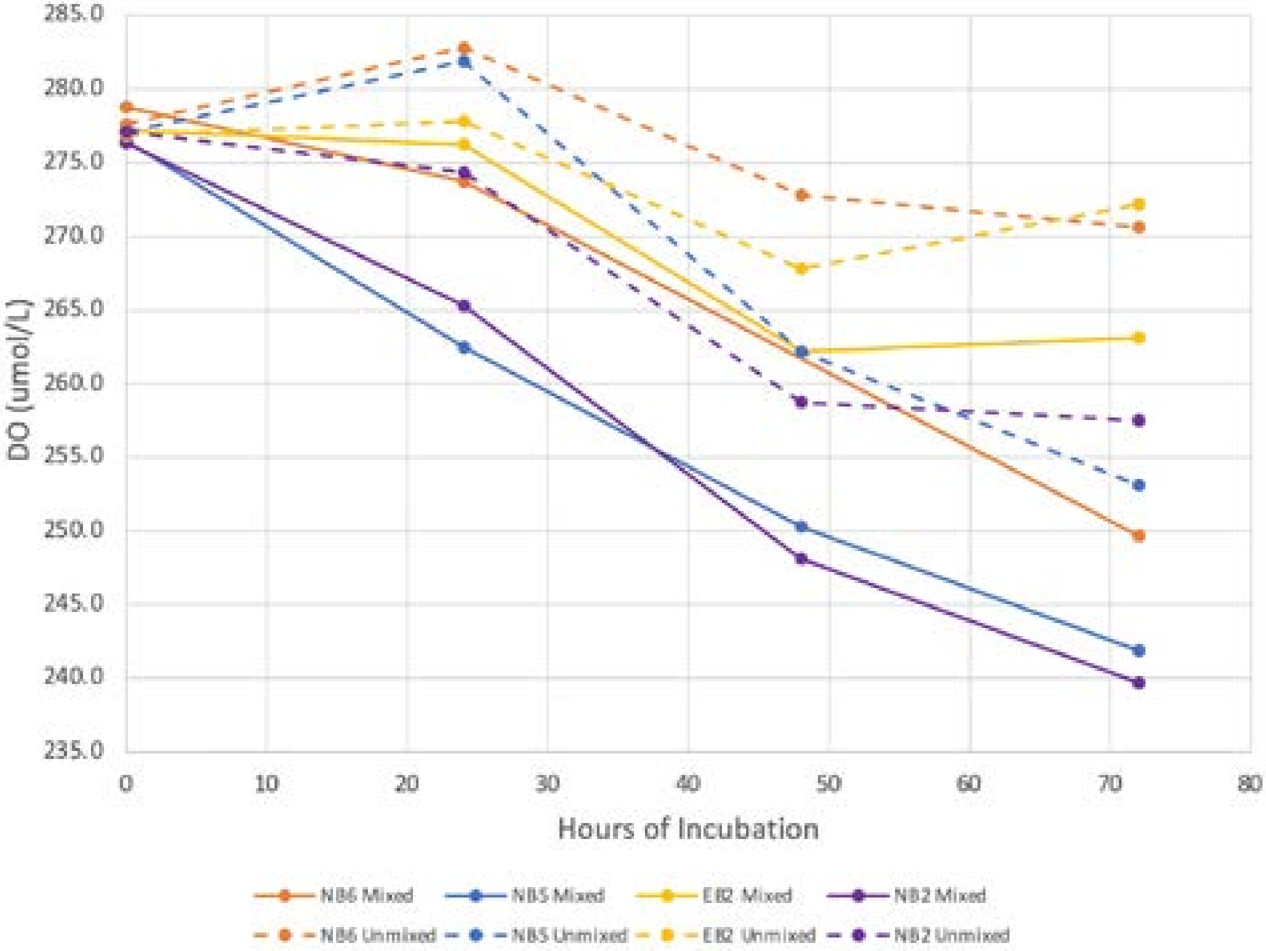


Although there was an increasing alkalinity trend found in both mixed and unmixed incubations, the average increase in alkalinity for the mixed incubations was much greater than for the unmixed incubations. This is likely due to the enhanced dissolution of carbonate ions from the suspended sediments, which increases alkalinity.

Discussion

The main goal of this study was to determine the primary processes that control pH in HB. We hypothesized that the pH in HB is controlled by: 1) the tidal input of coastal waters into the bay; 2) the reduction (increase) of CO_2 due to

Figure 11.
Dissolved oxygen evolution during our three-day incubations. Colors represent stations. Dashed lines represent unmixed samples, and solid lines represent mixed samples mixed by a stir bar during the incubation period. Note the 48-hour BOD bottle for Station NB6 broke, so no data was recorded.



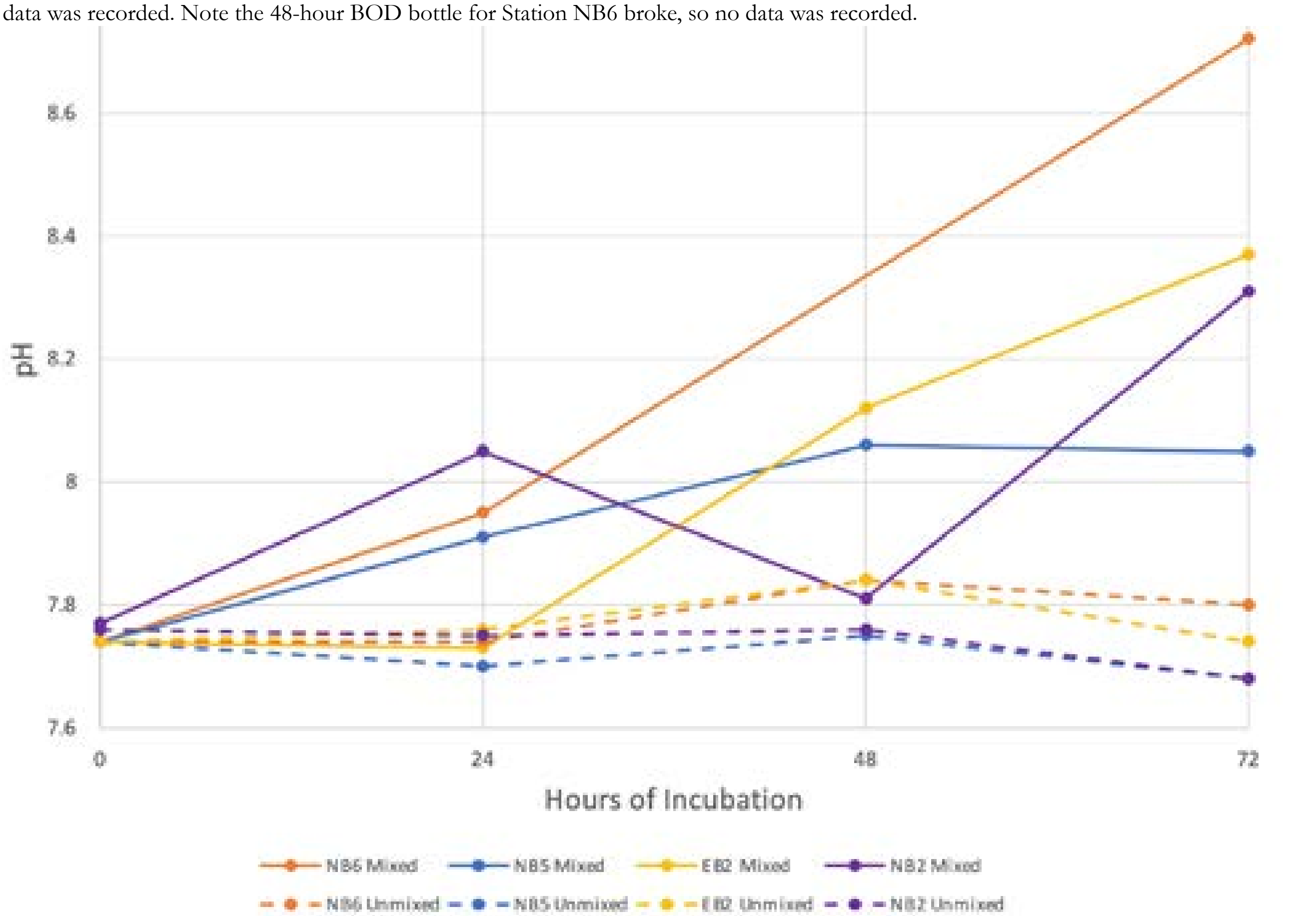
biological productivity (respiration); and 3) the dissolution of carbonate minerals within the sediments due to strong tidal mixing. Based on the results presented here, we conclude that the tides and biological factors each play a major role in controlling HB's pH while the dissolution of carbonates may play a secondary role.

