Incorporating drought risk modelling as a planning tool for climate change adaptation measures in Saint Kitts and Nevis

Water balance report

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1 Background

1.1 Project summary

In an effort to address the impacts of climate change and climate variability in a sustainable way, access to critical information within the water sector is vital. Drought prediction models can identify areas most susceptible to water supply variability and shortages, and therefore facilitate early action to manage risks. In doing so, this will increase resilience in the water sector to improve use of water resources and therefore ensure food security and water usage including from the agricultural, domestic and tourism sectors in the two islands of St. Kitts and Nevis.

The overall objective of this project is to incorporate drought risks modelling as a planning tool for climate change adaptation measures in St. Kitts and Nevis. The main outputs include to:

- Map stakeholders and establish a stakeholder working group;
- Assess drought risk and water resources in St. Kitts and in Nevis;
- Benchmark, design and implement a drought prediction tool in St. Kitts and in Nevis;
- Train administrators and users of St. Kitts and Nevis to use the drought prediction tool.

The project outcomes respond directly to SDG 13 'Taking early action to combat climate change and its impacts' by providing a system that will support planning and decision-making for the sustainable management and conservation of water resources in St. Kitts and Nevis. The project will also contribute to SDG 1 (End poverty), SDG 2 (Food security) and SDG 6 (Availability and sustainable management of water) as the drought prediction tool will improve agricultural practices and use of water resources, improve food security and increase the income of rural communities.

1.2 About this report

This report presents a water balance calculation for St. Kitts and Nevis. It provides an overview of the methodology, data description and results obtained using Earth Observation data. The thinking and analysis underpinning this report will be reviewed and updated when the modelling stage of the project is completed and will be taken into account during the scoping and design of the drought prediction tool (Output 3).

2 Water balance overview

Water availability and sustainable water management benefit from a good understanding of the hydrologic cycle and water balance. A water balance evaluation provides an accounting of the rates of water movement and the change in water storage in the atmosphere, land surface, and subsurface. It can also be beneficial in evaluating availability and sustainability of water supplies, underpinning effective water-resource and environmental planning and management (Healy et al., 2007).

The simplest form of water balance equation can be expressed as follows:

$$P = Q + E \pm \Delta S \qquad (2.1)$$

Where P is precipitation; Q is surface runoff; E is evapotranspiration and ΔS is change in storage.

Although simple in concept, water balance calculations are usually complicated by the lack of direct measurements of its components, as is particularly the case for evapotranspiration data. Often a water balance is calculated by numerical or hydrological models, and particularly useful is the use of numerical models to estimate groundwater recharge. However, a water balance can also be a simplified hydrological calculation to account for all the inputs, and outputs of the area of interest.

Several examples of such calculations exist in the literature from Palmer (1965), which will be used here for St. Kitts and Nevis, to Freeze and Cherry (1979), based on precipitation, runoff, evapotranspiration and changes in storage for surface water and groundwater. For groundwater-dominated catchments, water balance calculations such as the one proposed by Freeze & Cherry (1979), can be complex due to differences in groundwater and surface water boundaries and the uncertainties in inflows into and out of the systems.

To obtain a simplified water balance calculation of both islands, averages of Earth Observation (EO) -based data, for each island were used and certain assumptions were made. The EO-based data include precipitation, evapotranspiration and surface runoff. The main assumption made was to consider each island as an individual catchment, which solves the matter of having a closed system in which groundwater flow and/or surface runoff do not contribute to adjacent catchments. For this report we have also not considered groundwater abstraction. We will quantify this later when we undertake the recharge modelling, but for the purpose of this report groundwater abstraction impacts on the water balance have not been considered.

Due to the complexity of recharge processes and limited observations, estimating groundwater recharge without a numerical model is one of main difficulties for a water balance calculation. For the purposes of this assessment, a simple regression equation developed by Gemitzi et al. (2017) relating precipitation and evapotranspiration was used. Both calculations of groundwater recharge and water balance were compared to the scarce data available to provide an overview of whether this approach is valid. For this initial calculation of a water balance for the islands, abstractions were not considered and this is a consideration that will be taken into account when developing models of St. Kitts and of Nevis and the water balance calculation updated and improved. A discussion on water consumption in the islands has been included in the Water Resources Assessment report.

