Chapter

The Impacts of Climate Change and Wetland Restoration on the Water Balance Components of the Coastal Wetland

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Abstract

The coastal wetlands represent the critical interface between the terrestrial and ocean zones, which have gained vital importance in terms of economic and environmental aspects. Land cover change (LU) and climate change (CC) are considered the determinant factors for the changes in nutrient fluxes, thermal energy, and water balance components (WBCs). These factors are also expected to affect each other through interaction process effects. An essential tool that may be used to evaluate the sustainability and availability of water resources for food security and the ecological health of coastal zones is a hydrological modeling technique. The Heeia coastal wetlands in Hawaii, USA, are used as a case study in this study to evaluate the effects of LU and CC on WBCs.

Keywords: climate change, wetland restoration, SWAT model, water balance, coastal wetland

1. Introduction

Wetlands represent the natural kidney of the coastal environment and the supermarket of unique assemblages of flora and fauna. Wetlands have natural functionalities, which are qualified to be good habitats for birds, aquatic life, plants, and diverse organisms. Therefore, many researchers and policymakers have recently focused on preserving and protecting the wetlands in different regions of the world. For instance, the recent moral and financial support of federal wetlands preservation rules, including "no net loss of wetlands in the United States," has prompted numerous nonprofit organizations to repair the degraded wetlands [1]. In that sense, with assistance from the neighborhood and funding from US environmental protection organizations, the non-profit Hawaii-based organization Kakoo Oiwi has committed to restoring the Heeia coastal wetland (HCW), which is located on the Island of Oahu, Hawaii [2]. Globally, coastal wetlands play an important role against the impacts of climate change (CC), particularly in the coastal zones of pacific Islands such as Hawaii. Hawaiian coastal wetlands provide myriad other benefits associated with protecting coastal communities against storm surges, floods, sea level rise, and CC threats, as well as ecosystem services [3, 4]. Coastal wetlands store and decrease greenhouse emissions through carbon sequestration processes approximately 50% of all carbon is buried in global ocean sediments [5, 6]. As a result, in this chapter, the HCW was used as a case study to demonstrate the importance of wetlands in terms of their vital role in preserving the health environment of coastal regions of the Pacific Islands and mitigating the impacts of CC.

2. Economic and environmental importance

In the Hawaiian Islands, coastal wetlands serve as an important interface between the terrestrial and oceanic zones and are now important for both the ecology and the economy. Coastal wetlands naturally clean water by filtering out sediments and pollutants, converting nutrients, slowing the flow of freshwater from the mountains to the ocean, creating optimal habitats for assemblages of flora and animals, and reducing air temperature during the summer, decreasing greenhouse emissions through carbon sequestration processes, increasing oxygen emission through photosynthesis processes by phytoplankton, kelp, and algal plankton that live in coastal wetland and shoreline of Pacific ocean [7]. Furthermore, the coastal wetlands of Hawaii are regarded as very attractive and productive regions for both tourists and residents [1, 8].

These areas protect Hawaii from flooding, pollution, and the detrimental effects of climatic and land cover changes (LCs). They also operate as sponges, soaking up water during the rainy season and releasing it during the dry season [9, 10]. Many organizations, including scientific research facilities, were forced to take a more proactive approach to preserving and restoring the natural resources of the coastal wetland due to the dynamic nature of these ecosystems. Additionally, the current moral and monetary support for government legislation preserving protected wetlands, such as "no net loss of wetlands in the United States," motivates many non-profit groups to restore the degraded wetlands, such as HCW on Oahu Island [11].

Heeia means “washed way”, which is the famous name of Ahupuaʻa, watershed, stream, and fishpond [12]. In the past, the watershed’s hydrologic features enabled the indigenous society to meet their food and resource needs from land and sea in a prized coastal region [13]. The Heeia region holds much cultural and historical importance for the people of the Heeia community. The HCW is the southern edge of the Heeia watershed, which was regarded as one of Oahu's most productive coastal areas because of taro and rice farming. Moreover, the Heeia stream estuary, which is located in the area, is thought to be a significant economic resource because it is home to Oahu's largest fishpond. The Heeia watershed (**Figure 1**), which makes up roughly half of the coastal plain, is a steep, mountainous, and narrow valley that eventually converts into a flat marsh zone [8, 14]. Despite its economic and environmental significance, it faces numerous issues related to LC and CC, saltwater intrusion, flooding, the spread of invasive plants, deterioration of the coastal nearshore zone, habitat destruction, and sea level rise (**Figures 1** and **2**) [3–15].

Because of the boundary interaction between the largest federally protected wetland on the island of Oahu, the largest fishpond, and the largest sheltered coral

