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A participatory approach to assessing groundwater recharge under future climate and land-cover scenarios, Tutuila, American Samoa

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ABSTRACT

Study region: Oceania, South Pacific, Polynesia.
Study Focus: Changing climates have the potential to significantly impact global water resources availability. On many volcanic islands, groundwater is the primary drinking water source, thereby making it essential to manage this limited resource carefully. In this study, we developed high temporal and spatial resolution groundwater recharge estimates for the Island of Tutuila, American Samoa using the Soil Water-Balance-2 (SWB2) model. Additionally, we predicted future recharge by running the calibrated model with combinations of dynamically downscaled general circulation climate model (GCM) predictions, and future land-cover scenarios developed collectively with local stakeholder groups.
New hydrological insights: Present-day results indicate 57 % of Tutuila's rainfall becomes groundwater recharge, 8 % evaporates from the canopy, 15 % evapotranspires, and 20 % discharges as stormflow-runoff. Future climate scenarios suggest recharge may increase by 8 % or 14 % depending on global emissions. Land-cover was a less significant driver of hydrologic change, although increases in impervious surfaces showed a negative impact on recharge. This work is maintained as an active open-source project on GitHub, the world's leading software development platform, thereby enhancing transparency, reproducibility, and participation from stakeholders and managers in American Samoa. This study is the first of its kind from a location within the South Pacific Convergence Zone, and provides insights into how human activities on global and local levels affect the future sustainability of essential resources.

1. Introduction

Groundwater is the primary source of drinking water on most volcanic islands, and Tutuila, the main island in the U.S. Territory of American Samoa, is no exception (e.g. Peterson, 1972; Izuka et al., 2007; Join et al., 2016). In these isolated locations, the importance of limited water resources necessitates their careful management. Because drinking water availability is fundamentally controlled by groundwater recharge in these settings, accurate recharge estimates are essential for developing well-informed water resources management strategies (e.g. Falkland and Brunel, 1993; Gingerich and Oki, 2000; Xu and Singh, 2004). In a changing world, sustainable resource management must also consider drivers of future resource availability, such as changes in climate and land-cover. American Samoa has already begun to measurably experience effects of climate change; the number of days above 32 °C has increased

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by over 240 % since the 1960's and the frequency of extreme rainfall events has increased and is projected to increase even more in years to come (Menne et al., 2012; Keener et al., 2018). In addition to climatic drivers, changes in land-cover resulting from American Samoa's continued economic development could also influence groundwater recharge rates.

In American Samoa, a remote island archipelago in the South Pacific, groundwater meets the domestic needs of over 90 % of the island's residents (Shuler and Eyre, 2018). However, this supply is subject to numerous stressors including saltwater intrusion from over-pumping, high losses caused by leaky water mains, and surface water contamination in the island's highest producing aquifers (Izuka, 1999; ASEPA, 2014; Shuler et al., 2019). Therefore, water managers critically need the best available information to make proactive, rather than reactive, planning decisions. Unfortunately, accurate assessment of groundwater availability is often limited by uncertainty or poor discretization in recharge because this parameter is difficult if not impossible to directly measure (Scanlon et al., 2002). This makes detailed quantification and spatial mapping of inputs to and outputs from the groundwater system essential for informed water management and guiding planning and policy into the future.

Common approaches for quantifying groundwater recharge include analytical-regression equations (e.g. Shade and Nichols, 1996), surface water models (e.g. Arnold et al., 1998), coupled saturated-unsaturated zone models (e.g. Brunner and Simmons, 2012), and water budget models, such as the soil water balance (SWB) method, amongst others (e.g. Westenbroek et al., 2010). For regional scale groundwater management studies, the SWB method is generally considered to be reliable due to its versatility across a wide range of spatial and temporal scales, and the method has been widely used to assess future water availability through climate scenarios and assessment of change in other water budget drivers (Scanlon et al., 2002; Xu and Singh, 2004; Healy, 2010; Brewington et al., 2019). The SWB method integrates long-term climate records with geospatial data and is particularly effective for modeling tropical islands with high-spatial and temporal variability in precipitation and other hydrologic processes (e.g. Mair et al., 2013; Engott et al., 2017; Westenbroek et al., 2018).

A significant challenge for predicting future climate impacts on small scale features, such as high oceanic islands, is the fact that global scale general circulation models (GCMs) are not resolved enough to represent the climate patterns and steep orographic rainfall gradients that drive island-scale climate variability (Schroeder, 1993; Daly et al., 2006). For example, over a distance of 4 km between Tutuila's highest point and Pago Pago Airport, annual rainfall more than doubles from 275 cm to 575 cm. In comparison, most GCMs have cell size resolutions on the order of 50–100 km, a distance that exceeds the diameter of most basaltic islands (Timm and Diaz, 2009). Therefore, to be useful in these settings, climate predictions must be downscaled using dynamical or statistical methods to more accurately represent the significant climatic variability of high-basaltic islands (e.g. Elison Timm et al., 2015; Zhang et al., 2016; Wang and Zhang, 2016). Until recently, no downscaled climate models have been available for the Samoan region. However, Wang and Zhang (2016) produced the first high-resolution dynamically downscaled climate products for American Samoa, which now provide the opportunity to assess the effects of future climate on water resources at a highly resolved scale.

Another challenge in modeling future water resources is uncertainty in land-cover change. Humans have dramatically affected the hydrologic cycle through land-cover alteration (Abbott et al., 2019). In Pacific Islands, anthropogenic land-cover change has been linked to disruption of hydrologic processes, such as stream baseflow, cloud water interception, infiltration, soil moisture parameters, and surface water runoff (Loague et al., 1996; Ziegler and Giambelluca, 1998; Kagawa et al., 2009; Takahashi et al., 2011; Perkins et al., 2012; Izuka et al., 2018). Expansion of impervious surfaces associated with human development increases surface runoff, thereby decreasing groundwater recharge and other water budget components (e.g. NHEP, 2007; Chithra et al., 2015). Increasing population and development pressure in American Samoa makes continued landscape change all but inevitable (Crews and Lawson, 2015). However, development patterns are difficult to predict, as they are tied to a multitude of social, environmental, and economic factors (Veldkamp and Lambin, 2001; Han et al., 2015). Therefore, scenario based approaches to modeling land-cover change are commonly used to account for this uncertainty and to create informed products that are reflective of potential management actions (Hulse et al., 2004; Soliva et al., 2008; Kepner et al., 2012; Brewington et al., 2017). To consolidate rich and varied ideas from multiple sets of participants, scenario planning often organizes individual predictions into sets of stories or narratives that are plausible, thought provoking, relevant, and different enough from each other to facilitate meaningful comparison (NPS, 2013). Participatory development of scenarios with relevant stakeholder groups helps to not only produce well informed predictions, but also increases stakeholder engagement and acceptance of the products (Argent and Grayson, 2003).

In this study, we produced the first high-resolution, data-driven assessment of island-wide groundwater recharge on a high-basaltic island within the South Pacific Convergence Zone (SPCZ). Prior to this study, only speculative estimates of groundwater recharge have been available for islands in the South Pacific (Nullet, 1987; Döll and Fiedler, 2008), and these are generally based on global scale climatic parameters, thereby disregarding local scale orographic effects. We developed recharge and water budget estimates for Tutuila Island with the Soil Water-Balance-2 (SWB2) water budget model by incorporating up-to-date, high-resolution input data within a reproducible and open-source modeling framework. By substituting dynamically downscaled, end-of-century climate predictions into the model, we also assessed how projected changes in rainfall and temperature may directly affect the magnitude and spatial distribution of groundwater recharge. In addition, we worked with stakeholders in American Samoa to develop future land-cover narratives based on their understanding of present and future economic and environmental drivers. We then used geospatial land-cover expansion and contraction algorithms to produce a set of possible future land-cover scenario maps representing each narrative. Future climate and land-cover scenarios were combined to produce eleven possible groundwater recharge futures. These scenarios help to frame the likely extreme cases in groundwater recharge by the end of the century. This study is the first of its kind to undertake such a comprehensive approach to modeling water resources availability in the present and future within the South Pacific Region.