3 Methodology

3.1 Mathematical approach

The water balance equation used in St. Kitts and in Nevis is based on Palmer (1965), as part of the methodology used in Falalakis & Gemitzi (2020), describing the flow of water into and out of a system (Equation (3.1)):

$$P + L = ET + SR + I \qquad (3.1)$$

Where, *P* is precipitation, *L* is moisture loss from the soil in the form of capillary rise or transport through vegetation, *ET* is evapotranspiration, *SR* is surface runoff and *I* is the infiltration to the vadose zone (soil water) and to groundwater, which results in changes in subsurface storage. This *I* parameter can be approximated as groundwater recharge. All parameters are measured with units of volume per unit of time (e.g. m^3/day) or units of length (vertical depth of water) per unit of time (e.g. mm/day).

The system in St. Kitts and in Nevis is described by USACE (2004) as mainly formed by meagre to small quantities of fresh water, that are available from Oligocene to Recent age mixed volcanic rocks with minor amounts of Recent age alluvium, shown in both islands with yellow colour (Figure 3.1). The depth of the aquifer ranges from 2 to 70 metres (m). Along the coastline, variable quantities of brackish to saline water are available from Oligocene to Pleistocene mixed volcanic, limestone, and sedimentary aquifers, represented with red colour. The aquifer along the coast extends to less than 20 metres depth. Streams and reservoirs are also shown in Figure 3.1.

Figure 3.1: St. Kitts and Nevis groundwater map (USACE, 2004)

Based on the water balance proposed before, the system could be conceptualised according to Figure 3.2, where evapotranspiration is defined as the aggregation of evaporation and transpiration; and infiltration recharges the aquifers (represented as groundwater recharge).

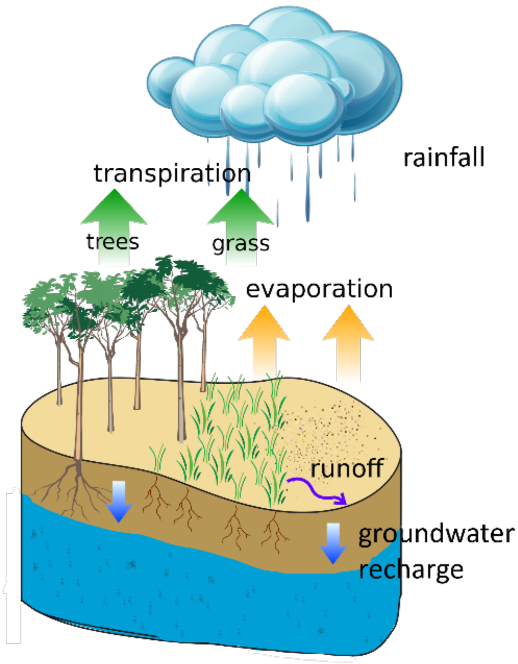

Figure 3.2: Conceptual diagram of water balance based on Palmer (1965) - modified from Toews (2007)

3.2 Data description

3.2.1 Precipitation

Spatial and temporal variations of precipitation are difficult to represent adequately due, mainly, to availability and quality of observed data. The quality of observed data, obtained from rainfall gauging stations, can be limited by the location and errors in measurements, and lack of temporal resolution. EO data, obtained from gridded precipitation products, can provide an alternative to observed data; however, estimates of precipitation from satellite data, can be limited by temporal sampling and algorithm errors (Centella-Artola et al., 2020).

This issue is also a key consideration when selecting EO precipitation datasets for St. Kitts and Nevis. The mountainous areas in the islands receive annual averages of approximately 2,500-4,000 mm in rainfall, while coastal areas 1,016 mm (World Bank, 2021). These differences are difficult to measure due to the lack of gauging stations in the mountains. Previous studies in the Caribbean evaluated the performance of different gridded precipitation datasets, derived from satellite data (Jury, 2009; Martinez et al., 2019; Centella-Artola et al., 2020). Gridded datasets based on gauging data (e.g. Climate Hazards Group InfraRed Precipitation with Station (CHIRPS), PRECL, GPCC025) perform best (lowest absolute differences) and reanalysis datasets underestimating the monthly mean precipitation, with ERAi (e.g. ERA5) producing the best representation of observations (Centella-Artola et al., 2020). The authors suggested (based on their analysis) that CHIRPS was the best gauge and satellite-derived dataset for the Caribbean sub-region where St. Kitts and Nevis is located.