Upwelling and relaxation appear to be the main control for pH in the coastal waters at Trinidad (Figure 5b). Upwelling events are clearly evident when temperature drops several degrees within a few days. This signature is accompanied by an initial drop in DO and pH. Almost immediately after the upwelling subsides, the oxygen saturation rises above 100% due to increased photosynthesis brought about by upwelled nutrients. Chl-a also increases, accompanied by a rapid increase in pH due to the drawdown of CO_2 during photosynthesis.

This coastal upwelling-driven, biological control sets the forcing for the water that enters HB. Water quality parameters within HB, including pH, vary with the tidal cycle. This variability is not consistent, but changes with coastal upwelling. During upwelling events low-pH water enters the bay on the flood tide, and mixes with higher-pH bay waters. The resulting pattern shows depth and pH varying inversely, with lower pH on the flood tide (reflecting the low pH coastal end member), and high pH on the ebb (reflecting the higher pH bay end member) (Figure 7a and the first half of Figure 8). During relaxation periods after upwelling, the trend is reversed. The coastal surface waters undergo a decrease in CO_2 as phytoplankton increase their productivity in response to the upwelled nutrients. This raises the pH and DO relative to the bay waters. This resulting pattern shows depth and pH co-varying with higher pH on the flood and lower pH on the ebb, as can be seen in the second half of figure 8.

The ever-present tidal pattern in pH and other water quality parameters provides strong support for the first hypothesis: HB's pH is strongly controlled by tidal influx. But that can't be the whole story. HB's pH may initially be set

Figure 12.
pH change during the 3-day incubations in artificial seawater. Colors represent stations. Dashed lines represent unmixed samples, and solid lines represent mixed samples mixed by a stir bar during the incubation period. Note the 48-hour BOD bottle for Station NB6 broke, so no data was recorded. Note the 48-hour BOD bottle for Station NB6 broke, so no data was recorded.



by the influx of coastal waters, but the modification of that pH on every ebb tide requires a biological or chemical process within the bay. Otherwise the pH of the bay would vary less with each subsequent tidal cycle until the bay water matched the coastal value and further tidal variation was minimal.

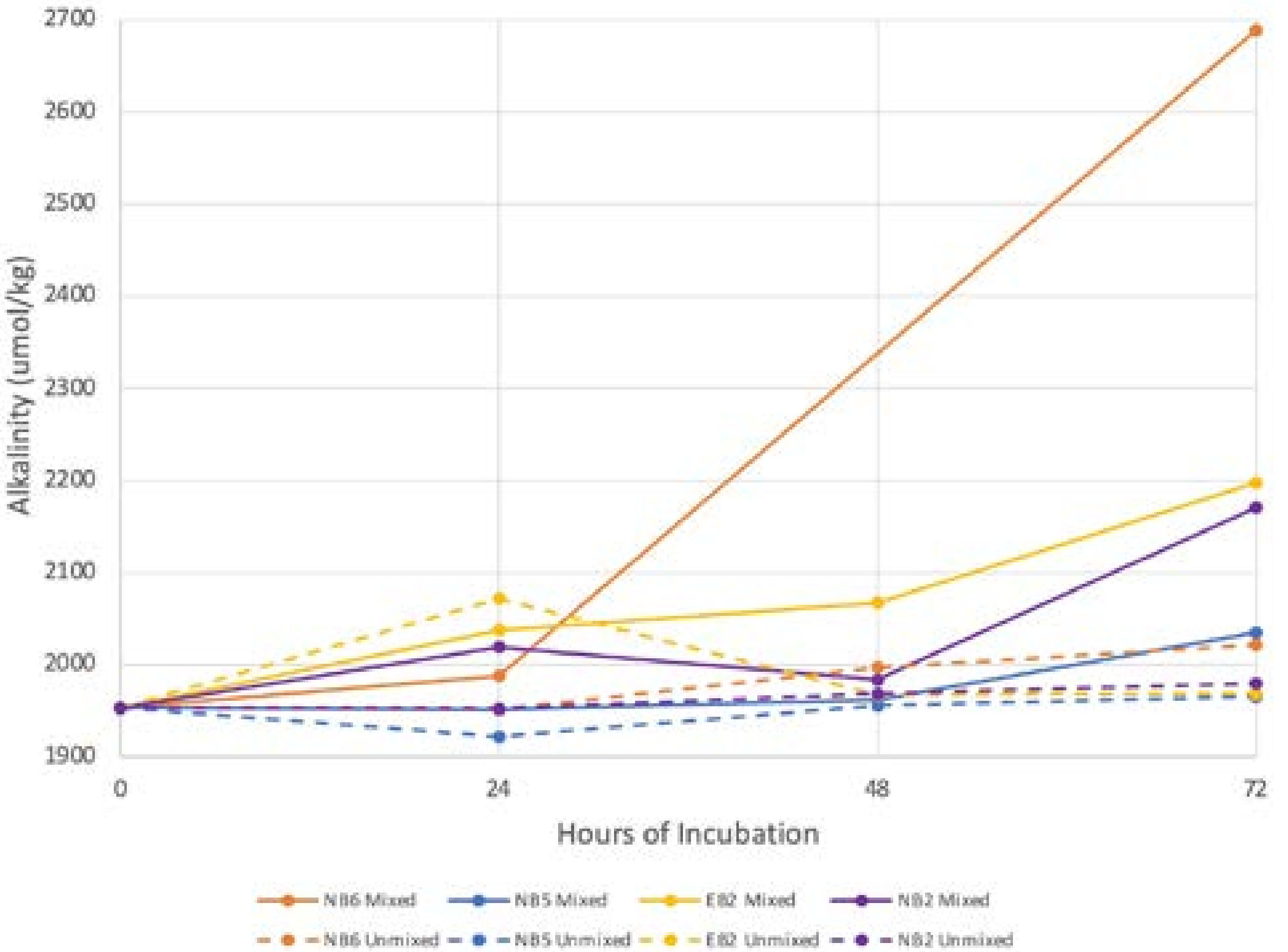
Looking at the biological processes within HB more closely, there is clear support from the CeNCOOS data that primary productivity is raising the pH relative to coastal waters. As at Trinidad, pH and oxygen saturation show strong correlation within the bay. Peaks in pH are accompanied by oxygen saturations greater than 100% (Figure 9). Such high saturations are attainable when excess primary productivity elevates oxygen above the amount expected due to gas exchange alone. Aligning with these peaks in pH and oxygen, chl-a also increases, indicating elevated phytoplankton (Figure 10). The magnitude of chla-a and pH peaks are not always proportional, however, since chl-a is an indicator of phytoplankton but not eelgrass. The data from this study cannot constrain its magnitude, but eelgrass is likely playing a large role in the primary productivity cycle of the bay, which would impact pH and DO without altering chl-a. This could explain some of the mismatch between the timing and magnitude of pH peaks compared to chl-a (Figure 10).