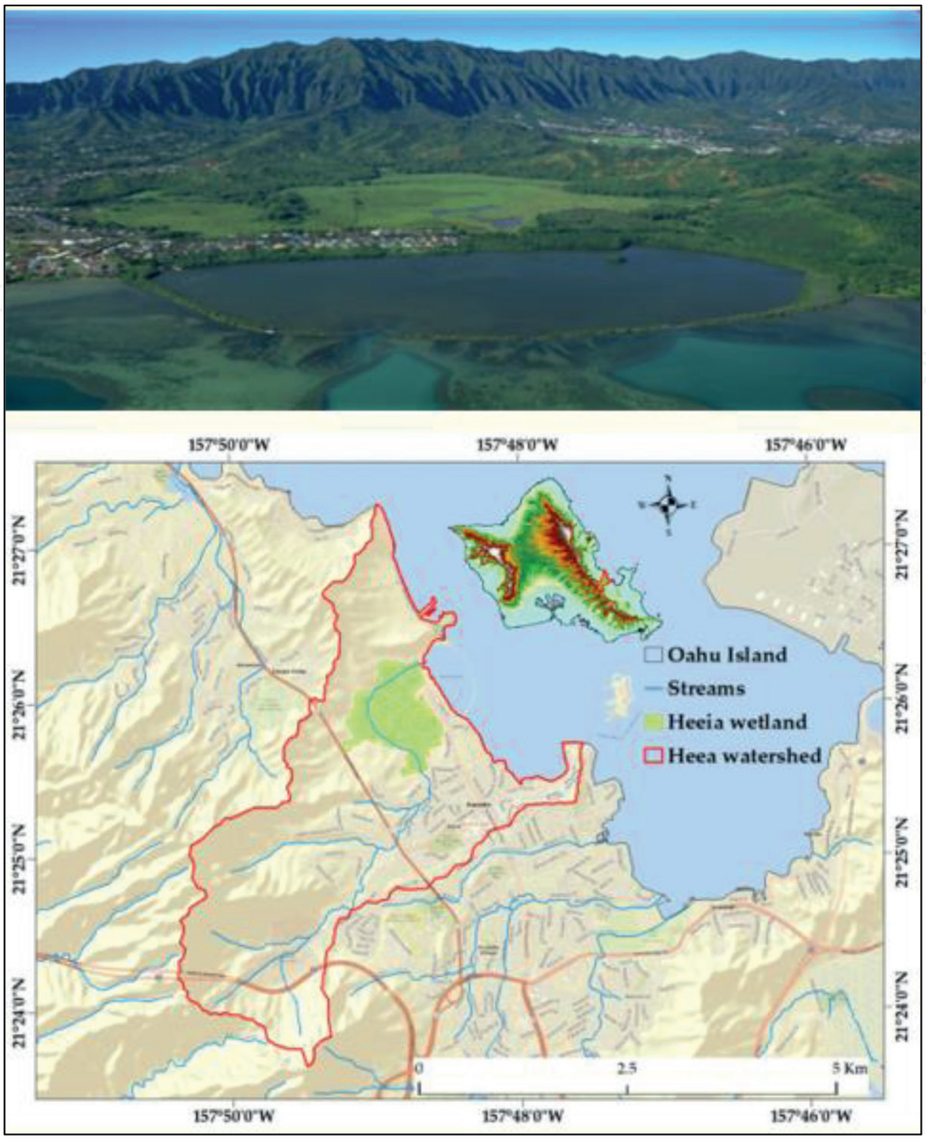


Figure 1.
The landscape view, geographic, and topographic maps of the HCW.

reef system in Kaneohe Bay, the Heeia coastal zone in Hawaii is a typical example of groundwater-dependent ecosystems [16, 17]. In order to protect native ecosystems and marine biodiversity, it is essential to comprehend the processes that take place along the boundary between terrestrial and marine environments [18].

Freshwater flows are critical to the preservation of native adjacent ecosystems. For instance, the availability of nutrients and light influences the growth of diverse groups of plankton in water bodies such as the ocean, lakes, and wetlands. The importance of plankton is obvious because it provides a vital source of food for large aquatic organisms while also reducing greenhouse gas emissions in the coastal zone [7]. Assessing the freshwater discharge and associated nutrient fluxes into the ocean by streams, rivers, and fresh submarine groundwater discharge (FSGD) has piqued the interest of researchers, managers, and policymakers, particularly those concerned with coastal environmental health. [19, 20]. Therefore, to fully comprehend the relationships between coastal hydrological processes and ecosystems, it is necessary to quantify the volumetric freshwater discharge through surface runoff and FSGD in coastal zones.

Figure 2.
The main challenges face HCWs.

3. Wetland restoration

The HCW is a representative example of the Hawaiian wetlands that have been deteriorated and where wetland restoration has been planned [21]. Prior to the 1950s, it was thought to be Oahu Island's most productive environment for both marine and terrestrial food resources [22]. After the 1950s, the Heeia wetland lost the majority of its excellent ecological functions as a result of the invasive California grass (*Urochla mutica*). The degraded marsh cannot be significantly restored using the passive restoration technique (i.e., restoration based on nature's work) unless physical human interventions are directly used in restoration to manage various processes. [23]. As a result, human involvement in the restoration of the coastal wetland is crucial for the HCW. In the recently proposed Heeia wetland restoration plan, about 69 hectares of wetland covered in California grass (**Figure 3**) will be converted into organic wetland taro (*Colocasia esculenta*), and eight hectares of wetland mangrove forest will be transformed into wetland sedges papyrus, which will act as a convenient habitat for native birds and a nursery site for young fish [11]. The ecological functioning of a coastal wetland can be improved by wetland restoration initiatives, but the site's hydrologic cycle components may also be significantly impacted. For instance, the wetland evaporates water more quickly than other types of land, reduces air temperature through the evaporation process, traps carbon, maintains stream temperature (by shading, storing, and releasing cool water during dry season), and controls stream flows by acting as a sponge (**Figure 4**) (absorbing water during the wet season and releasing it during the dry season) [25]. Such studies are required to aid the HCW restoration process by assessing the effect of restoration on the hydrologic cycle components. The water balance components (WBCs) of HCW were assessed under current and future LC conditions in this study. The HCW restoration plan was utilized to