EO-based products (CHIRPS, ERA5, NASA-TRMM, CRU TS) were considered for the calculation of the water balance in this report and compared with data from a gauging station (RL Bradshaw) with a record from 1980 to 2014 (Figure 3.3). Other data available from rainfall gauging stations show monthly averages covering the period from 1930 to 2006, which makes the comparison to EO data less meaningful (since the individual year data are not available). The analysis of these products highlighted the uncertainty in the data. CHIRPS, ERA5 and NASA-TRMM perform similarly, however data produced by the Climatic Research Unit

(CRU) of the University of East Anglia, generates higher levels of precipitation. Based on previous studies mentioned above, and the analysis of different datasets compared in this report, and considering the temporal and spatial resolution of the data, and the need for a product with regular updates, CHIRPS was selected as the most appropriate dataset to calculate the initial water balance of St. Kitts and Nevis, however it is recognised that when compared to other data sets it may be conservative and this would impact on the water balance, understating recharge. We will address this issue when we develop our recharge model, reviewing in more detail the different rainfall datasets and gauged data from both islands.

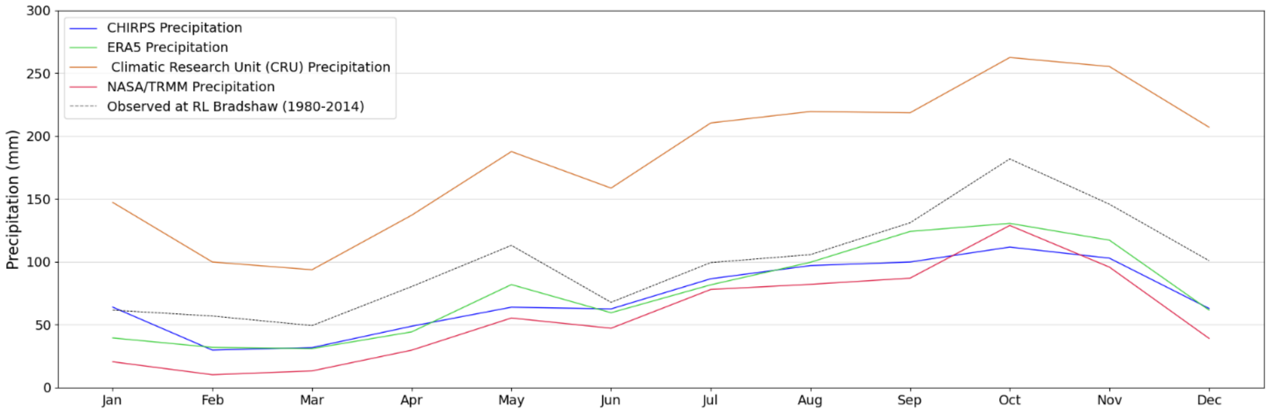

Figure 3.3: EO datasets compared against observed data from RL Bradshaw rainfall gauging station in St. Kitts

Precipitation data was obtained from the CHIRPS data monthly timeseries, which are rainfall estimates from rain gauge and satellite observations (Funk et al., 2015). The CHIRPS dataset extends almost globally and ranges from 1981 to near-present. It uses the Tropical Rainfall Measuring Mission Multi-satellite Precipitation Analysis version 7 (TMPA 3B42 v7) to calibrate global Cold Cloud Duration (CCD) rainfall estimates incorporating station data in a two-phase process, as shown in the schematic description in Figure 3.4.