1.1. Study area

The Island of Tutuila (Fig. 1), located near 14 °S and 170 °W, is the main population center of American Samoa, and at 142 km^2 is the third largest island in the Samoan Hot-Spot Island Chain. Due to its position within the South Pacific Convergence Zone, the island experiences abundant year-round rainfall, with increased precipitation during the wet season from October to May. Monthly average rainfall in the wet season is roughly twice that of the dry season's still significant rainfall amounts. Rainfall varies considerably with location and elevation and ranges between 175 cm/yr near the Tafuna Airport up to more than 500 cm/yr along the crest of the highest mountains (NWS, 2000; Daly et al., 2006). Strong tropical storms and hurricanes also influence the region about once every other year, and an average of 25–30 significant thunderstorms affect the island annually (Kennedy and Chilton Consulting Engineers, 1987).

Tutuila consists of two distinct regions: (1) the Tafuna-Leone Plain, a highly-permeable rejuvenated-phase lava delta, which due to its low slope contains concentrated human development and (2) the remainder of the island, a mountainous assemblage of Pleistocene age shield volcanoes that generally consist of lower-permeability rock. (Stearns, 1944).

2. Methods

2.1. SWB2 water budget model

To develop spatially and temporally distributed estimates of groundwater recharge we used the U.S. Geological Survey (USGS) SWB2 model, an open-source code based on a modified Thornthwaite and Mather (1955) soil water balance approach (Westenbroek et al., 2010, 2018). The SWB2 model is particularly suitable for sites on tropical basaltic islands such as Tutuila (Westenbroek et al., 2018). The model applies a rectangular gridded approach and uses a daily time-step for soil-moisture processing, though due to input data resolution outputs are limited to monthly or annual time steps. For this project, we implemented our modeling framework with Jupyter Notebooks (Kluyver et al., 2016) for the purpose of making the results and methodology open and as reproducible as possible. All of the model input data, code, and output files are open source (under the GNU General Public License v3.0) and archived permanently on GitHub (Shuler et al., 2020). Users familiar with the Python environment can download and run the model with minimal effort. Major benefits of developing scientific models within the open-source paradigm include enhanced reproducibility and transparency, as well as providing the opportunity for end-users to modify or substitute different input datasets, assess different scenarios, or change the cell size resolution as desired.

2.2. Input datasets

All input datasets were collected from existing publications or documented resources and are described below with references to their sources provided. An expanded version of the methods we used is available in Section 2 of this manuscript's supplementary material.

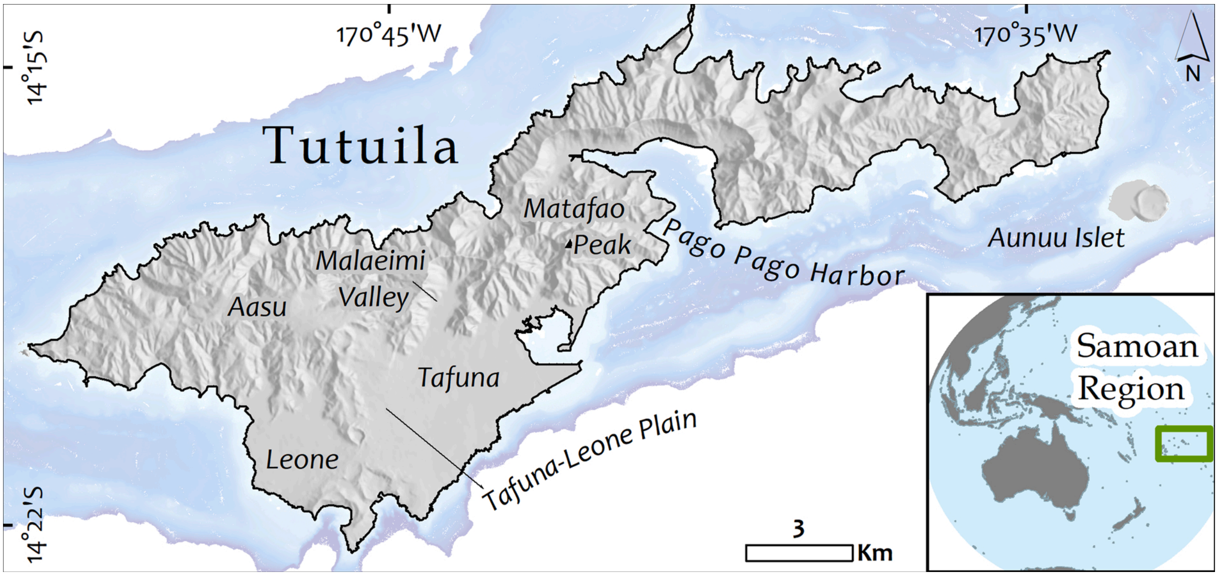

Fig. 1. Map of Tutuila island with landmarks and locations relevant to this study labeled.

2.2.1. *Precipitation*

The SWB2 model requires spatially distributed precipitation data in a gridded format. While the model runs on a daily time-step to account for antecedent soil moisture conditions, daily resolution precipitation datasets are uncommon for isolated oceanic islands. This problem was handled by applying the method of fragments (Oki, 2002; Westenbroek et al., 2018), which disaggregates monthly gridded rainfall data by allocating fractions of monthly precipitation totals into individual days based on observed daily rainfall patterns from rain gauge records. For the present day precipitation, we used 90 m by 90 m gridded monthly rainfall data covering the entire island of Tutuila (Daly et al., 2006). We applied the method of fragments by supplying the model with daily precipitation records from 18 distinct rain gauging stations scattered throughout Tutuila (NWS, 2000; Shuler and Mariner, 2019).

2.2.2. *Evapotranspiration*

We used island-wide monthly resolution potential evapotranspiration (PET) data developed by Izuka et al. (2005) by using the Penman (1948) method. Actual evapotranspiration rates (AET) were calculated by the SWB2 model using the FAO–56 Method (Allen et al., 1998).

2.2.3. *Land-cover and soil types*

Site-specific land-cover parameters were assigned via a high-resolution wildlife habitat map (Meyer et al., 2016) developed using an object-based remote-sensing approach on high-resolution orthoimagery and island-wide LIDAR data. Water budget parameters including rooting zone depth, canopy storage capacity, trunk storage capacity, stem-flow fractions, and curve numbers associated with each land-cover type were parameterized using a tabular lookup table from Westenbroek et al. (2018), which provided equivalent parameters for the island of Maui, Hawaii, as there are no known site specific studies constraining these parameters for American Samoa (Table 1). An island-wide soil study of Tutuila was completed by Nakamura (1984) and includes descriptions of each soil type, predictions of soil behavior, suitability of each soil type for specified uses, and hydrologic soil groupings. We used these data to develop gridded datasets of hydrologic soil groups and soil moisture capacity.

2.2.4. *Direct infiltration*

Anthropogenic activities can significantly affect the spatial distribution of water balance components through irrigation, infrastructure leakage, and wastewater disposal. While no crop irrigation is documented on Tutuila, a large fraction of water in the municipal delivery system is lost to underground water leakage, termed non-revenue water (NRW). We estimated island-wide NRW from American Samoa Power Authority (ASPA) records to be approximately 23 mL d or about 56 % of all water produced from pumping wells on Tutuila (Shuler and Eyre, 2018). No data were available on the distribution of water line leakage, so we included NRW in the model as direct infiltration by equally distributing 23 mL d across all model cells that intersected with water main locations as provided by ASPA. In addition to NWR, direct infiltration from On-Site wastewater Disposal System (OSDS), leachate was also added to the model using data from local stakeholders (AS-DOC, 2009) and methods based on those used by Shuler et al. (2017).

Table 1
Water budget parameters assigned to land-cover types as defined by Meyer et al. (2016) habitat map. Values except for curve numbers (CNs) were assigned based on those used by Westenbroek et al. (2018) to parameterize land-cover classes in the Maui SWB2 model. Values for CNs were parameterized through model calibration and are given here as a range because each of the four soil-hydrologic-groups has an individual CN.