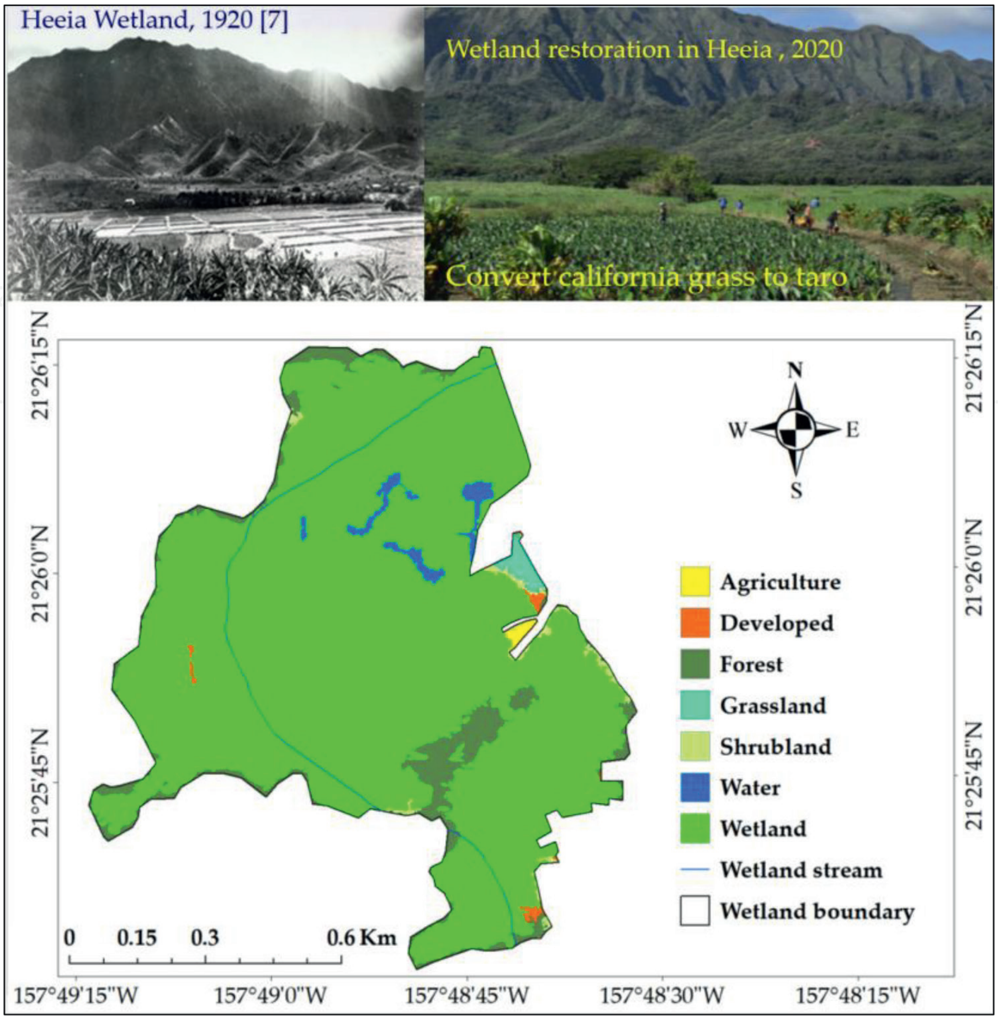


Figure 3.
The pre-development (top, left) and current land use (top, right, and bottom) maps of the Heeia wetland.

develop the future LC [11]. In addition, the study investigated the LC impacts on the spatial and temporal variability of the hydrologic processes within the coastal wetland and its relationship with the hydrologic processes in the highly elevated land of the Heeia watershed [26]. Such studies need a tool to assess the WBCs of HCW.

The Soil and Water Assessment Tool (SWAT) model is a helpful resource for evaluating the WBCs under the conditions of both current and future land use [27]. The SWAT model is suitable for the research area because it is a dynamically processed model, able to adjust the input data of land use and climatic projections over time to predict the future effects of wetland restoration on the WBCs [28]. Additionally, it is computationally efficient to operate at various sizes and appropriate to simulate the consequences of management changes over extended time periods. The model has enormous promise for simulating and analyzing the impact of changing land cover on WBCs [29].

4. The water balance after restoration

Approximately 8% of the Heeia watershed is planned to be converted to taro fields and impoundments. Based on the land use map, the impacts of this change on water

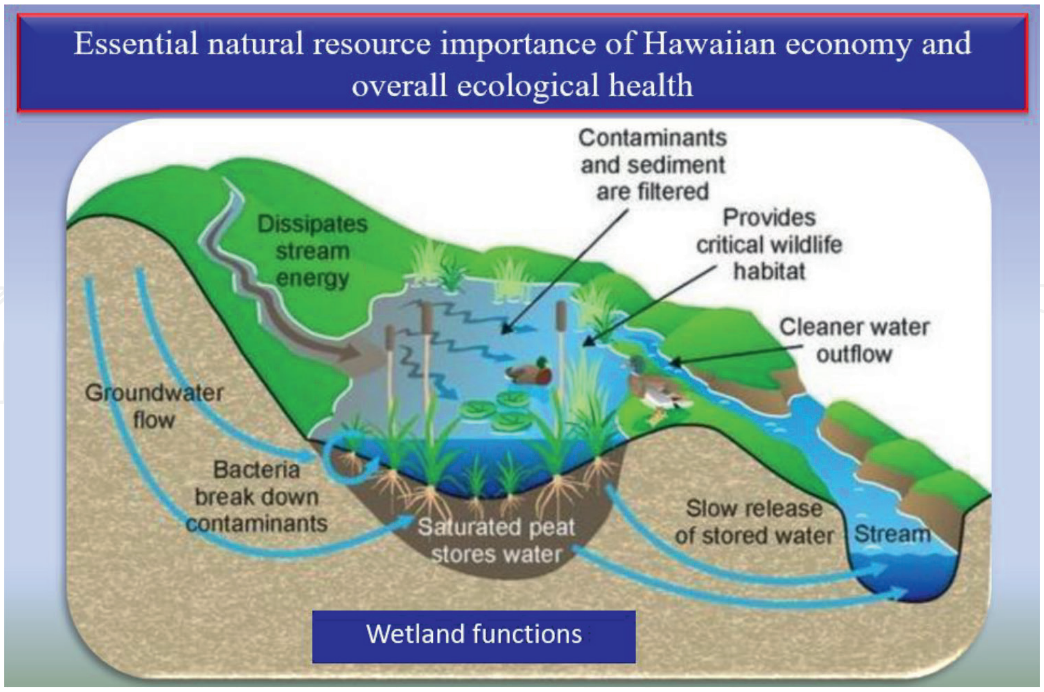


Figure 4.
The hydrological aspects and wetland functions of HCWs [24].