While primary productivity raises pH, respiration counters this effect, lowering pH... When the pH in the bay is less than the pH nearshore, net respiration must be occurring. Net respiration could be caused by a lack of sunlight (night time, overcast, etc.) or nutrient depletion -- both limiting photosynthesis. When the pH nearshore is high, photosynthesis is a primary cause. Excessive photosynthesis raises the nearshore pH, but can also deplete the nutrients in surface waters, limiting the nutrients that get delivered to HB.

In addition to the correlation between pH, DO, and chl-a, the difference between HB and Trinidad pH at similar times provides another indicator that primary productivity and respiration alter pH within the bay. pH is elevated in the bay at the outset of upwelling periods, and is lowered by incoming low-pH coastal waters, but then rises again, showing that photosynthesis effectively raises the pH of the acidic coastal water that enters the bay. Primary productivity provides an

Figure 13.

Mixed and Unmixed Incubation Alkalinity levels. Alkalinity evolution during our three-day incubations. Colors represent stations. Dashed lines represent unmixed samples, and solid lines represent mixed samples mixed by a stir bar during the incubation period. Note the 48-hour BOD bottle for Station NB6 broke, so no data was recorded. Note the 48-hour BOD bottle for Station NB6 broke, so no data was recorded.



important contribution to the pH fluctuation observed within the bay that cannot be attributed to the tidal cycle alone.

Looking more closely at the chemical processes within HB reveals some support that sedimentary carbonate dissolution could act as a pH buffer. Due to the experimental set-up, our incubations indicate the upper limits of the buffering capacity of the sediments. pH and alkalinity varied little in incubations where the sediment was not resuspended, but varied considerably where the sediments were continuously stirred. In these mixed incubations, the pH change over the 3-day experiment (Figure 11) exceeded the observed pH anomalies in HB (Figure 9), and total alkalinity was up to 150 greater than in the unmixed incubations. This indicates that resuspension of the sediments enabled the release of carbonate or silicate ions from the sediment, which reacted with H^+ in the water column to form bicarbonate and silicic acid, respectively. This is the likely reason the mixed incubation pH increased.

Carbonate dissolution alone may be sufficient to drive the observed alkalinity increase. We estimate a maximum of 80 μmol/kg of carbonate available in each incubation (assuming each 0.5 g of sediment added to the 300 g of artificial seawater contained 0.5 weight% $CaCO_3$ in accordance with Bolster et al., 2015). At 2 equivalents of alkalinity per mol carbonate, sedimentary dissolution of all the estimated calcium carbonate would result in a 160 μmol/kg increase in alkalinity. This is on par with the observed results (Figure 11), but complete dissolution over just a 3-day period seems unlikely as carbonate minerals take time to dissolve. Some of the observed alkalinity change could also be due to silicate dissolution, which unfortunately, was not measured during the incubations.

Nonetheless, if carbonate minerals did dissolve, our incubations suggest a substantial impact on the pH of HB that would rival the impact of primary productivity. Given the incubation set-up, we do not believe that is likely for several reasons: 1) the incubation bottles were prepared with artificial seawater that had no Ca^{2+} ion. This created a very low calcium carbonate saturation state despite the realistic levels of CO_3^{2-}. With no calcium ion, dissolution would have taken place more quickly and to a greater extent in the incubation bottles than what would naturally occur in HB; and 2) Sediment resuspension in HB is not constant but occurs periodically for about an hour at a time around max flood and ebb tides. The turbidity observed in the bay fluctuates considerably with the tides and therefore constant resuspension in the bay is unlikely. If we were to confine our incubation results to 4 hours of resuspension per day (i.e. two max flood and two max ebbs); the total pH change of +0.5 would be constrained to +0.03 per day. This is about 20% less than the changes observed due to tidal exchange, primary productivity and respiration.

The increase in pH and alkalinity indicates that carbonate minerals within the sediment likely buffer pH, supporting Hypothesis 2, but the magnitude of that pH change is likely secondary compared to tidal and biological factors.

Conclusion

After analyzing our three hypotheses, we found that there is support that the pH of HB is impacted tidally, and biologically, but to a lesser degree through sedimentary carbonate dissolution. The tidal cycle's effect works similarly to the flushing of a toilet, bringing in coastal water with every flood tide. The pH of the water that enters the bay is primarily determined by the pH of the coastal ocean, which can be higher or lower than the pH seen within the bay depending on the degree of upwelling. Once inside HB, biological processes increase or decrease the pH of the water, depending on the strength of primary productivity relative to respiration. In addition to these major controls, the resuspension of sediment on each max flood and ebb tide likely increases pH due to the buffering effect of carbonate mineral dissolution. The strength of the buffering ability of the carbonate sediments is dependent on turbidity levels and the saturation state of carbonate minerals.

Further study is required to quantitatively ascertain the role of these three processes in controlling pH in HB. Incubations with Ca^{2+} in the artificial seawater, and with a mixing pattern matching the tidal period would better mimic the role of carbonate dissolution in buffering bay pH. Output data from combined tidal and productivity models compared with CenCOOS observations could quantify the primary factors controlling HB's pH. Perhaps more importantly, such models could provide future scenarios for stakeholders and managers to assist in decision making about aquaculture and recreational use of HB.