Tutuila Description (Meyer et al., 2016)	Tutuila Land-use Code	Maui Description (Westenbroek et al., 2018)	Rooting depth [in]	Canopy Storage Capacity [in]	Trunk Storage Capacity [in]	Stemflow Fraction	CN Range
Cultivated Land	400	Diversified Agriculture	10	0	0	0	41–63
Agroforest	500	Macadamia	60	0	0	0	37–70
Open Space	700	Developed Open Space	12	0	0	0	31–66
Developed Woodlands	800	Developed Low Intensity	12	0	0	0	46–67
Buildings, Impervious Surfaces	1000	Developed High Intensity	12	0	0	0	68–79
Marsh, Mangroves, Swamp	1200	Wetland	39	0	0	0	78–93
Landslips, Landfills and Quarries	1300	Sparsely Vegetated	5	0	0	0	63–88
Grassland/Herbaceous	1400	Grassland	39	0	0	0	42–90
Upland Scrub, Coastal Scrub	1500	Shrubland	12	0	0	0	43–76
Lowland Rainforest, Coastal Forest	1600	Native Forest	30	0.05	0.01	0.04	32–87
Successional Scrub Vegetation	1700	Alien Forest	60	0.05	0.01	0.04	33–72
Montane Rainforest	2100	Native Forest Fog	30	0.05	0.01	0.04	25–61

2.2.5. *Mountain front recharge*

Infiltration on the Tafuna-Leone Plain is enhanced by the process of Mountain Front Recharge (MFR), where surface waters and overland runoff from watersheds above the plain infiltrate into streambeds or soil once reaching a more permeable geologic substrate. This process is analogous to the MFR frequently observed in arid climates (Wilson and Guan, 2004), and its occurrence on Tutuila has been previously described. For this study, we used the previously constrained information from Izuka et al. (2007) and Perreault (2010) to determine the spatial extent and estimated magnitude of MFR on the Tafuna-Leone Plain.

2.2.6. *Surface runoff*

The SWB2 model provides two options for quantifying surface runoff: the curve number (CN) method (Cronshey, 1986) and an externally supplied runoff-ratio method. With the CN method, SWB2 performs an internal calculation of surface runoff (Woodward et al., 2003). This method relies on supplying the model with CNs, which are typically looked up from published values based on soil type and vegetation cover. Because published CNs exist for most general land-cover and soil types, this method can be applied quickly and broadly. However, published CNs are a generalization and can only approximate actual runoff conditions at field sites, and very few studies have actually developed CNs specifically for volcanic island sites (Cooley and Lane, 1982).

SWB2 also provides the option of using measured runoff to rainfall ratios (R:R ratios) as determined for individual watersheds through analysis of field data. While R:R ratios are based on directly measured field data, this method's limitation is the difficulty and cost of measuring streamflow and precipitation across the entire landscape, which, for Tutuila, would equate to continuously gauging at least 83 perennial streams. For this study, we used data from current and historical gauges (Wong, 1996; USGS, 2018; Shuler and El-Kadi, 2018; Shuler and Mariner, 2019) to calculate monthly R:R ratios for 15 basins throughout Tutuila. Ratios from gauged watersheds can be interpolated or mapped to ungauged watersheds through regression equations, but this technique is limited in its accuracy and lack of validation, making surface runoff one of the most difficult parts of the water budget method to constrain (Engott et al., 2017).

2.3. *Model calibration and sensitivity analysis*

2.3.1. *Curve number calibration*

To address the limitations of each of the runoff calculation methods mentioned above, we developed a procedure to benefit from the strengths of both. We first ran the SWB2 model using the R:R ratio method for the fifteen watersheds where continuous record streamflow data was available. We then extracted the mean annual groundwater recharge from each basin area to be used as calibration data for optimizing CNs in these watersheds. We then switched the SWB2 model to run using the CN method and wrapped the whole model into a single Python function. With the CNs as free parameters, we applied an optimization function to calibrate each of the CNs for each land-cover type. The calibrated CNs were then applied to the island-wide model for the final model runs. The resulting Tutuila specific CN values are shown in Table 1. Overall, the calibrated CNs for Tutuila were lower than the initial (from Maui) CNs for most of the human impacted land-cover types, developed lands, and cultivated areas, and were higher for grassland and native forest land-covers. This is reasonable and reflects the generally more rural nature of Tutuila as compared to Maui.

2.3.2. *Sensitivity analysis*

To assess the effects of different input parameters on model outputs we conducted a sensitivity analysis on both the tabular parameters associated with different land-covers, as well as those spatial parameters with numerical (as opposed to geographic) uncertainty. Sensitivity test parameters included precipitation, PET, maximum and minimum daily temperatures, direct infiltration from anthropogenic sources, CNs, rooting depth, canopy storage capacity, trunk storage capacity, and stemflow fraction. Each of the model input parameters were multiplied by six different test-factors, 50 %, 75 %, 90 %, 110 %, 125 %, and 150 %. The model was run

Table 2
Sensitivity test results expressed as relative percent differences (RPD) in model calculated net infiltration between the base case (present day) model and sensitivity test runs. For each parameter, individual model input parameters were multiplied by test constant values of 50 %, 75 %, 90 %, 110 % 125 %, and 150 %.

	% change in recharge between base case and test case					
Input Parameter	50 % change in input	75 % change in input	90 % change in input	110 % change in input	125 % change in input	150 % change in input
Precipitation	−53.5%	−24.7%	−9.4%	8.6 %	20.6 %	38.2 %
Curve Number	25.2 %	18.1 %	9.4 %	−15.5%	−71.6%	−82.5%
Max Temperature	**	**	8.3 %	−6.3%	−14.0 %	−24.4 %
Min Temperature	−11.4 %	−7.5 %	−3.7 %	5.3 %	22.9 %	**
PET	12.4 %	6.0 %	2.30 %	−2.3 %	−5.6 %	−10.7 %
Canopy Storage	3.0 %	1.5 %	0.6 %	−0.6 %	−1.4 %	−2.0 %
NRW	−2.2 %	−1.1 %	−0.4 %	0.4 %	1.1 %	2.2 %
Trunk Storage Capacity	0.4 %	0.2 %	0.1 %	−0.1 %	−0.2 %	−0.3 %
Stemflow Fraction	0.2 %	0.1 %	0.0 %	0.0 %	−0.1 %	−0.1 %

** These temperatures were outside of the model acceptable range and caused a model error.

repeatedly, changing each parameter by each test-factor to assess how the primary model output parameter, island-wide groundwater recharge, was affected by relative change in each input parameter. Effects of using different fragment sets for daily rainfall distributions was also tested by running the model with five unique fragment sets, which yielded a mean %-difference from the base-case of 3.4 %. All other sensitivity analysis results are shown in Table 2.

2.4. *Future climate and land-cover scenarios*

2.4.1. *Dynamically downscaled climate projections*

Wang and Zhang (2016) produced dynamically downscaled mid- and late-21st-century climate projection datasets for Tutuila at an 800m × 800m grid resolution. Their projections included three scenarios: (1) modeled present-day climate calculated for the years 1990–2009, (2) future climate (2080–2099) reflecting a lower-carbon emissions scenario (RCP4.5), and (3) future climate (2080–2099) climate reflecting a higher emissions scenario (RCP8.5). Overall, both of the future climate scenarios indicated projected increases in temperature, as well as significant increases in precipitation, island-wide. Future climate scenarios were incorporated in the Tutuila SWB2 model by substituting the original monthly precipitation and maximum and minimum air temperature grids with grids from Wang and Zhang (2016). The SWB2 evapotranspiration method was also changed to internally calculate PET with the Hargreaves-Samani Method (Hargreaves and Samani, 1985) so the effects of air temperature change could be considered.

2.5. *Development of participatory land-cover change narratives*

The process of developing future land-cover change narratives started with interviewing over twenty representatives from seven government and educational agencies on Tutuila. Interviews were conducted with staff at the American Samoa Environmental Protection Agency (ASEPA), the American Samoa Community College (ASCC), the American Samoa Power Authority (ASPA), the Department of Public Works (DPW), the American Samoa Department of Commerce (ASDOC), the National Oceanic and Atmospheric Administration's Coastal Zone Management Program (NOAA CZMP), and the Coral Reef Advisory Group (CRAG). Interviewees were presented with information about the project and were asked to discuss the specific drivers of land-cover change on the island and their thoughts and assumptions regarding what future economic and land-cover decisions were likely to be made in the future. We compiled all notes from these discussions, and organized them into three specific themes related by likely drivers of change. Each is represented by one of the three separate land-cover narratives detailed below. We then developed geospatial land-cover change algorithms to automatically modify the Meyer et al. (2016) land-cover map into scenario maps that represented each of the three narratives. To assess effects of future climate and land-cover together, we then ran the SWB2 model using all 12 combinations of present and future land-cover and climate scenarios, each of which is summarized in Table 3.