balance were evaluated at three spatial scales of the SWAT model, which included the hydrologic response units (HRUs), subbasins, and watersheds [2]. Within the eight subbasins of the SWAT model in the coastal plain, taro cultivation and a pond were created from the coastal wetland. The anticipated negative effects of changed land cover were depicted in **Figure 5**. Based on the graph, it was anticipated that the restoration would affect the WBCs' yearly average (2002–2014). To maintain ponding water in taro patches, the recharge will be reduced due to soil layer compaction under the taro patches. However, due to lateral seepage from the taro patches, the neighboring areas of the taro patches would receive more recharge [30].

The other elements of the water balance may be affected, and there may be an increase in evaporation from the ponding water area since evapotranspiration (ET) was predicted to grow [4]. Also, as can be predicted, the conversion of an existing wetland (California grass) to taro agriculture would result in a reduction in the site's overall stream flow since stream water would be diverted for taro field irrigation and more pond water would evaporate. A modest percentage change in the restored land cover area relative to the overall watershed area, however, can be blamed for the relatively negligible change in WBCs at the watershed scale. The management of water ponds and taro farming are likely to be to blame for the predicted 41% decline in recharge at the wetland scale under all irrigation diversion scenarios. In comparison, in scenario 4, if 90% of the lowest stream flow was diverted from the main channel, the lateral flow and surface runoff would increase by around 76% and 61%, respectively. While a baseflow reduction of up to 23% is forecast for scenario 4, a substantial increase in surface runoff and lateral flow was predicted to result in a stream flow gain of 13%. Also, it was shown that most WBCs were affected more by the wet season than by the dry season (**Table 1**).

Finally, despite the lack of hydrologic data, the SWAT model accurately captured the temporal variability of the observed daily streamflow hydrographs, exhibiting acceptable performance and satisfactory statistical assessment values. The results

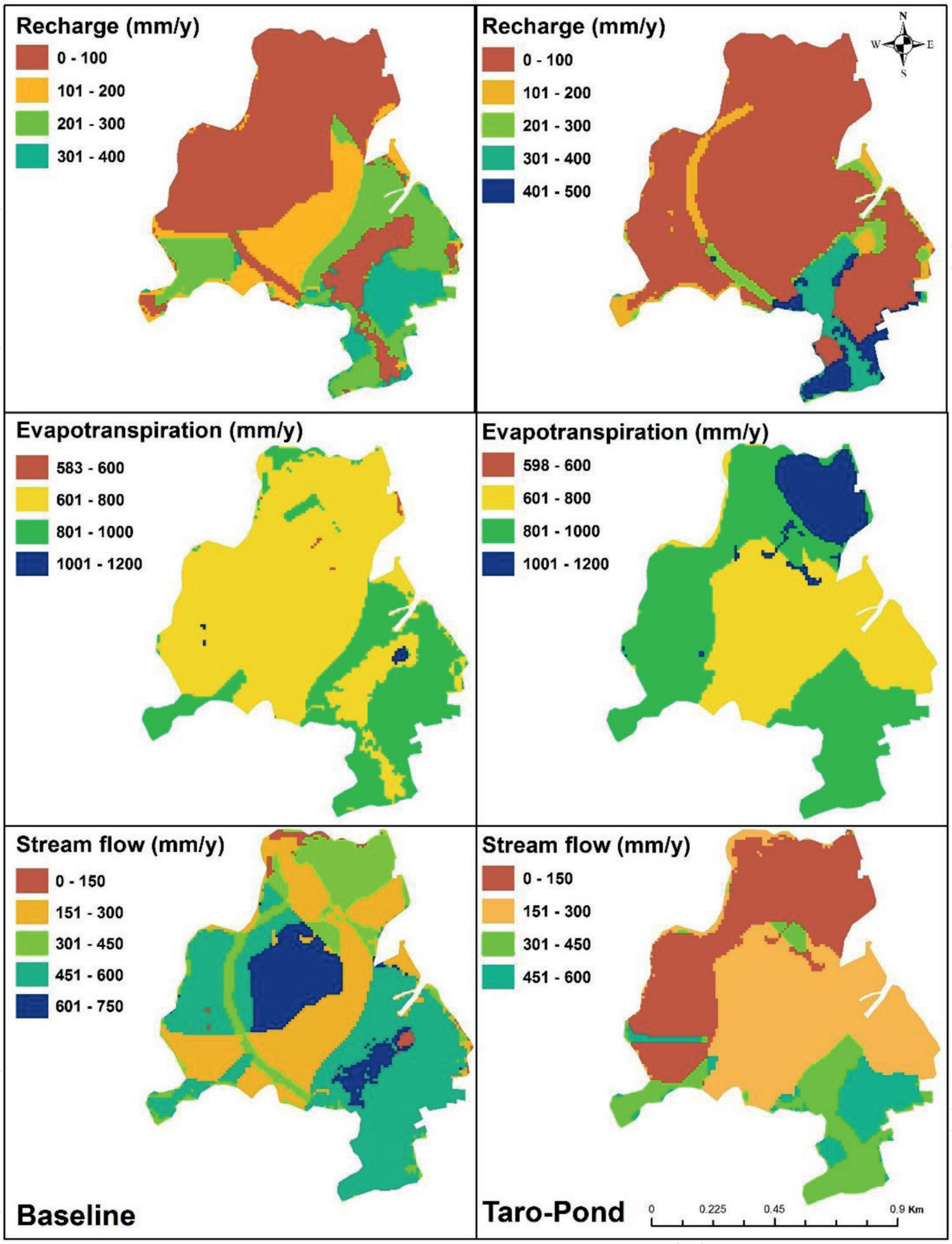


Figure 5.
Yearly average WBCs map of HRUs within the Heeia Wetland [2].