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Wellness Among University Employees: A Holistic Assessment During Traumatic Times

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There has been a growing awareness of the importance of worksite wellness among employees. Assessing the wellness needs of the University campus communities following traumatic events is a pressing topic. From 2017- 2021, Butte County, including California State University, Chico (Chico State), experienced a series of extreme traumas. This research aims to provide a holistic needs assessment of wellness among University employees after experiencing traumas. This study used a survey administered from December 2020 to January 2021, the end of the second semester of remote instruction during the COVID-19 pandemic at Chico State, to assess employee wellness needs. The quantitative results from a total of 324 survey responses showed that two dimensions of wellbeing that employees rated highest in terms of what their organization engages or promotes were intellectual and relational wellbeing. The two dimensions rated lowest were physical and spiritual wellbeing. The qualitative results showed specific areas of concern that emerged from the survey, including a need for increased healthy lifestyle behaviors, a balanced workload, and a desire for a sense of value within the institution. The findings of this study provide opportunities for improving the wellness among Chico State University employees and also inform other university campuses.

Introduction

Worksite wellness has become a growing area of interest for employers in recent years (Abraham, 2019; Jones et al., 2019; Reif et al., 2020; Song & Baiker, 2019). In a report on the state of workplace health promotion and protection programs in the United States (US), the Centers for Disease Control and Prevention (CDC) (2018) noted that the workplace and the health and safety of its employees are interconnected. They also noted that improved health is associated with increased productivity at work while poor health is associated with increased health care costs.

Currently, 50% of the US population has a chronic disease and 86% of national health costs go to treating these diseases (Holman, 2020). While many of these diseases are preventable, the US invests only about 2.9% of its total health expenditures on preventative health care (Organisation for Economic Cooperation and Development, 2023). Galea and Maani (2020) suggested that the high cost of treating preventable diseases should serve as an urgent call to "invest in the conditions that generate health, creating a world where preventable disease is no longer part of our vocabulary."

Since the workplace is where most adults spend a large portion of their waking hours, it is a setting that deserves careful examination about how organizational cultures impact wellness. The Institute for Health and Productivity Studies at the Johns Hopkins Bloomberg School of Public Health (2015) recommended that employers not only identify the risk factors of individual employees but also explore organizational factors that either support or negatively impact wellness efforts. In addition, the Johns Hopkins report advised that worksite wellness programs are most effective when they create a culture of health where the institution provides opportunities for employees to engage in healthy behaviors.

In recent years, numerous books on workplace wellness have emerged that outline strategies to create healthier organizational cultures (Day et al., 2014, Putnam, 2015; Stockley, 2016; Stringer, 2016). Suggestions to improve workplace wellness included spending time with nature, improving sleep hygiene, reducing stress, improving workflows, increasing physical activity, offering health screenings, funding wellness coaches, and providing healthy food options.

Only a few studies have researched wellness programs among university employees. One study concluded that a worksite pedometer-based physical wellbeing program on campus effectively increased physical activity and cardiovascular fitness, decreasing cardiovascular risk factors among university employees (Butler et al., 2015). Another study found that being female, white, non-union staff, and employees who seek preventive care, are more likely to participate in wellness programming (Beck et al., 2016). There is a gap in the literature about holistic assessment of wellbeing among university employees and effective university holistic wellness programs. Moreover, little is known about university employee wellness needs during traumatic times.

From 2017-2021, Butte County in northern California experienced a series of traumatic events. Some were environmental disasters, while others were personal tragedies on the California State University, Chico campus (Chico State). The cumulative impact of these events significantly impacted residents in this rural community. Chico State has an enrollment of approximately 14,000 undergraduate and graduate students, 44% of whom are first generation students. It is a Hispanic Serving Institution (HSI) with a 56% minority majority (California State University, Chico, 2023a). Disasters tend to have negative effects on survivors and the community as a whole because these large-scale events " …create crisis in terms of community capacity and individual wellness." Therefore, enhancing community resilience is essential to recovery from disasters (Gim & Shin, 2022). The researchers were concerned that Chico State employees may be experiencing unique health risks as a result of these tragedies. This paper aims to assess the wellness needs among university employees after the following traumatic events.

The first crisis in the community occurred in 2017. After years of historic droughts, heavy rainfall finally arrived and caused flooding that damaged the Oroville Dam (30 miles from the Chico State campus), the tallest earth-fill dam in the United States according to California Department of Water Resources (2022). Erosion on the spillway threatened a collapse of the dam (Hollins et al., 2018), which required the immediate evacuation of over 180,000 residents. Many Chico State students, faculty, and staff live in Oroville and were impacted by this crisis.

As our residential campus community was emotionally recovering from the dam crisis, another tragedy occurred in early 2018. A Chico State student died by suicide on campus while classes were in session. Many students, faculty, and staff witnessed the death. University Police, mental health providers, and Student Affairs personnel responded to support those who were present during the incident and those who were grieving.

Shortly after the public suicide, a homicide victim was discovered in front of the campus administrative building. Again, students, faculty, and staff were provided access to counseling.

Later that same year, the deadliest and most destructive wildfire in California history, known as the Camp Fire (Cal Fire, 2018), began on the morning of November 8th in Butte County and burned ferociously for over two weeks. The fire left the community devastated with 85 deaths and thousands homeless. The Camp Fire caused damage to over 18,000 buildings throughout Paradise (15 miles from Chico State campus) and the surrounding communities, including homes, businesses, schools, and a hospital. It burned over 153,000 acres according to Mohler (2019). The homes and belongings of many students, faculty, and staff were destroyed. Chico State campus closed for 14 days due to poor air quality and out of concern for those impacted by the fire.

In early 2019, Chico experienced a supercell flood that included a tornado warning, quarter-sized hail, and nearly 4 inches of rain that fell in a 15-minute period, exceeding the city's ability to drain the water. Cars were destroyed, classrooms were flooded, and local residents faced yet another historic disaster.

The following year, Chico State, along with universities around the world, had to move to remote instruction due to the COVID-19 global pandemic. This further compounded the fear, anxiety, and uncertainty the Chico community had been experiencing for years. Depression, substance abuse, and suicide were identified as top health risks in Butte County where Chico State is situated (Butte County Public Health, 2022).

After each tragedy, University leadership communicated with the campus community and managed recovery efforts through emails, announcements, and forums. While counseling and programming were offered to support mental health and overall wellbeing, the cumulative impact of trauma and stress exposure put campus employees at risk for anxiety (Ayazi et al., 2016), compassion fatigue, and burnout.

The purpose of this study was to obtain feedback from campus employees about their health behaviors and assess their needs to inform future efforts on improving campus wellness. This paper shares the results of a survey administered from December 2020 to January 2021, the end of the second semester of remote instruction during the COVID-19 pandemic. The cumulative impacts of the aforementioned tragedies were examined utilizing survey questions incorporating eight dimensions of wellness, identified by the Substance Abuse and Mental Health Services Administration (SAMHSA, 2016): emotional, environmental, financial, intellectual, physical, spiritual, relational and vocational life domains.