2.5.1. *Geospatial land-cover change algorithms*

To produce future land-cover maps representing changes outlined in the future land-cover narratives, we developed a series of geospatial algorithms within Jupyter Notebooks to modify the original Meyer et al. (2016) land-cover map via a series of computational steps enacted through the use of an expansion function that redistributed the proportion of land under different land-cover types. This method was designed to make the process more reproducible and transparent than methods that use direct editing of features, and it also preserved the existing distribution of land-cover types across the island to avoid bias inherent in manual edits. Fig. 2 shows static maps of land-cover change scenarios, and animated high-resolution land-cover change maps are provided as supplementary material Figs. 1–3 and in this project's associated GitHub repository (https://github.com/cshuler/Tutuila-SWB-Scenarios).

2.5.2. *Land-cover change narrative 1: economic boom and unrestricted growth*

The "Unrestricted Growth" narrative, represents a possible future where socio-economic conditions lead to an increase in population and development, which is allowed to proceed without zoning or regulation (Fig. 2). The stakeholders identified potential drivers of this change including: (1) new telework jobs from improved telecommunications infrastructure, (2) increased growth driven by the tourism sector (3) geopolitical conditions resulting in increased immigration. Specific land-cover changes included:

Table 3
Island-wide annual changes in groundwater recharge shown for all combinations of possible climate or land-cover scenarios. The present day scenario result is presented in Million Liters per Day (Mld) of recharge, whereas results for all other scenarios are presented as %-difference in recharge from the base case. Note that tables of %-difference for each scenario are summarized at finer watershed- and region-scales in the associated data repository (Shuler et al., 2020).

	Present Day Climate	RCP4.5 Emissions	RCP 8.5 Emissions
Present Day Land-cover	Base case: 878.0 Mld	20.1 %	12.2 %
Land-cover Scenario 1: Unrestricted Growth	−0.35 %	19.9 %	12.2 %
Land-cover Scenario 2: Population Attrition	0.59 %	21.5 %	13.7 %
Land-cover Scenario 3: Managed Growth	−0.66 %	20.2 %	12.5 %

* Present Day Climate scenarios were run to demonstrate the magnitude to which land-cover change affects groundwater recharge. However, it is unlikely that either the effects of land-cover or climate change will manifest independently.

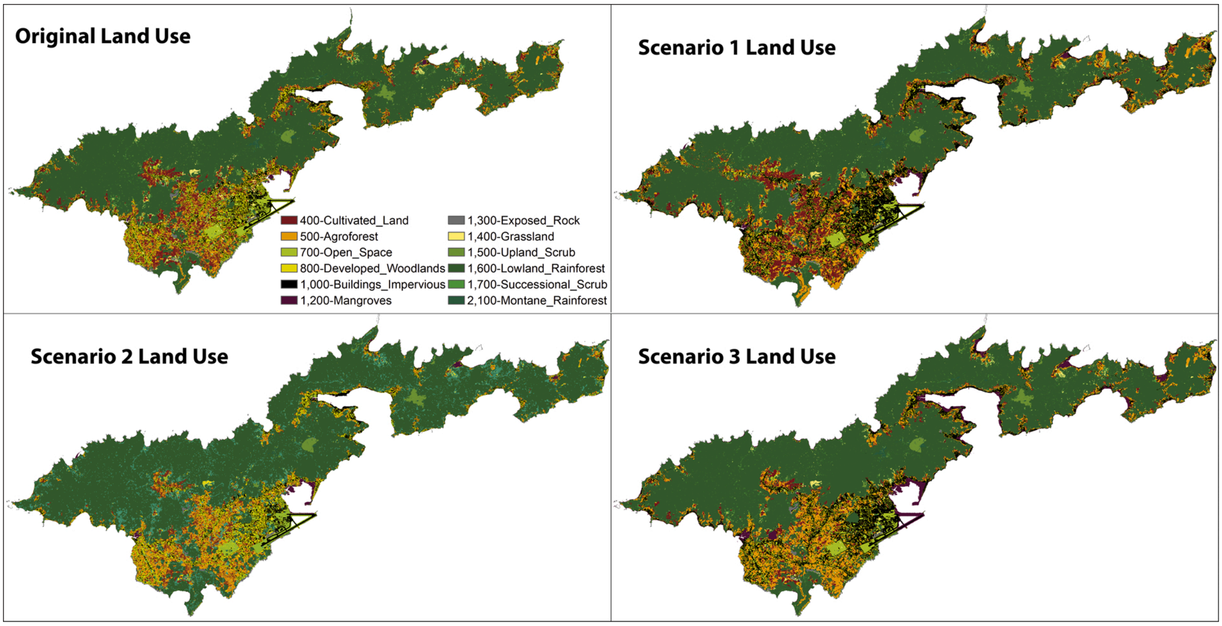

Fig. 2. Land-cover maps for the present day and future scenarios. The present day scenario (upper left) is based on the land-cover map of Meyer et al. (2016). Scenario 1 (upper right) represents the Economic Boom and Unrestricted Growth Narrative, Scenario 2 (lower left) represents the Population Attrition Narrative, and Scenario 3 represents the Population Boom with Enhanced Zoning and Management, or Managed Growth Narrative.

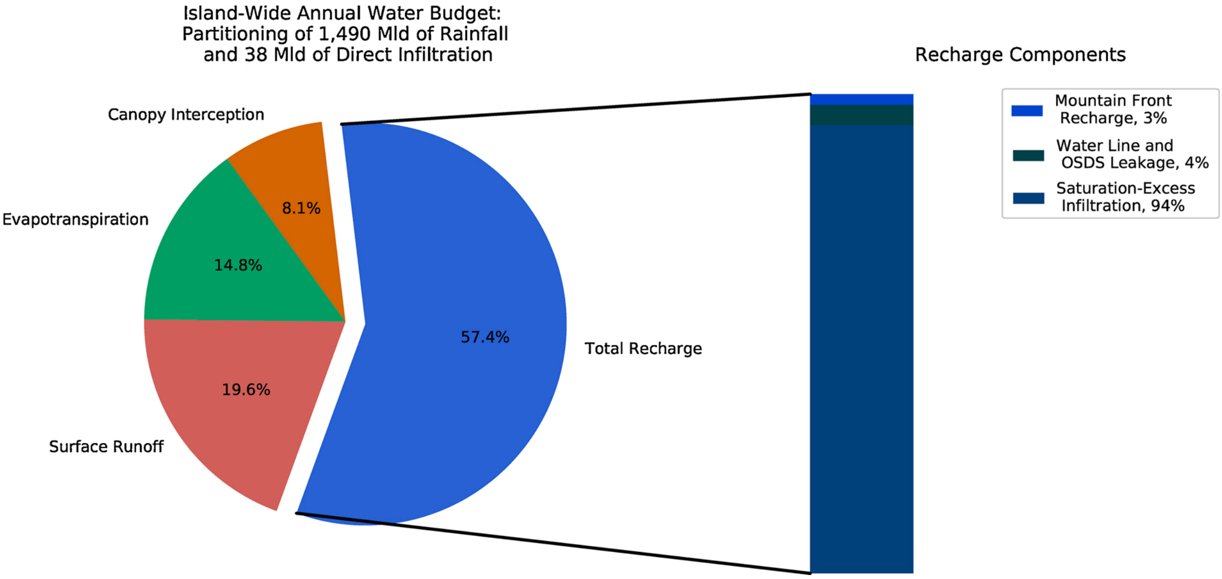

Fig. 3. Partitioning of water inputs to water budget components. Total groundwater recharge occurs as three separate processes, saturation excess infiltration from the excess soil-moisture reservoir, direct infiltration from leaking water lines and OSDS units, and MFR infiltrating into the Tafuna-Leone Plain.