showed that 34% of the watershed's annual rainfall (2043 mm) recharged groundwater (699 mm), 15% of it went to lateral flow (307 mm), 6% of it went to runoff (119 mm), and 45% of it was due to actual evapotranspiration (AET) (917 mm). In addition, 87% of the yearly water supply was contributed by baseflow and lateral flow. In comparison to surface runoff, the baseflow was discovered to be the primary factor in the water yield, as shown in the SWAT output graph (**Figure 6**).

For the wetland area, the HCW restoration plan's effects on WBCs are anticipated to be significant. Furthermore, the restoration strategy is expected to improve lateral flow and surface runoff values while decreasing recharge and baseflow values.

Scale	Scenario	Rainfall	Streamflow	Runoff	LF	BF	Recharge	Soil Moisture	ET	PET
Wetland	Baseline	1065	292	39	91	130	140	115	791	1533
	Irrigation-S1	1065	313	62	137	76	82	144	792	1534
	Irrigation-S2	1065	313	62	137	76	82	144	792	1534
	Irrigation-S3	1065	314	63	138	76	82	144	793	1534
	Irrigation-S4	1065	329	69	147	76	82	147	796	1534
Watershed	Baseline	2043	904	119	306	459	699	171	916	1412
	Irrigation-S1	2043	923	125	331	447	687	176	898	1412
	Irrigation-S2	2043	923	125	331	447	687	176	898	1412
	Irrigation-S3	2043	924	125	331	447	687	176	898	1412
	Irrigation-S4	2043	932	129	336	447	687	177	900	1412

Note: S1 = Scenario one (initial minimum streamflow); S2 = Scenario two (decrease 50% of minimum streamflow); S3 = Scenario three (decrease 75% of minimum streamflow); S4 = Scenario four (decrease 90% of minimum streamflow).
LF = lateral flow; BF = baseflow; ET = evapotranspiration; PET = potential evapotranspiration (except rainfall, all are SWAT outputs).

Table 1.
The percent changes in the seasonal water balance components (WBCs) relative to the baseline for the Heeia Wetland and Watershed.

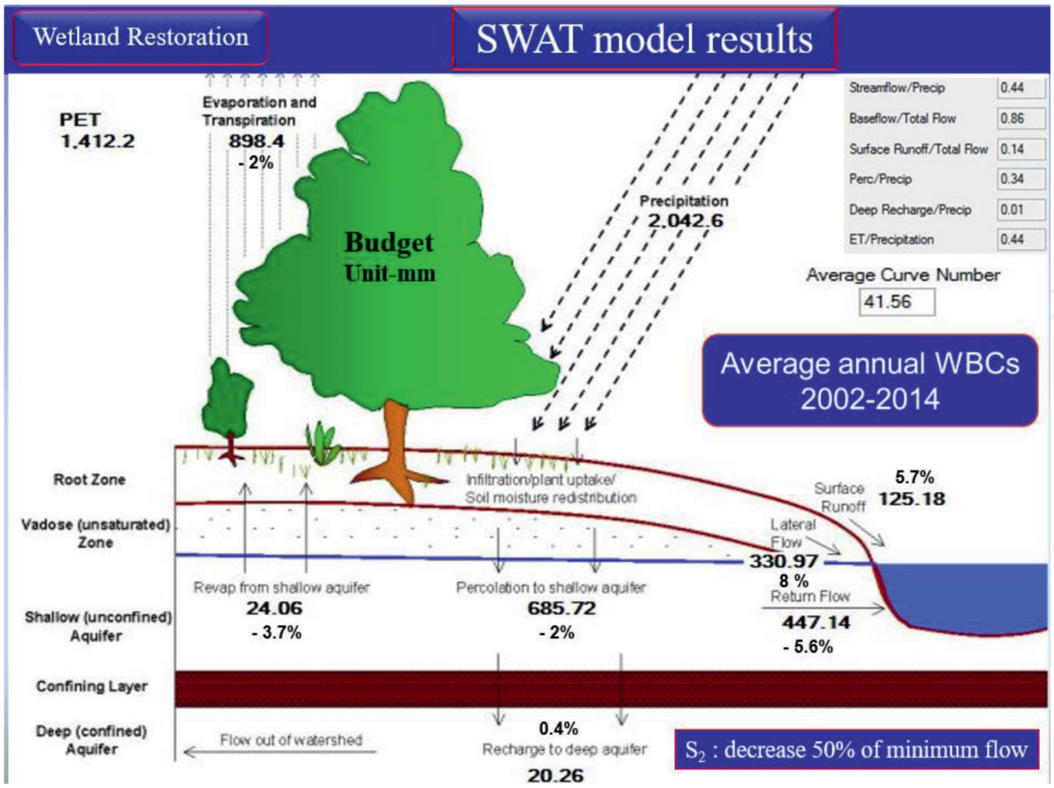
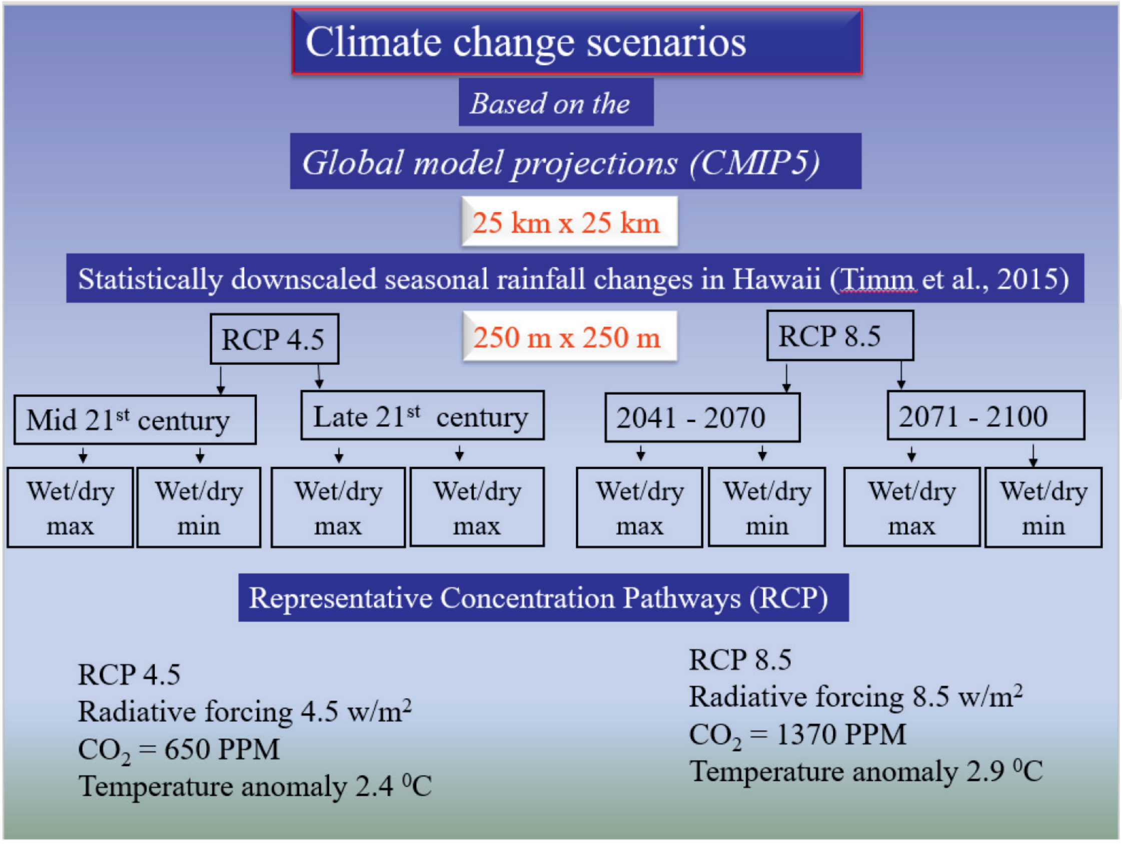