Methods

Survey Instrument

This exploratory study used a 44-question survey to collect responses from current faculty, staff, and administrators at Chico State. The University employs 1,497 faculty including professors, lecturers, counselors, librarians, and coaches. Additionally, there are 1,031 staff who serve the needs of the campus. All participants provided consent to participate in the survey. The questions in this survey, designed to identify health and wellness needs of faculty and staff, were based on the Eight Dimensions of Wellness model used by SAMHSA (2016), adapted from Swarbrick (2006). The researchers chose this model as it provided a comprehensive measure of holistic wellbeing to expand the concept of health to multidimensional wellbeing (Geronimo, et al, 2023).

The web-based survey tool Qualtrics XM was used to create the survey. The survey included an informed consent; demographic information including age, gender identity, race/ethnicity, primary language, role on campus (faculty/staff/administrator), and length of time employed at the University; followed by quantitative and qualitative questions.

Table 1
Eight wellbeing areas and their explanations

Wellbeing Area	Explanation
Emotional wellbeing	ability to tune into emotions including coping with stress, regulating emotional challenges, recognizing personal resiliency, and all other aspects of emotional wellbeing
Environmental wellbeing	ability to connect to the dynamic relationship between ourselves and our environment, including our immediate environment, the community, and the natural
Financial wellbeing	ability to act on mindful financial decisions that support and enhance our personal and professional life including financial stability, fulfilling short-term and long-term goals, and/or other financial needs
Intellectual wellbeing	ability to stimulate our minds including engaging in critical thinking, igniting curiosity, solving problems, sparking creativity, and other pursuits to intellectual growth
Physical wellbeing	ability to act on intentional aspects of our bodies to enhance our health, including nutrition, movement, sleep and sexual health
Spiritual wellbeing	ability to establish and engage in fulfilling practices that connect us to a greater sense of internal purpose and meaning including faith, belief, morals, values, ethics, and principles
Relational wellbeing	ability to create and maintain personal and professional meaningful connections at the individual, group, and community level
Vocational wellbeing	ability to find value and gratification in our work through the interconnectedness between ourselves and our institutions, including finding value and sustenance within the institutions for which we work, along with practicing work-life balance

Quantitative questions included yes/no, multiple-choice, check-all-that-apply, and Likert scales. One Likert scale including eight specific wellness areas (table 1) was designed to explore the eight dimensions of holistic health (SAMHSA, 2016), ranging from 1 (Never, 0% of the time) to 7 (100% of the time).

Another Likert scale allowed participants to rate the likelihood they would participate in various health and wellness resources that were or could be provided by the institution, ranging from 1 (Not at All) to 7 (Very Likely). Health behavior survey questions asked participants to self-report their utilization of wellness programming, sleeping hours, consumption of vegetables and fruits per day, and engagement in calming activities. Other variables of interest include stress level and workload level. Stress level was reported on a 7-point Likert scale by answering the question: On a typical workday, my stress level is ranging from 1 (very low, Never) to 7 (very high, 100 % of the time), while workload level was reported on a 7-point Likert scale by answering the question: I perceive my current workload to be ranging from 1 (very low) to 7 (very high).

Qualitative measures consisted of open-ended questions including: (a) share reasoning behind rating, (b) how could participants increase their rating for each wellness domain by at least one point, (c) what wellness programming activities interested them, but had not been listed, (d) what is important to include in a wellness program, (e) what participants perceive to be their most significant wellness challenges, (f) what participants do now to enhance their health, and (g) provide additional ideas or questions about leading a healthy life.

Responses to open-ended questions were divided into four demographic groups based on their roles (faculty, staff, administrators, and those who did not identify) using qualitative content analysis (Miles & Hubberman, 1994; Patton, 2002; Weiner et al, 2001). This provided insight into how each unique cohort responded to the survey. All 445 quotes from the 324 respondents were examined for themes, patterns, and categories. Data were then uploaded to Quirkos 2.4 Qualitative Analysis Software to assist with sorting and organizing the responses. After sorting responses, reports were generated with visual representations of the data to help further organize and visualize the emerging themes. To enhance trustworthiness, a series of peer debriefing sessions (Lincoln & Guba, 1985) were conducted with colleagues familiar with the survey and qualitative analysis. Peer debriefers reviewed the open-ended survey responses to determine if emergent themes were over/underemphasized and to consult about any key areas that may have been overlooked.

Procedure

The survey instrument was vetted through a piloting process using a convenience sample (n=3) of faculty and staff, and the Interim Vice President of Student Affairs gave final approval of the survey. The study received approval from the University Institutional Review Board, and the survey was administered by the University's Office of Institutional Research. The target population included all employees on campus. Participant recruitment was conducted through Campus Announcements and individual emails sent from the Faculty Development Office and the faculty and staff unions. Department Chairs were prompted to remind faculty and staff to complete the survey. Incentive gift baskets were offered to 10 randomly selected participants. A total of 324 survey responses were received.

Statistical analysis methods

Numerical data was described using mean and standard deviation, and categorical data was analyzed using counts and percentages. Density plots were used to visualize the distribution of participants' perceptions of the organization promoting and engaging in best practices that promote eight different wellness areas. Stress levels were visualized among different roles of employees using a bar plot after dichotomizing stress levels. A boxplot was created to compare perceived workload among different roles of employees. The Chi square test was used to compare stress levels among different roles of employees because these variables are categorical. A nonparametric Kruskal-Wallis rank sum test was used to compare perceived workload levels among different roles of employees because the perceived workload levels did not follow the normal distribution.

Results

Data description

Two hundred fourteen participants self-identified as white and 36 identified as not white, while 74 chose not to respond to this query. Most respondents (246) identified as female, 67 identified as male, and 11 did not respond to this item. Regarding the position category, 24 self-identified as administrators, 109 as faculty, and 187 identified as staff; four respondents did not provide an answer to this item. Compared with the distribution of University employees at the time of the survey, participants were more likely to identify as female (75% vs 55.4%), less likely to report as white (66% vs 72.7%), more likely to report as staff (57.7% vs 43.3%). Regarding longevity, 121 respondents reported they worked at the university for five or fewer years, 69 reported they worked on campus for 6-10 years, 58 reported having worked on campus for 11-15 years, and 60 survey respondents reported having worked at the university for 16+ years. Sixteen respondents did not respond to this query.

How has organization helped the wellbeing of the participants?

Descriptive statistics on participants' perceptions of the organization promoting and engaging in best practices that promote eight different areas of wellbeing on a 7 Likert scale ranging from 1 (0 % of the time) to 7 (100 % of the time) were described in table 2. A total of 246 responders completed all the survey queries. Compared with the attritors, those who completed all survey queries have the same gender distribution (78.3% female vs 79.4% female), but are more likely to identify as white (87.5% vs 78%) and faculty (35.8% vs 28.6%). The higher the score, the better the respondent perceived the organization helps with promoting and or engaging in best practices that promote wellbeing in that area. Wellbeing variables were treated as numerical variables, and the means and standard deviations were calculated in table 2.

The reported intellectual wellbeing and relational wellbeing have higher means than others. Physical wellbeing and spiritual wellbeing have lower mean scores than other areas. This pattern is also viewed from density plot shown in figure 1 with peaks representing the mode. The density plot for intellectual wellbeing is skewed more to the left than others, indicating a higher rating for intellectual wellbeing.