(1) New development on the now forested Aasu uplands (Fig. 1).
(2) An increase in island-wide 'impervious surfaces' by +96 %, from 8.3 km^2 to 16.3 km^2, including a 13 % (0.8 km^2) loss of 'developed open space' and 63 % (3.3 km2) loss of 'developed woodlands' surrounding residential and commercial areas.
(3) An island-wide increase in 'agroforestry plantations' by 44 % from 8.1 km^2 to 11.8 km^2.
(4) An increase in cultivated land of 7 % from 10.9 km^2 to 11.8 km^2.
(5) Expansion of developed-land covers into adjacent undeveloped areas with slopes <25°, resulting in reduction of 'lowland rainforest' by 7 %, or 6.1 km^2.

(6) Infiltration from OSDS units was increased by 96 %.
(7) In addition to scenario specific drivers, effects of 1 m of sea level rise (SLR) were included in the algorithm by changing all coastal land-covers that intersected with 1 m SLR flood zones (NOAA-OCM, 2016), except for bare rock, to mangrove land-cover.

2.5.3. Land-cover change narrative 2: population attrition

This narrative represents a future of economic contraction that causes Tutuila's population to shrink (Fig. 2). Specific drivers discussed with stakeholders included: (1) shutdown of the tuna cannery, the island's largest private employer, (2) increase in natural disasters, such as coastal flooding and severe cyclones due to climate change, and (3) reduction in economic opportunity due to losses of external funding and reduction in government jobs. Changes to the land-cover map included:

(1) A 52 % reduction in cultivated land from 11.0 km^2 to 5.2 km^2 and a 11 % reduction in agroforestry plantations from 8.2 km^2 to 7.2 km^2 island-wide.
(2) An island-wide decrease in impervious surfaces by 33 % from 8.3 km^2 to 5.6 km^2, and a decrease in open space by 35 % from 6.9 km^2 to 4.5 km^2.
(3) Direct net infiltration from OSDS units was decreased by 33 %.
(4) Reduced population pressure may reduce the need for residents to live in areas prone to flooding. To represent migration away from these areas, we identified all structures and impervious surfaces within 4 m of a stream, and changed these land-cover types to open space. In addition, all land-covers (except for bare rock) within the 1 m SLR flood zone on the coastline were converted to mangroves as described in Narrative 1.

2.5.4. Land-cover change narrative 3: population boom with enhanced zoning and management

The "Managed Growth" narrative, represents growth conditions as described in the Unrestricted Growth Narrative, but with additional controls on development through new zoning and land management regulations (Fig. 2). Possible regulatory actions we considered were identified through discussions with stakeholders and included: (1) designation of new or enforcement of existing special management areas (SMAs) designed to protect and enlarge ecologically significant remnant areas of native ecosystems, (2) protection of existing undeveloped lowland rainforest, (3) management of riparian corridors, (4) support for more agroforestry plantations, and (4) development of green infrastructure and buffer zones in areas vulnerable to coastal flooding. The land-cover change algorithm for this narrative reflected these activities by:

(1) Delineation of SMAs, and conversion of land-cover in SMAs to native lowland forest. Specifically, SMAs included a) the sparsely developed Malaeimi Valley area, b) lowland rainforest on the Tafuna Plain, c) the Aasu Uplands (Fig. 1), and d) all existing wetland areas.
(2) All existing lowland rainforest was preserved. This plus conservation of SMAs resulted in an increase in rainforest by 0.3 % (85.8 km^2 to 86.1 km^2).
(3) Agroforestry plantations were increased by 52 % from 8.2 km^2 to 12.5 km^2.
(4) Riparian development buffers were represented by converting all buildings and impervious surfaces within 5 m of a stream into open space.
(5) Coastal flooding buffer zones were created by replacing all land-cover types (except for bare rock) in the 2 m SLR flood zones (NOAA OCM, 2016) with mangroves.
(6) Population expansion was accommodated through densification of existing land-cover represented by an island-wide increase in impervious surfaces of 64 % from 8.3 km^2 to 13.7 km^2, and decreases in open space and developed woodlands by 20 % (6.9 km^2 to 5.5 km^2), and 65 % (5.3 km^2 to 1.9 km^2), respectively.
(7) Direct net infiltration from OSDS units was increased by 64 %.

3. Results

3.1. Present day water budget

Summarized at an island-wide scale, mean annual groundwater recharge calculated by the present day (base case) SWB2 model was 884 mL d. Total mean annual island-wide water inputs included precipitation (1490 mL d) and direct infiltration from water lines OSDS (38 mL d). Groundwater recharge was the largest output component of the water budget representing 57 % of the total mean annual island-wide water inputs. Other water budget components on the output side included canopy interception and actual evapotranspiration representing 125 mL d or 8 % and 228 mL d or 15 % of total water inputs, respectively. Island-wide runoff was initially calculated to be 313 mL d or 21 % of total water inputs, of which 19 mL d was captured and re-introduced to the model as MFR, thereby reducing the amount of surface runoff lost to the sea to 294 mL d or 20 % of water inputs (Fig. 3). Water inputs totaled 1,528 mL d, which accounted for 99.8 % of the 1,531 mL d of summed water outputs, thereby leaving a model mass-balance error of less than 0.3 % likely due to rounding or differences in resolution during post-processing. While we primarily report results at an annual island-wide resolution, SWB2 produces finely resolved NETCDF outputs that can be summarized at higher temporal and spatial resolutions. Watershed scale and monthly resolution results are available within this project's associated GitHub repository (https://github.com/cshuler/Tutuila-SWB-Scenarios).

Monthly resolution outputs were also examined to assess seasonal patterns. Predictably, the annual distributions of recharge, ET, and runoff followed the same pattern as rainfall with the absolute magnitude of all water budget components falling in the dry season (austral winter) and rising in the wet season. (Fig. 4, (a)). However, different patterns emerged when comparing the *fraction* of total precipitation allocated to each water budget component (Fig. 4, (b)). In dry season months, ET generally exceeded surface runoff, but the model predicted the reverse during the wet season. Recharge dominated the water budget all year, but the ratio of recharge over monthly precipitation in the dry season was somewhat higher than during the wet season. These patterns may be caused by changes in rainfall intensity throughout the year as Tutuila receives more intense convective storms in the austral summer.

3.2. *Results: future climate scenarios*

On the average annual scale, both the high and moderate emissions future climate scenarios (RCP8.5 and RCP4.5) project significant island-wide increases in annual precipitation on the order of 11 % and 18 %, respectively. Because precipitation is the main driver of the water budget, island-wide annual groundwater recharge totals showed a commensurate increase of 8 % and 14 % for the RCP8.5 and RCP4.5 scenarios, respectively (Fig. 5). Annual island-wide ET increased from the base case only marginally by 0.6 % and 1.1 % but annual surface runoff increased dramatically, by 31 % and 49 %, which drove a corresponding increase in MFR of 11 % and 17 %, for the RCP8.5 and RCP4.5 scenarios, respectively. Monthly resolution downscaled projections showed an interesting result, where the present-day wet and dry season precipitation signals were absent from the downscaled model's monthly totals, with precipitation varying fairly randomly throughout the year (supplementary material Figs. 4 and 5). Prepetition totals for all future projected months were always above the present day monthly totals, but the additional amounts varied significantly. Tropical cyclones are one major driver of precipitation in Tutuila's wet season, and Wang and Zhang (2016) call attention to their projections showing a significantly decreased frequency of weak and strong tropical cyclones over American Samoa. This might account for at least part of the decay of the typical seasonal rainfall signal.

3.3. *Results: future land-cover scenarios*

Effects of changes in land-cover alone (without climate scenarios) were most pronounced at the sub-watershed scale, whereas a large proportion of individual model cells showed increases or decreases in key water balance components of over 20 % (Fig. 6). However, once the differences were summed at the watershed scale, these patchwork changes balanced out to the point where the greatest predicted change in groundwater recharge for any of the land-cover scenarios was about 3 %, seen in three to five of the island's most affected watersheds for each scenario. At the island-wide scale, the changes averaged out even more, yielding annual recharge percent differences (%-difference) between the present day and future land-cover scenarios of -0.35 %, 0.59 %, and -0.66 % for the Unrestricted Growth Scenario, the population attrition scenario, and the Managed Growth Scenarios, respectively (Table 3). While quite small, these changes nonetheless followed an expected pattern where both of the growth scenarios predicted slightly less recharge, and the population attrition scenario predicted a slight increase in recharge. The magnitudes of change in whole-island AET and surface runoff were more significant, with AET decreasing by 11 % in the attrition scenario and increasing by 8% and 0.5 % for the two growth scenarios. Runoff increased by 3 %, 0.6 % and 5.3 % for the Unrestricted Growth, the Population Attrition, and the Managed Growth Scenarios, respectively.