Figure 6.
The WBCs of the Heeia watershed after wetland restoration according to SWAT model outputs [2].

In order to determine the best course of action for achieving sustainable growth of the taro crop without jeopardizing the streamflow values in the main channel and at the downstream fishponds, which are crucial to the downstream coastal ecology of the study area, various irrigation water diversion scenarios were completed to taro fields. According to the results of the study [4], an optimum management strategy for the restoration of the wetland and coastal coastline in the study region is possible by maintaining streamflow and providing the water requirements of the taro patches.

5. The impacts of climate change on water balance components

Both the RCP 4.5 and RCP 8.5 scenarios were evaluated for the relative sensitivity of WBCs to the baseline in terms of percent change for the yearly WBCs due to the combined effects of rainfall, temperature, and solar radiation factors (**Figure** 7). With the exception of PET, both the RCP 4.5 and RCP 8.5 scenarios anticipate a decline in the annual average of WBCs relative to the baseline. The increase in temperature and solar radiation throughout the dry season is anticipated to result in a continuous rise in the relative percent change of PET. The AET did, however, fall short of the baseline value, most likely as a result of a decline in rainfall that constrained the availability of soil moisture. Rainfall was therefore identified as the determining element [31, 32]. The effect of rainfall at the coastal region change would be more pronounced at the coastal region, compared to the upstream regions. Because of the fluctuating rainfall, temperature, and solar radiation under both scenarios (RCP4.5 and 8.5) of CC, the results using monthly time steps showed that the dry season generated a more severe relative negative shift in the WBCs than the rainy



RCP 4.5
Radiative forcing 4.5 w/m²
CO_2 = 650 PPM
Temperature anomaly 2.4 °C

RCP 8.5
Radiative forcing 8.5 w/m²
CO_2 = 1370 PPM
Temperature anomaly 2.9 °C

Figure 7.
The CC scenarios of Hawaii Islands [4].

season [4]. The relative negative change in WBCs was larger in the coastal wetland than further upland in the watershed due to the variance in climatic conditions at both the geographical and temporal scales [33]. Moreover, RCP 8.5 had a greater relative negative change in the dry season than RCP 4.5, particularly for the late (2080s) period as compared to the middle (2050s) period. Due to climatic parameter variation, these adverse effects were more obvious for the seasonal changes in recharge, surface runoff, lateral flow, and rainfall, especially at the wetland scale as compared to the entire watershed scale [32, 34, 35]. Due to the low value of recharge within the wetland, there was a large value of relative change in recharge compared to other components. The results showed that streamflow dropped, especially during the late 2080s of RCP 8.5 (**Figures 8** and **9**). In addition, the CC is expected to cause decrease in the streamflow, baseflow, and groundwater recharge for the whole watershed (**Figure 10**). This could be due to a consistent decrease in rainfall for both wet and dry seasons.