Table 2
Study Participants' perception on how the organization helped their wellbeing (7 Likert scale ranging from 1 (Never) to 7 (100 % of the time).

Perceptions	Score*
Intellectual wellbeing	4.84 (1.51)
Relational wellbeing	4.53 (1.42)
Vocational wellbeing	4.31 (1.54)
Environmental wellbeing	4.30 (1.49)
Emotional wellbeing	4.12 (1.61)
Financial wellbeing	3.77 (1.65)
Physical wellbeing	3.75 (1.61)
Spiritual wellbeing	3.50 (1.62)

*Mean (SD)

Behavioral responses description

Campus employees provided a mixed response to choices they made regarding their wellbeing. Seventy-seven percent of the respondents provided answers to the health behavior questions with the results shown in table 3. The majority (69%) noted they slept an average of six to eight hours each weekday and 22% responded they slept four to six hours. Approximately half of the respondents (51%) indicated they

Figure 1.
Density plot of Study Participants' perception on how the organization helped their wellbeing.

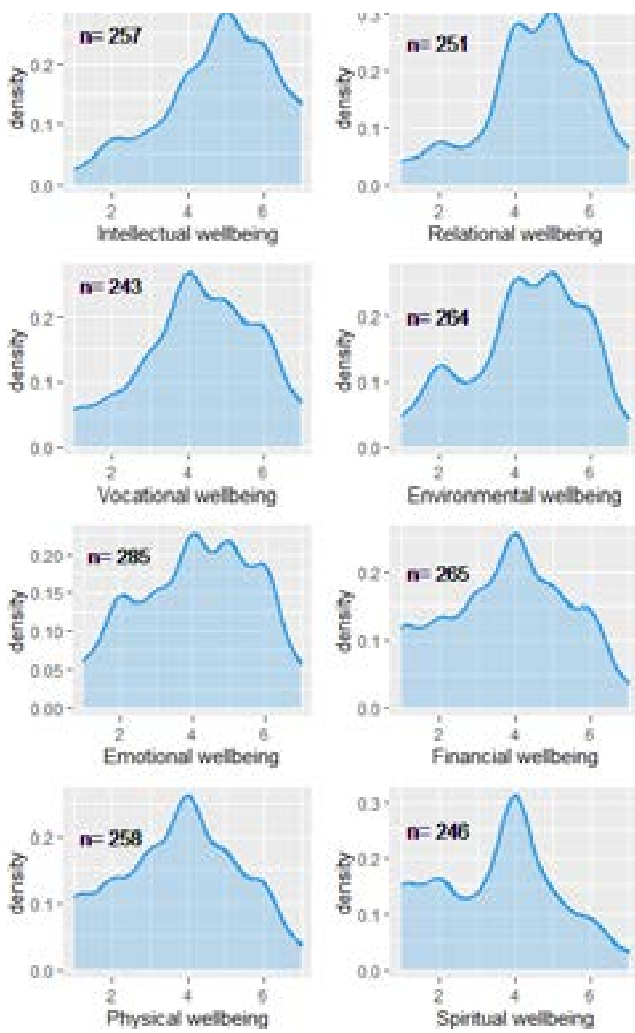


Table 3
Participants' health behavior characteristics.

Health Behavior Characteristics	N	n(%)
How many hours do you sleep each weekday on average?	249	
Less than 4 hours		4 (1.6%)
4-6 hours		55 (22%)
6-8 hours		171 (69%)
More than 8 hours		19 (7.6%)
How many days per week do you exercise?	249	
0 days		69 (28%)
1-2 days		66 (27%)
3-4 days		60 (24%)
4+ days		54 (22%)
How many total hours per week do you engage in calming activites?	250	
Less than one hour		62 (25%)
1-3 hours		107 (43%)
4-7 hours		56 (22%)
7+ hours		25 (10%)
Consumption of vegetables and fruits per day	250	
0 servings		8 (3.2%)
1-3 servings		162 (65%)
4-7 servings		70 (28%)
8+ servings		10 (4.0%)
Utilization of wellness program	250	58 (23%)

exercised one to four days per week, with 28% who did not exercise at all. A notable proportion of respondents (43%) indicated they engaged in at least one to three hours per week of calming activities, with an additional 22% reporting they engaged in four to seven hours of such activities. Regarding the consumption of fruits and vegetables on a daily basis, a majority of respondents (65%) indicated they consumed one to three servings, with an additional 28% indicating they consumed four to seven servings daily. Less than one-quarter of participants (23%) utilized wellness programs available to campus employees through health insurance.

Participants' perceived stress level and workload

Because the expected number for each cell of contingency table should be greater than five to apply Chi square test, stress level was dichotomized INTO two categories: frequently or more (5 or more) and sometimes or less frequently (4 or less). Stress levels and workloads were compared among different roles of employees as shown in figure 2 and figure 3. Figure 2 shows that administrators reported having the greatest percent of higher perceived stress level, followed by faculty, and then staff. Figure 3 shows the box plot for perceived workload level among three different roles of employees. Compared with administrators and faculty, staff reported having lower workload level.

Inferential statistics

The results from Chi square test suggest that stress level is statistically significantly associated with roles (administrator, faculty, staff) (X-squared = 8.3343, df = 2, p-value = 0.0155). The proportion of feeling frequently stressed or more among university employees with different roles showed statistically significant difference, with staff members the lowest proportion, and the administrators the highest proportion of feeling frequently or more stressed. The perceived workload is statistically significant different among employees with

Figure 2
Comparison of the stress levels among different roles of employees.

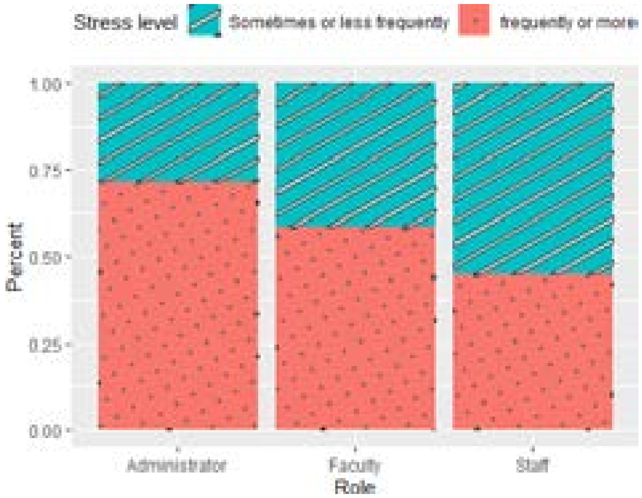
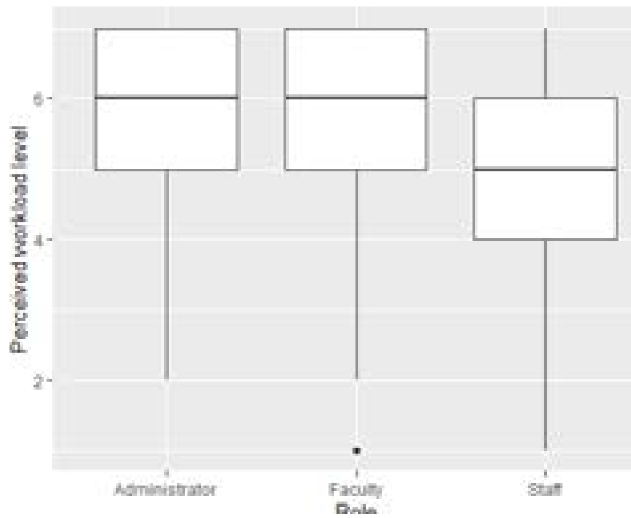


Figure 3
Comparison of the perceived workload among different roles of employees.



different roles from the results of Kruskal-Wallis rank sum test ($p < 0.0001$). Faculty and administrators reported having higher perceived workload than that of staff as shown in figure 3.