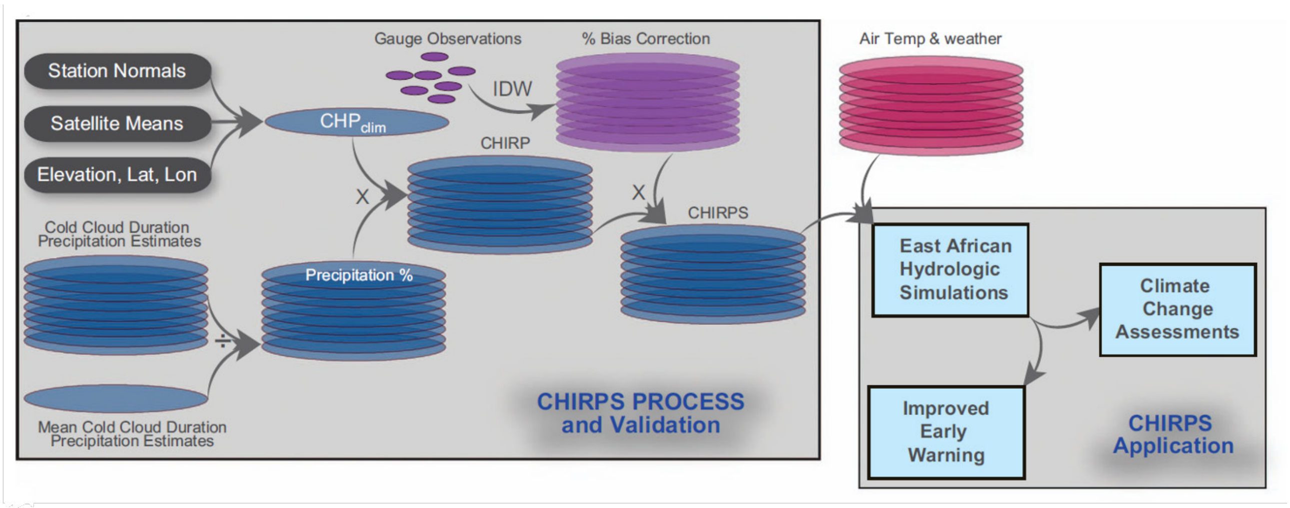

Figure 3.4: Overview of CHIRPS process validation, production and example application scheme (Funk et al., 2015)

An example of a spatial daily gridded data set for St. Kitts and for Nevis is shown in the next figure (Figure 3.5). Figure 3.6 shows the monthly mean rainfall, averaged across each island, for the period 2001-

2022. Precipitation values are marginally higher in St. Kitts for monthly values but very similar when annual means are analysed.

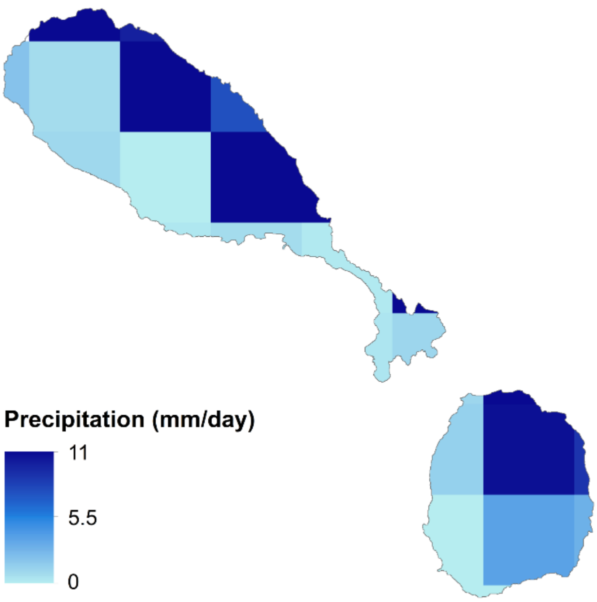

Figure 3.5: Example of daily gridded precipitation data for St. Kitts and Nevis

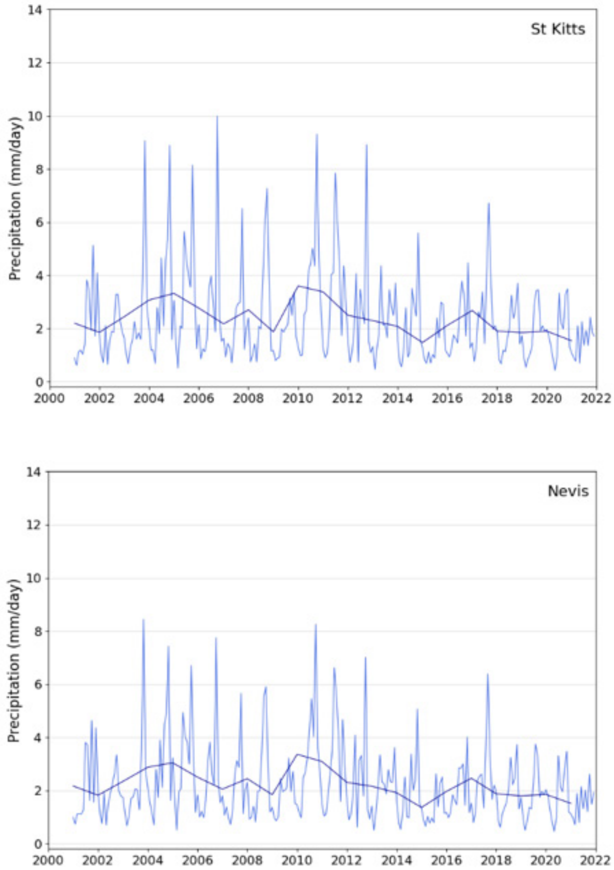

Figure 3.6: Monthly timeseries of average precipitation for each island. Dark blue line represents the annual mean precipitation