Nonetheless, despite the limited change in recharge on watershed or larger scales, we were also able to isolate the effects from changing each land-cover type to any of the other types in isolation by analyzing the scenario results on a cell by cell basis. This was done by filtering only those individual cells that were assigned a specific land-cover type in the base case and were then changed to another land-cover type in one of the future scenarios. This analysis essentially provided a controlled experiment to assess the effects of changes driven only by varying a single land-cover in isolation. We processed 132 of these experiments for each of the three scenarios

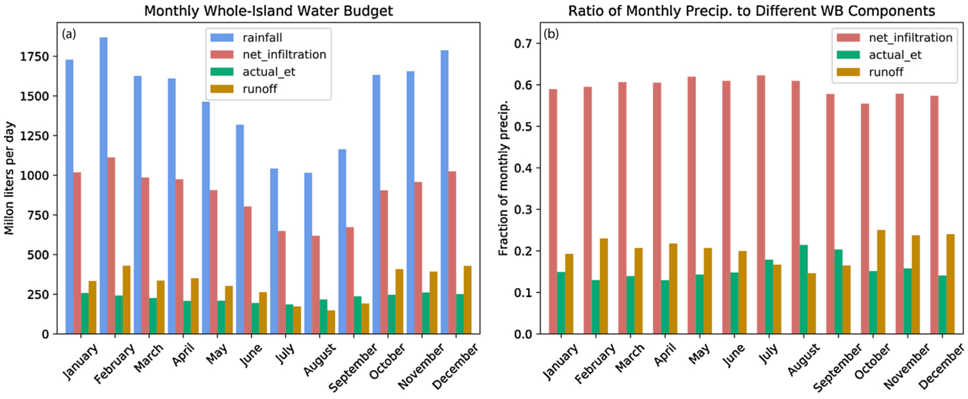

Fig. 4. Monthly island-wide water budget results presented as absolute magnitudes of water partitioned to each component (a) and as the fraction of total precipitation (b) thereby normalizing each component by rainfall to show the relative importance of each component within the island's water budget on a monthly basis.

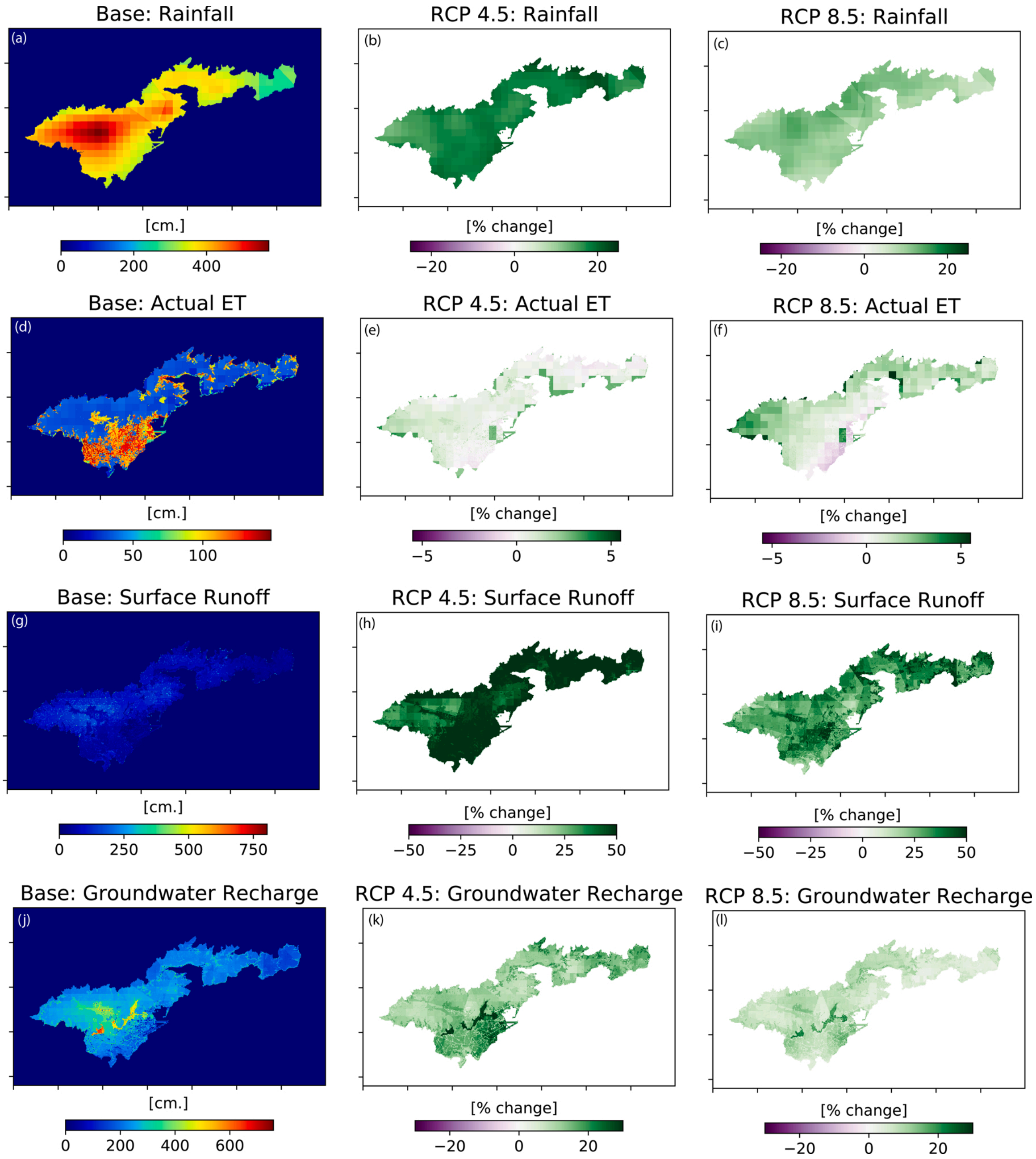

Fig. 5. Spatially distributed water budget model results using dynamically downscaled rainfall and temperature projections (Wang and Zhang, 2016). Present day predictions are shown as depth of water (left column (a, d, g, j)) whereas future predictions are shown as % change from the present-day scenario for the RCP4.5 (center column (b, e, h, k)) and RCP8.5 (right column (c, f, i, l)) scenarios. Note variable scales on color maps.

(12 land-cover types that can change to one of the 11 other types) and in summary found that the most impactful changes in recharge were generally seen when more vegetated land-covers, such as cultivated or forested land, were changed to a developed land-cover type, such as impervious surfaces. Most notably, and considering results of all three scenarios, when native lowland forest was changed to impervious surfaces, recharge was generally reduced by about 20 %. Changing lowland forest to open space or developed woodlands also reduced recharge by about 6 % and 12 %, respectively. Generally, conversion of lowland rainforest to agroforest or cultivated land generally only produced reductions in recharge on the order of 1%–3%, and sometimes even increased recharge by a small amount.