Qualitative Results

Four primary themes emerged from coding the data: (a) a desire for workload to decrease, (b) a desire for salaries to increase, (c) a desire to feel respected, valued, and acknowledged by campusleaders, and (d) a desire for wellness programming as shown in table 4.

A Desire for Workload to Decrease

Decreasing workload was the most prominent theme to emerge from the data. Faculty desired reduced teaching loads, fewer students per class, fewer committee assignments, more course release time opportunities, and no teaching overloads (i.e. assignments that exceed 24 units/year).

It was noted by some employees that the workload seemed to grow incrementally each year. One staff member articulated, "There is an expectation to do more (work) and at a higher quality all the time." Another staff employee mentioned the connection between workload and health by stating "…a lot of the people I work with are tired and stressed from massive workloads with virtually no available time to do anything which could help our health in the long run. People are starting to burn out. Even younger staff are second guessing if they can maintain the unhealthy work-life balance perpetuated by the university."

When asked about solutions to workload, staff most often mentioned the importance of hiring. "Quickly filling vacant staff positions rather than having the remaining staff member do the extra work uncompensated" was one suggestion offered. Another recommended that the university, "Hire more individuals so work loads aren't so high that people can't get a moment to breathe."

Faculty also noted challenges with balancing work and health. "I feel as though I'm too busy with work related matters to allow time for my physical health" wrote one professor. Faculty mentioned that, over the years, preparation time for teaching has increased as a result of new educational technologies that need to be implemented (Blackboard, Polleverywhere, Kaltura, textbook publisher content, Zoom, etc.). Additional time was noted to be required to address equity gaps, connect better with first-generation students, and ensure that all course materials are accessible compliant. One faculty member noted frustration with workload by saying, "We talk about wellness and self care, then expect you to give your life over to your job. The demands are unrealistic…"

A Desire for Salaries to Increase

The desire for higher salaries was also a prominent theme that emerged from the survey. One faculty member wrote, "The CSU could give raises without forcing employees to almost go to strike every contract." Faculty also expressed the desire to be paid for work they do while off-contract. Said one professor, "Faculty (are) expected to work in summer but are not paid." Another faculty member suggested that "when additional workload is added above and beyond what's normally expected, stipends would be nice."

Staff were the most vocal about salaries compared to the

Table 4.
Categories of response themes to qualitative questions in questionnaire

Themes	Respresentative Responses
A desire for workload decrease	• "I feel as though I'm too busy with work related matters to allow time for my physical health." • "Hire more individuals so work loads aren't so high that people can't get a moment to breathe."
A desire for salaries to increase	• "The CSU could give raises without forcing employees to almost go to strike every contract." • "When additional workload is added above and beyond what's normally expected, stipends would be nice." • "Pay staff a salary they can live on. People who work here full time should not have to apply for food stamps and stand in line at the food pantry." • "Provide meaningful ways for staff to advance… instead of creating an environment where staff must fight with their institution to qualify their value. It's demeaning, especially as administrators get annual and automatic raises."
A desire to feel respected, valued, and acknowledged by campus leaders	• "We are told to have compassion for students, but sometimes I don't feel that same compassion from admin towards faculty/lecturers." • "More listening from leadership," • "respect for the duties performed," • "acknowledgment of work well done" • "wellbeing check-ins during department meetings"
A desire for more wellness programming	• "Campus resources for staff and faculty that mirror students would be a vast improvement" • "Current institution focus seems to be only on students' well-being" • "Some onsite counseling for staff"

other three employee groups. One staff member proposed that the university "pay staff a salary they can live on. People who work here full time should not have to apply for food stamps and stand in line at the food pantry." Another staff member connected income to health outcomes by recommending that the university "increase staff salaries so we can afford to take care of our physical wellbeing." With inflation and the increasing cost of employee contributions to health insurance plans, one staff noted, "The pay is low and people are struggling with no hope of raises or increases. Our benefits keep getting cut and our pay does not go up with the cost of living."

Several staffers expressed the desire for salary increase opportunities as a result of performance evaluations. One staff member called for the University to "Provide meaningful ways for staff to advance…instead of creating an environment where staff must fight with their institution to qualify their value. It's demeaning, especially as administrators get annual and automatic raises."

Staff also wanted an improvement of the existing promotion process. One staff member argued for the University to "add step increases to the salary scale. It makes no sense to force an employee to move from position to position to earn more money. That discourages an employee who is very good at their job to leave, which does NOT benefit the employee, their coworkers or the STUDENTS." Another staff member wrote, "Get step raises brought in. I have been here almost 12 years and not had one raise."

A Desire to Feel Respected, Valued, and Acknowledged by Campus Leaders

Survey respondents also expressed a desire to feel a greater degree of respect, value, and acknowledgement from campus leaders. Employees indicated they wanted "more listening from leadership," "respect for the duties performed," "acknowledgment of work well done," "wellbeing check-ins during department meetings," and "ways for an employee to feel valued." One employee specifically wanted their manager to "stop treating me like a machine that can work 60+ hours week after week in a high stress environment." Another staffer was specific in their justification for not feeling valued by stating, "It's hard to find value in your work when you don't feel valued. When you are passed over for promotions and have to fight tooth and nail for an (in-range progression), while 'new' positions are 'created' out of the blue and the people hired to fill them are paid hundreds of dollars per month more than you after working here for almost 20 years."

Much of the evidence that supports this theme was about more than just being acknowledged verbally. Employees also wanted to be acknowledged in ways that demonstrate tangible value such as reduced workloads, increases in pay, or changes to policy. As an example, one respondent said, "Hey when someone is asked/told to do additional work to fill in because of a vacancy, then compensate them during that time. Let them know they are valued and not used." Another employee desired "feeling valued from the top of the hierarchy, this includes actions, not just words. Please no more words lacking action. It makes me want to scream." Specifically regarding wellness, one employee expressed a need for "having managers that value and ensure work life balance. I feel like a lot of managers say to take care of yourself, but they don't really respect that." In some cases, employees simply wanted compassion from leadership. "We are told to have compassion for students, but sometimes I don't feel that same compassion from admin towards faculty/lecturers", noted one employee.