6. Conclusion

The HCW restoration is significantly influenced by the hydrological processes of the whole watershed. In order to prioritize the actions of the coastal wetland restoration, it is important to examine the hydrological processes at the watershed scale and comprehend their influences on the coastal wetland. Additionally, it is believed that managing the water resources of coastal wetlands is the key to maximizing

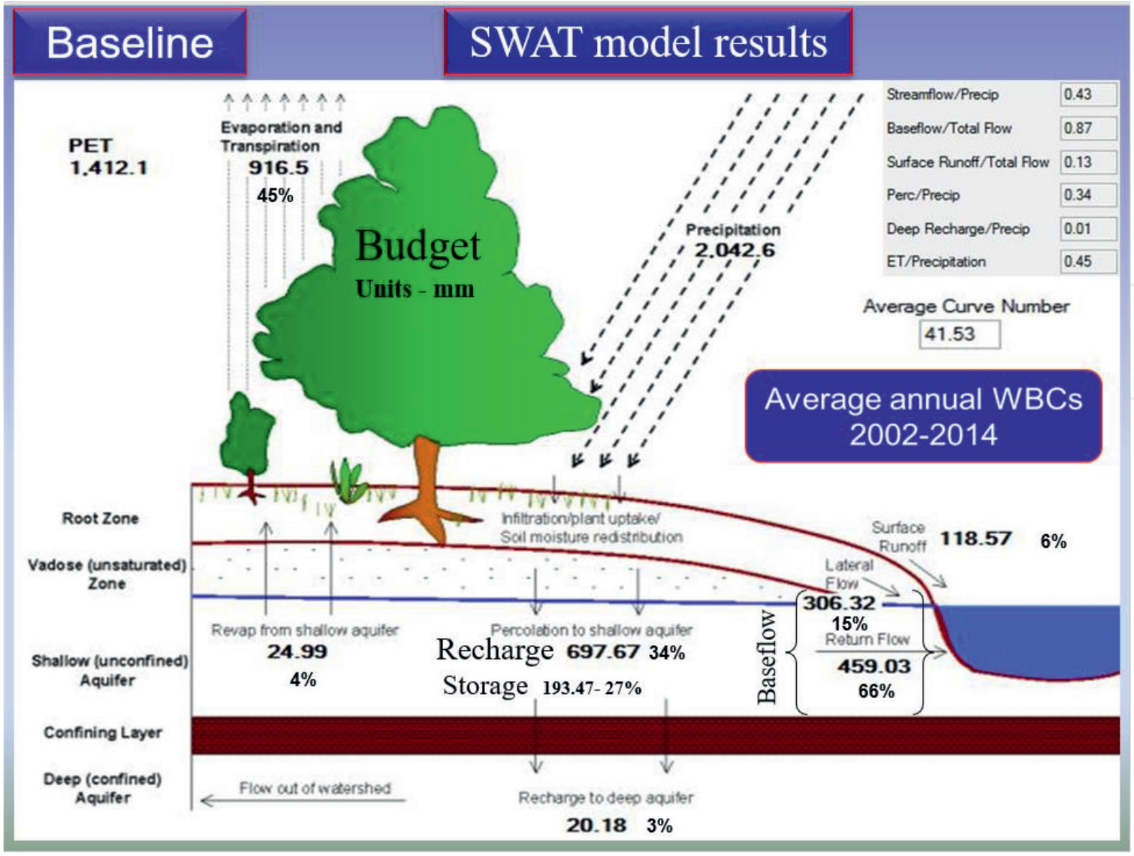


Figure 8.
The baseline of WBCs of Heeia watershed [4].

the sustainability of the coastal ecosystems. Tools that can assist in evaluating the coastal water resources are required for such an approach. Hydrological models were the tools utilized to evaluate the management of the water resources in the Heeia coastal zone.

The coastal wetland restoration would be expected to be impacted by the WBCs. When compared to the baseline, the ET is expected to rise, potentially reducing the other WBCs and increasing the ponding water area. Reduced baseflow would lead to a decrease in stream flow overall as a result of the conversion of an existing wetland (California grass) to taro agriculture. When water diversion was adjusted to 50%, 75%, and 90% of the minimum streamflow, the effects of applied irrigation diversions were roughly 23, 109, 437, and 3886 mm/y, relative to the baseline (no-irrigation), after the restoration of taro farming and the construction of ponds. The minor percent change in California grassland area relative to the Watershed's area may be the cause of the generally negligible change in WBCs at the Watershed scale. The WBCs at the wetland scale, however, were considerably impacted by this land cover shift. In contrast to ET, surface runoff, and lateral flow, for instance, recharge is projected to increase.

The combined effects of wetland restoration and CC may have a substantial impact on the WBCs of Heeia Wetland. The variance in rainfall over both space and time was the main contributor to the adverse effect on WBCs. The components that were most vulnerable to the combined effects of land cover and climatic changes, particularly during the dry season, were recharge and baseflow. The WBCs were generally more impacted in the late 2080s than in the 2050s timeframe.