When future land-cover and future climate scenarios were combined, the effects of the dramatic increase in island-wide precipitation was the strongest driver of change. The magnitude of recharge and AET in the combined scenarios were approximately the same as the additive effects of the climate and land-cover scenarios alone. However, it is interesting to note that for all scenario

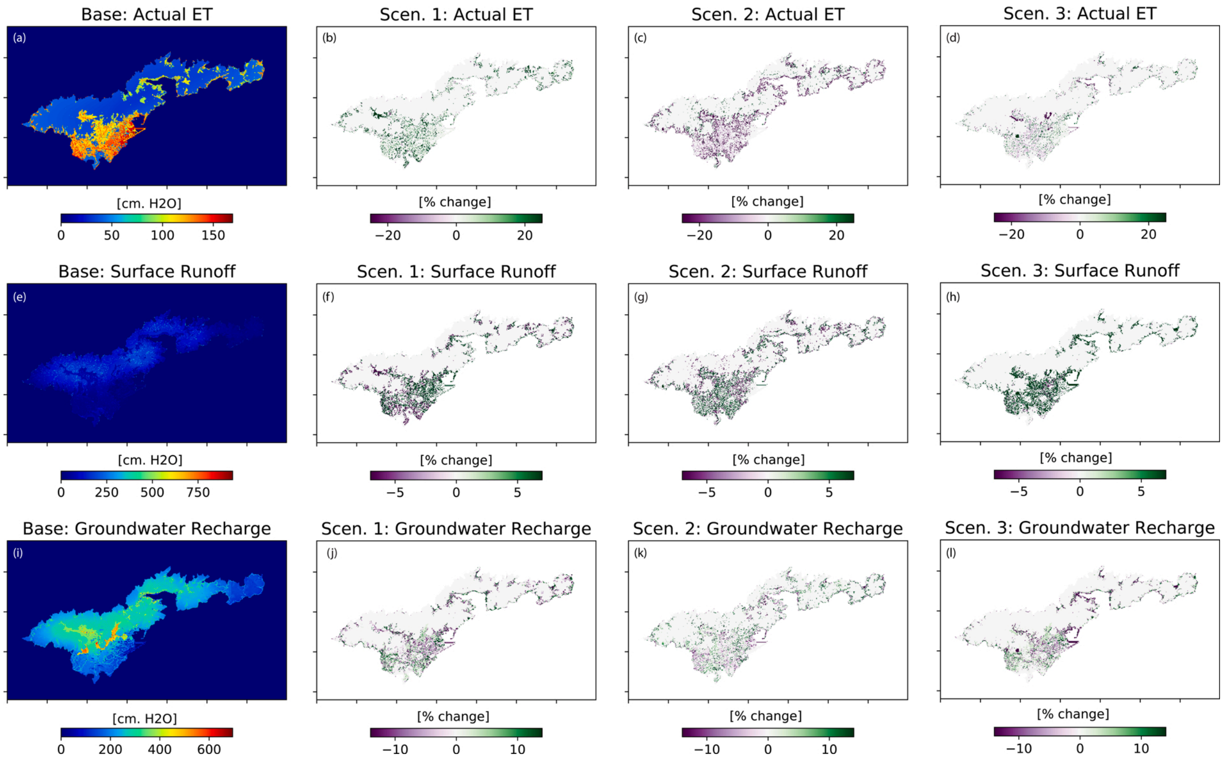

Fig. 6. Spatially distributed water budget model results for future land-cover scenarios, without any change in future climate. Present-day predictions are shown as depth of water (left column (a, e, i)) whereas future predictions are shown as % change from the present-day scenario for the Unrestricted Growth Scenario (Scen. 1), the Population Attrition Scenario (Scen. 2) and the Managed Growth Scenario (Scen. 3).

combinations, the model predicted small but significant increases in runoff beyond the additive impacts of the climate or land-cover scenarios alone, with these additional %-differences ranging between 0.3 % and 3.3 % more surface runoff.

4. Discussion

4.1. *Comparison to other water budget studies*

Although this study details the first known island-wide, high-resolution groundwater recharge estimate conducted for Tutuila, a former USGS study authored by Izuka et al. (2007) developed a similar water budget for just the western portion of Tutuila using the Hawaii Water Budget Code. Comparison between our study and the Izuka et al. (2007) work showed reasonably similar results, based on calculation of water budget components within the equivalent area of Western Tutuila. Specifically, our annual resolution water

Table 4

Summary of water budget components from existing high-resolution water budget studies of other high-basaltic islands. Results from Tutuila shown for comparison. Rainfall shown in Million liters per day (Mld) and other results expressed as percentages of island-wide annual average precipitation.

Island	Island-Wide Annual Precip. (Mld), (cm/yr.)	Groundwater Recharge (% of Precip.)	Surface Runoff (% of Precip.)	ET + Canopy Evaporation (% of Precip.)	Source
Oahu, HI	6,895, (163 cm)	29 %	15 %	55 %	Engott et al. (2017)
Maui, HI	10,621, (206 cm)	32 %	29 %	39 %	Johnson et al. (2018)
Guam, U.S.	3,781, (251 cm)	38 %	13 %	49 %	Johnson (2012)
Jeju Island, Korea	10,537, (210 cm)	42 %	9 %	49 %	Mair et al. (2013)
Hawaii, HI	50,643, (177 cm)	45 %	12 %	43 %	Engott (2011)
Western Tutuila	1,060, (458 cm)	50 %	24 %	26 %	Izuka et al. (2007)
Tutuila	1,490, (382 cm)	56 %*	21 %	24 %	This Study

[*] Because not all studies include direct net infiltration from all sources, such as OSDS and leaking water lines, direct net infiltration is subtracted from recharge totals where applicable.

fluxes in W. Tutuila were within -2 %-difference for precipitation, -12 %-difference for runoff, -14 %-difference for ET, and +15 %-difference for recharge (with negative values indicating comparatively more water calculated by the Izuka model). Part of the difference between the models can be attributed to the fact that the Izuka et al. (2007) study did not include additional recharge contributed by direct net-infiltration from OSDS units or leaking water lines, which our study calculated to be about 4% of the total SWB2 calculated recharge. Another difference can be attributed to our use of calibrated CNs, whereas the previous work used a single runoff to rainfall ratio to parameterize runoff across the entire model domain. Regardless, comparison between the two studies helps to support the reasonableness of our SWB2 calculated water budget estimates, as well as those produced by the Izuka et al. group.

Comparison between Tutuila's water budget and water budgets of similar island environments can also be useful for examining differences between the large-scale hydrology of different regions. To do this, we consolidated as many other water budget studies as possible from other high-basaltic islands in the Pacific Basin. We considered only those studies that used high-resolution spatially distributed models to calculate island-wide water budgets. One obvious difference between Tutuila and other islands is the large (>50 %) fraction of precipitation that our and the Izuka et al. (2007) models allocated to groundwater recharge. Table 4 shows these differences by normalizing major water budget components by island-wide volumetric precipitation. On most of the Hawaiian Islands, Jeju Island, and Guam, AET is the dominant water budget output, whereas AET only represented about a quarter of the water budget output on Tutuila. This is likely due to Tutuila's location within the SPCZ, which is characteristically cloudy and rainy as a result of the prevalence of large-scale convective systems (Vincent, 1994), whereas the other islands in this comparison all lie outside of the SPCZ and ITCZ (Salinger et al., 2014). On average, Tutuila receives nearly twice the rainfall of the other islands in this comparison, with the rainier western portion of the Tutuila receiving a region-wide annual average of 458 cm of rainfall according to Izuka et al. (2007). The larger number of cloudy days on Tutuila also serves to reduce incoming net radiation, a key driver of PET. This in conjunction with frequent year round rainfall events, keeps soil moisture availability high, thereby driving AET to approximate PET on Tutuila much of the time (Izuka et al., 2007).

With available radiative energy limiting the amount of water that can be evaporated, it is reasonable for Tutuila's surface runoff and groundwater recharge to be higher than in other islands, such as Guam where average solar radiation is higher (Kabir et al., 2017). However, we calculated Tutuila's recharge to be nearly three times larger than surface runoff, and proportionally, Tutuila's recharge was the highest of any of the other islands examined. This might be explained by Tutuila's hydrogeology, whereas a relatively large portion of the island, the Tafuna Leone Plain, is composed of young highly-permeable lava flows. The Plain makes up about 22 % of the island's land mass, and as Izuka et al. (2007) states, is devoid of drainage features, indicating very little of the rainfall or surface runoff from the mountains above actually makes it to the sea. This is analogous to the leeward side of the Big Island of Hawaii, where young permeable lavas also reduce surface runoff fractions to minimal amounts. Indeed, the water budget for the Big Island indicates higher relative recharge and lower relative surface runoff fractions compared to the other islands (Engott, 2011).