A Desire for More Wellness Programming

The data indicated that wellness is important to campus employees. As an example, one employee explained, "Healthy people…are happier people, happier people are more productive at work and enjoy (their) jobs and lives more. All of this (wellness) is extremely important to the success of our University." When asked about strategies to enhance wellness, respondents mentioned a desire for various types of wellness programming and access to wellness resources. One respondent suggested that the university "implement (an) employee physical wellbeing program (open gym use, yoga, coaching in exercise and nutrition)."

In many instances, employees expressed a desire to engage in these wellness offerings as part of their workday such as one individual who wanted "availability of wellness opportunities on campus during 9-5 work shift. Build it into our work day so that it isn't one more thing to have to do after work."

In general, employees indicated they wanted access to similar wellness resources that students have access to. As one faculty respondent noted, "Campus resources for staff and faculty that mirror students would be a vast improvement." Another faculty stated, "Current institution focus seems to be only on students' well-being."

As part of a desired wellness program, employees expressed wanting to access the campus gymnasium called the Wildcat Recreation Center (WREC) or another fitness facility in town for free or at a reduced-cost. Presently, the cost of the WREC is approximately \$50/month and thus may be one possible barrier to accessing it. Since the WREC is typically open before and after standard work hours and group exercise classes are offered throughout the day, employees felt that this facility would be an ideal place to be active if it were more accessible. One respondent noted, "At the very least, having a place for faculty and staff to be able to workout or use athletic facilities without having to pay a fee would go a long (way) towards balancing work and healthy habits in the workforce."

In addition to accessing the WREC as part of wellness programming, employees also expressed a desire for mental and emotional wellness policies such as "including a mental health day as a legitimate sick day" and "some onsite counseling for staff." Another element of wellness programming frequently mentioned was a desire for on-campus childcare. One employee articulated, "Childcare on campus would be lovely for staff and faculty. It would transform my ability to do my job more effectively."

Conclusions and Discussion

The two dimensions of wellbeing that employees rated highest in terms of what their organization engages or promotes were Intellectual and Relational. The two dimensions rated lowest were Physical and Spiritual (table 2). Chico State employees rated highly (6 out of 7) that health and wellness is important to them personally. However, employees gave a lower rating (4 out of 7 on average) that Chico State promotes a culture of wellness. This indicates a gap between the degree of wellness that employees value compared to what they perceive is promoted at work.

In recent years, Chico State has implemented numerous wellness initiatives that could potentially close this gap. Chico State has made strides to provide wellness opportunities for employees, covering many of the eight dimensions of wellbeing. On the physical and emotional wellbeing levels, health insurance is available to all full-time employees, which offers wellness programming in addition to providing physical and mental health care. Employees are able to buy memberships to the campus gym. A June wellness month has been instituted which encourages 90-120 minutes/week of wellness woven into the work schedule that also provides one pass per week to the campus gym. Emotional wellbeing is promoted via Employee Assistance Programs and grant funds offering onsite counselors for campus employees. Sitting meditation groups, an on-campus yoga classes, and forest therapy walks are regularly offered to develop physical, emotional, relational and spiritual wellbeing. Financial wellbeing dimensions are covered via recent pay raises, retirement plans and for those who were impacted by the Camp Fire, FEMA and local grants offered aid. Vocational wellbeing offerings have been in the form of trainings to manage workload stress. The study revealed that only 23% of respondents took advantage of these programs, revealing a gap between the availability and utilization of wellness programs. More research is needed to further explore the barriers to accessing wellness programs.

The limitations of the study include several aspects. First, approximately 320 staff, faculty and administrators responded to the survey out of over 2,500 possible meaning that there was roughly a 13% response rate. The poor rate of response could be attributed to the timing of the release of the survey near the end of the Fall semester. Typically, this is a busy time of the academic year when grades are submitted, then followed immediately by winter break. Second, the survey instrument consisted of 44 items which, combined with poor timing of the release of the survey, likely contributed to an incompletion rate that grew larger the further the respondents went into the survey. Specific questionnaires were used instead of previously validated questionnaires. Finally, the Chico State community had been heavily stressed by a string of incidents which when experienced in isolation may be perceived quite differently than when those same incidents occur within an abbreviated time frame. While all survey respondents may not have been directly impacted by the tragedies, the indirect impact of these events was felt by the entire campus community.

As noted earlier, the University administration was responsive to the traumatic events by offering support and resources. In 2022, the administration instituted June Wellness month. But as with many organizations, there is a need for an ongoing, comprehensive wellness program to support overall employee wellbeing. This study sets the necessary groundwork for the University to accomplish the Johns Hopkins (2015) and the CDC (2017) recommendations, as the findings identified areas to improve overall wellness.

Specific areas of concern that emerged from the survey included a need for increased healthy lifestyle behaviors, balanced workload, and a desire for a sense of value within the institution. Also of note was the high levels of stress identified among administrators. Resources for health behaviors are available but could be better utilized. The on-campus resources available to employees, such as the WREC and counseling services, could be better promoted. Partnerships with off-campus resources could also be developed, including options for discounted childcare. Collaboration with the University health insurance company might provide opportunities for a comprehensive evidence-based wellness program which could include a funded Wellness Coordinator position. Other practices could include prompt hiring to fill vacant positions, opportunities for faculty and staff recognition, and building a culture of wellness on campus where each department builds wellness routines into each workday.

A natural next step for future research would be implementing and evaluating different wellness programming that would further promote the holistic wellness of employees in a university setting. Of the few studies available on workplace wellness interventions in higher education, many have reported encouraging results. For example, Radler et al. (2012) examined quality of life and clinical measurements after implementing a workplace wellness program for university employees. After 26 weeks, participants showed significant reductions in weight, waist circumference, blood pressure, fasting glucose, and days with anxiety. Participants also showed a significant increase in vitality days. More recently, an educational wellness intervention at East Carolina University was conducted that resulted in modest increases in physical, emotional, social, occupational, spiritual, environmental, and intellectual dimensions of wellness (Das, et al., 2019).

These studies demonstrate that improving workplace wellness in a university setting is possible. The University of California (UC) implemented one of the largest wellness interventions in higher education in 2017. The "Systemwide Well-Being Initiative" was implemented shortly after the

University of California System Campus Climate Project Final Report was published in 2014. Some of the data in the final report indicated a positive climate, however, 38% of staff and 39% of faculty indicated that they had seriously considered leaving the campus in the past year (UC Systemwide Final Report, 2014). The mission of the wellbeing initiative that began soon after publishing the climate report is to improve the collective emotional, financial, nutritional, and physical wellbeing of faculty and staff across the system of universities (University of California, 2019).

The results of the UC climate report are similar to the most recent climate report at Chico State, where 34% of staff and 44% of faculty indicated that they were either very likely or somewhat likely to leave Chico State in the next three years (California State University, Chico, 2023b). With over one-third of employees indicating a likely departure from the institution soon, it is imperative that holistic wellness in the workplace be considered as part of the organizational culture. University employees who stay at the university and have a high quality of life are necessary to serve students and carry out the mission of the institution. The findings of this study, and outcomes of any programs implemented, could not only positively impact the Chico State community, but could inform other university campuses as well.

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