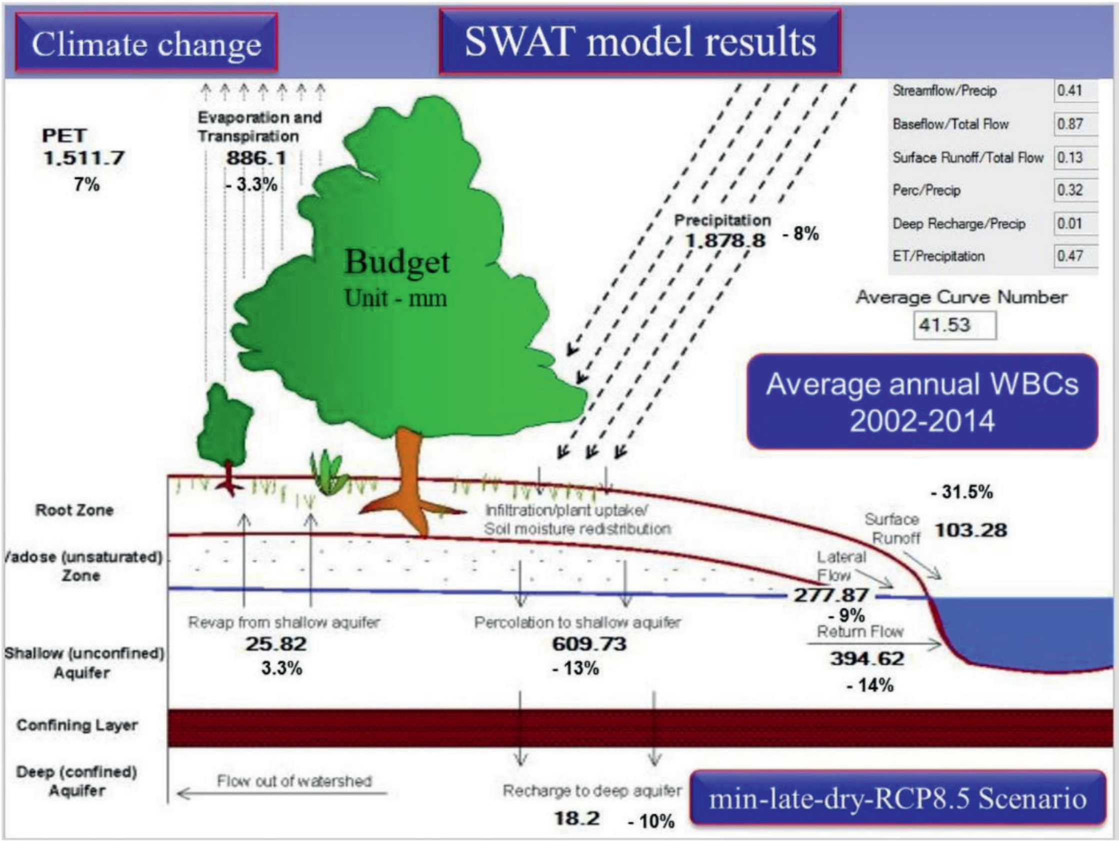


Figure 9.
The CC impacts on WBCs of Heeia watershed [4].

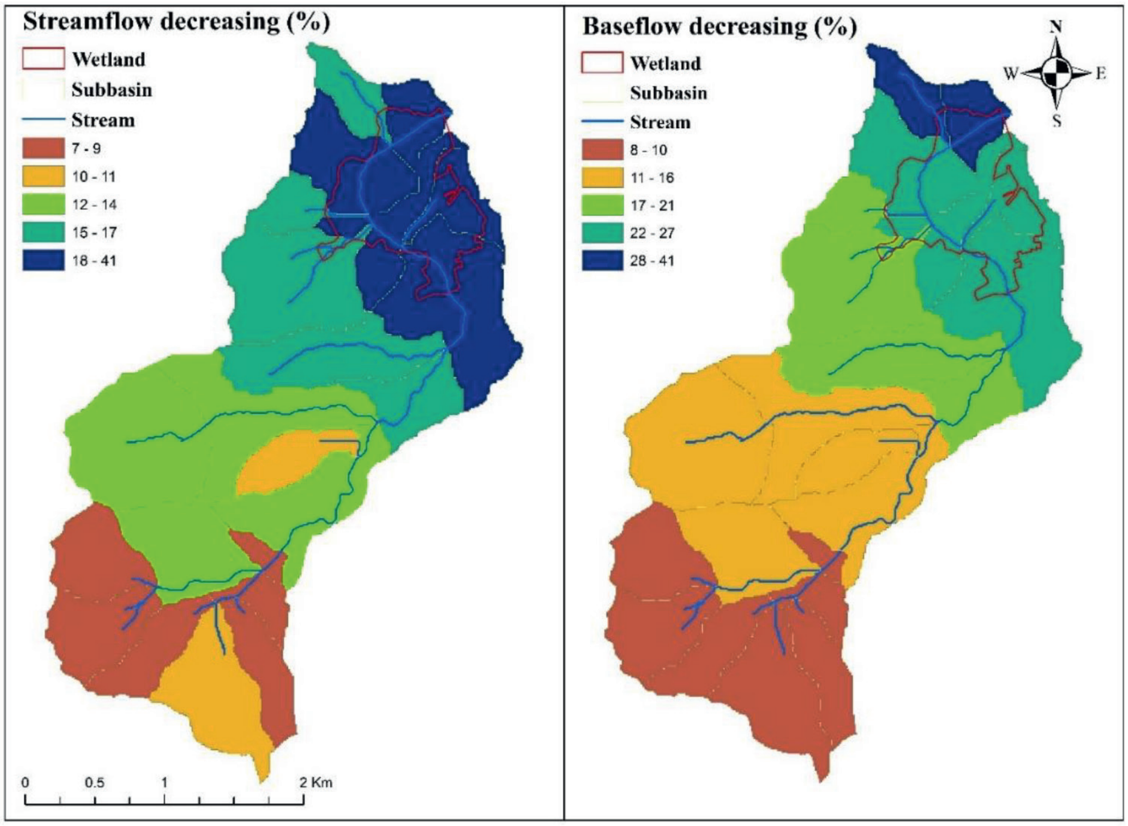


Figure 10.
The yearly average percent change in the WBCs of the Heeia watershed due to CC relative to the baseline [4].

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Conflict of interest

The author declares no conflict of interest.

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