3.2.2 Evapotranspiration

Due to the difficulty in measuring evaporation and transpiration directly, there is a lack of reliable data, and accurately estimating evapotranspiration (ET) can be complex. This is no different for St. Kitts and Nevis, but remote sensing can be used to estimate values of ET globally. For the water balance calculation, MODIS ET gridded data sets at 500 m spatial resolution were used (Running et al., 2017). These are 8-day composites of ET, Latent Heat Flux (LE), Potential ET (PET) and Potential LE (PLE) along with a quality control layer. The initial algorithm for computation of MODIS ET (Mu et al. 2007) used the Penman–Monteith ET formula (Monteith, 1965) and MODIS land cover, albedo, Leaf Area Index (LAI), Fraction of Photosynthetically Active Radiation (FPAR) and Enhanced Vegetation together with daily meteorological reanalysis data from NASA's Global Modeling and Assimilation Office. Timeseries of ET for St. Kitts and for Nevis are shown in Figure 3.7. ET values are very consistent for the 20-year period analysed and very similar in both islands.

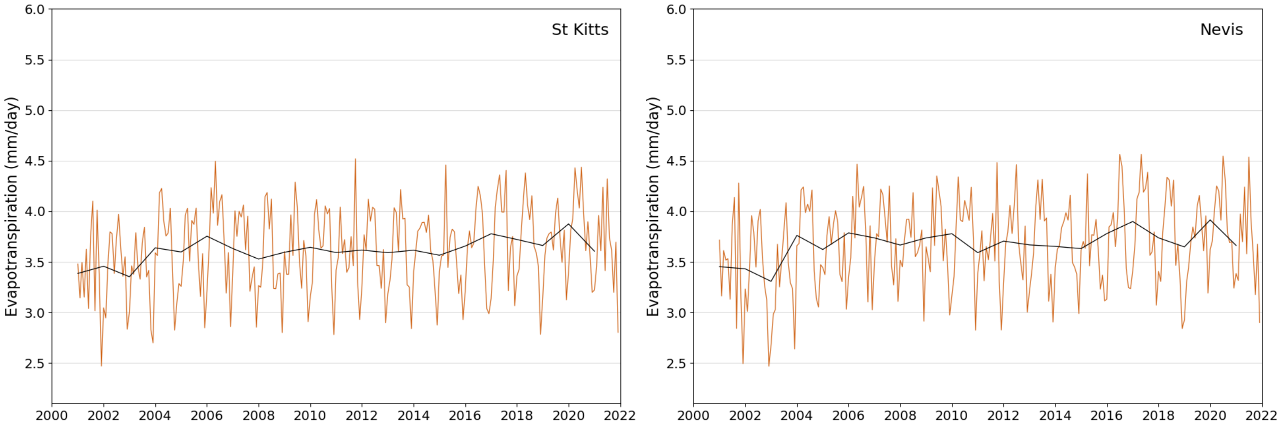

Figure 3.7: MODIS evapotranspiration timeseries for St. Kitts and for Nevis, for the period 2001-2022. Dark brown line represents annual mean ET

3.2.3 Surface runoff

Surface runoff for the water balance was obtained from ERA5, the 5th generation reanalysis project from the European Centre for Medium-Range Weather Forecasts (ECWMF). Reanalysis products combine model data and observations, using a technique called data assimilation, based on the method used by numerical weather prediction centres, where every few hours (12 hours at ECMWF) a previous forecast is combined with newly available observations to produce a new best estimate of the state of the atmosphere, called analysis, from which an updated, improved forecast is issued. Surface runoff is defined as the water that drains away over the surface. Runoff is a measure of the soil water availability, and can be used as an indicator of drought or flood (Hersbach et al., 2019). Timeseries of surface runoff for St. Kitts and for Nevis are shown in Figure 3.8.