These differences show how other hydrologic factors besides precipitation amounts can influence the overall availability of water resources on different islands. Understanding water resources availability at this scale is useful for water managers to compare policies and regulations between different jurisdictions. For example, in the state of Hawaii, water resource managers are currently very interested in constraining the effects of invasive vegetation on hydrologic variables, which specifically relates to modification of AET since different plant species utilize water from different depths and with different efficiencies (Cavaleri et al., 2014: Brewington et al., 2017). On the Island of Oahu, where ET makes up 55 % of the total water budget, management of invasive forest species may prove to be a useful practice for increasing groundwater recharge, and thus groundwater availability. However, on Tutuila, this practice is likely to be less impactful, considering that AET typically already matches PET and also considering that a much smaller fraction of Tutuila's total rainfall is evapotranspired in comparison to Oahu.

4.2. Effects of land-cover and climate change scenarios

A caveat that must be considered before examining the future climate and land-cover scenario results is that the climate projections we used here (Wang and Zhang, 2016) are only representative of a single regional climate model result developed with a single downscaling technique. Different climate projections and GCMs can vary widely, in part reflecting the inherent uncertainty between different downscaling methods (Brewington et al., 2019; Mair et al., 2019). For example, in Hawaii, comparison between statistically downscaled climate models (Timm and Diaz, 2009; Elison Timm et al., 2015) and dynamically downscaled models (Zhang et al., 2016) shows strongly divergent rainfall trends in certain parts of the islands. However, for Tutuila, the Wang and Zhang (2016) projections are the only downscaled GCM results available for the region at this time. Additional limitations and assumptions of the SWB2 model and future scenarios are detailed in Section 3 of the supplementary material.

When considering future land-cover results, it should also be remembered that the future land-cover maps were produced by expanding or reducing the existing footprints of present-day land-cover types but not significantly modifying their locations. While it is reasonable to assume that large shifts in the mixture and the locations of particular land-covers are unlikely to occur, it is possible that large swaths of land could one day be subject to a drastic change in their land-cover makeup, which would not be represented by our land-cover scenarios.

With these considerations in mind, the most apparent change seen in all the scenarios was the overwhelming effect of projected future precipitation increases. Sensitivity tests showed that rainfall was the most important driver of the water budget (Table 2), so this finding can easily be expected. In a broad sense, increases in precipitation would be a major boon to water resources managers, as the availability of groundwater and surface water should significantly increase. Increases in groundwater recharge would also help to mitigate drinking water salinity issues in areas affected by upcoming from excessive groundwater withdrawal rates.

However, a more nuanced analysis of our scenarios showed possible implications that may be less welcome. Whereas the increase in future groundwater recharge was predicted to be about equivalent to the increase in precipitation, increases in surface runoff were significantly higher, up to 50 % more than present-day surface runoff on an island-wide annual scale, and often more than double present-day surface runoff magnitudes on monthly scales. Sensitivity testing corroborated the large impact that runoff, and specifically CNs, have on groundwater recharge, considering the model was found to be about as sensitive to the CNs as it was to precipitation. With increased surface runoff comes increased flooding, which is already a major issue in Tutuila's present-day landscape (Leta et al., 2017). Because the finest temporal resolution our water budget approach allows for is monthly, the model cannot provide assessment of event scale effects or changes in precipitation intensity. However, these sub-daily factors most certainly have a significant impact on the overall water budget as well, and should be explored more thoroughly with other types of hydrologic models in the future.

Interestingly, the model predicted that AET would not be much higher in any of the future scenarios, likely due to the fact that even in the present-day scenario, Tutuila's already high rainfall provides ample soil moisture driving AET to approximate PET most of the time, as has been seen in other tropical high-rainfall areas (Bidlake et al., 1993; Izuka et al., 2005). Sensitivity test results suggested that air temperatures were likely to be the most important parameter controlling evaporative losses, especially because canopy interception parameters had very little effect ($\leq$ 3 %) on recharge. However, it should also be noted that air temperature values examined in sensitivity tests were much larger than the changes predicted by the GSM climate models, which only predicted increases of $3-4^\circ$ in maximum and minimum average monthly temperatures for both of the emissions scenarios.

Examining the effects of land-cover scenarios alone (without future climate change) provided insight into how effective land-cover management activities might be in influencing groundwater recharge rates. Interestingly, we found that despite the fairly significant changes in recharge caused by conversion of various land-cover types to other types on local cell-by-cell scales, the effects on recharge under the land-cover change narratives were limited. One reason these scenarios did not show much island-wide impact is the prevalence of very steep forested land on Tutuila that is costly to develop for any human use. These areas are also where the island experiences its highest precipitation rates and thus its highest groundwater recharge. Because these steep mountainous areas will probably always remain undeveloped, only the lower elevation areas with less influence on recharge are able to drive change. Another reason for the small simulated changes in recharge was the broad mixture of different and potentially competing effects bundled within each of the land-cover change scenarios. For example, the footprint of impervious surfaces increased dramatically in both of the growth scenarios (scenarios 1 and 3); but these scenarios also included increases in agroforest land-cover, which grew at the expense of developed woodlands and open space land-covers, both of which produce relatively less recharge than agroforest. Therefore, in these scenarios, a decrease in recharge from more impervious surfaces was offset by an increase in recharge from changing less recharge-efficient land-covers to more efficient agroforest or cultivated land. The socio-economic driver of both these changes was the same, this being the conversion of low-economic value land-cover types such as open space, to higher value ones, either for residential purposes (buildings, roads) or economic ones (development in the agricultural sector). This result also demonstrated the importance of maintaining cultural practices, such as traditional Samoan agroforestry, and indicated that economic development does not always necessitate environmental degradation, from a water resources perspective. While the interactions between different land-cover changes can convolute the water-budget effects of each one, these complex interactions nonetheless provided a more nuanced and likely depiction of future conditions based on current trends and existing socioeconomic drivers. We contend this method is preferable to the alternative of arbitrarily changing land-cover parameters and running the model repeatedly without incorporating the valuable knowledge and experience of local stakeholders and water resources managers.

5. Conclusions

This study details the first high-resolution water budget model developed for an entire high-basaltic island within the South Pacific Convergence Zone. This, in addition to application of the model to project future conditions under both climate change and land-cover change scenarios, make this project one of the more rigorous assessments of present and future water resources availability in the South Pacific Region to date. Because the model was developed with the goal of stakeholder engagement and use in mind, we applied a participatory approach to developing future land-cover scenarios and we constructed and hosted the model on an open-source software development platform to make results available and reproducible. Present-day model results indicate that of Tutuila's annual average of 1,490 mL d of precipitation, 23 % was lost to evaporation, 21 % was discharged as surface runoff, and 56 % or 827 mL d (plus another 57 mL d of direct infiltration), became groundwater recharge. Comparison to water budget studies from similar islands showed that Tutuila had a higher rate of recharge relative to precipitation, which we attributed to higher rainfall amounts and intensities found in the SPCZ relative to other regions. Also, Tutuila's unique geology, which imparts very high permeabilities to parts of the island may contribute to this effect as well.

The dynamically downscaled GCM projections we used indicate an increase in annual average precipitation of 11 % and 18 % in their RCP8.5 and RCP4.5 scenarios, respectively, by the end-of century. This translated to island-wide groundwater recharge increases of 8% and 14 %, respectively. While increases in recharge roughly mirrored increases in precipitation, showing that precipitation is a primary driver of groundwater recharge, increases in surface runoff were significantly higher, on the order of 50 % more for the future scenarios. This indicated that while water resources availability may increase in the future, it will not be without consequences, likely in the form of increased flooding. Land-cover scenarios showed how conversion of vegetated types to more urbanized types could result in localized reductions in recharge of up to 20 %. However, on an island-wide scale, we found our stakeholder informed land-cover change narratives caused only limited effects on groundwater recharge. This result could be partially attributed to the offsetting effects of increases in urbanization with concurrent increases in cultivated land and agroforest, which served to increase recharge relative to developed land-cover types.

CRediT authorship contribution statement

Chris Shuler: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing - original draft. **Laura Brewington:** Writing - review & editing, Funding acquisition. **Aly I. El-Kadi:** Writing - review & editing, Funding acquisition, Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.ejrh.2021.100785.

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