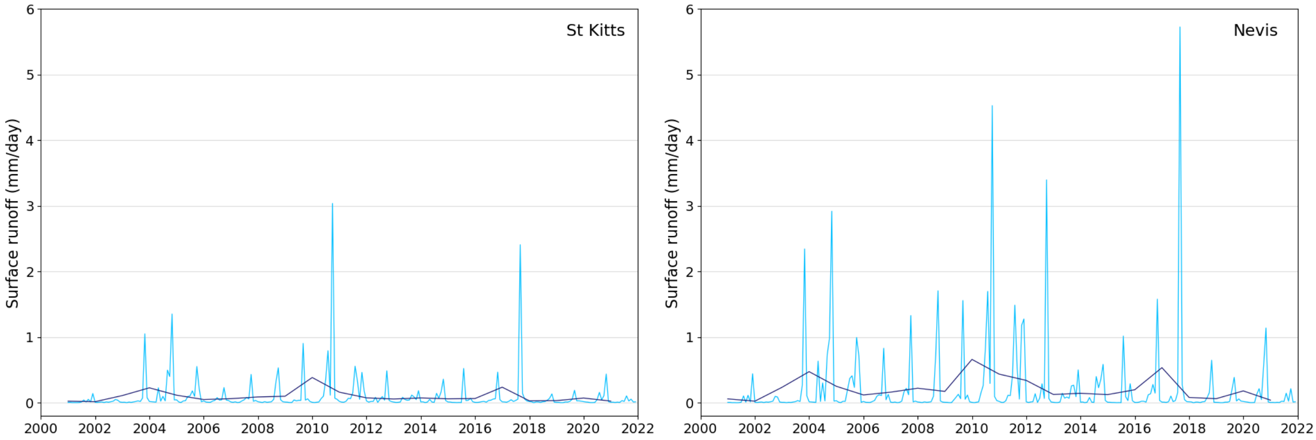

Figure 3.8: ERA5 surface runoff timeseries for St. Kitts and for Nevis, for the period 2001-2022. Dark blue line represents annual mean surface runoff

3.2.4 Estimation of groundwater recharge

Groundwater recharge (GR) is computed using the regression equation developed by Gemitzi et al. (2017). As one of the main components of the water balance that is difficult to quantify due to the complexity of recharge processes and limited observations, GR for St. Kitts and for Nevis is estimated by a simple regression equation developed by Gemitzi et al. (2017), shown below (Equation (3.2)). The water quantity that infiltrates the surface to the subsurface can be used as an approximation of the infiltration (*I*) parameter in the water balance equation (Equation (3.1)).

$$GR = 0.5174 * (P - ET_{MODIS}) + 0.2154 \quad (3.2)$$

Where *GR* is groundwater recharge; *P* is precipitation; and *ET* is evapotranspiration.

For St. Kitts and for Nevis, whenever monthly ET exceeded monthly precipitation, negative groundwater recharge values were set to zero. Timeseries of GR for St. Kitts and for Nevis are shown in Figure 3.9.

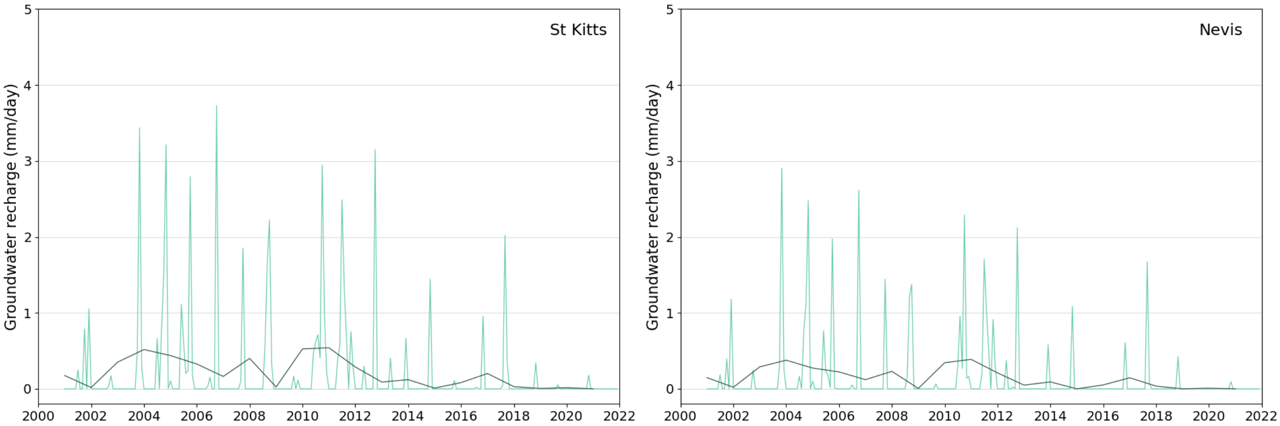

Figure 3.9: Estimated groundwater recharge timeseries for St. Kitts and for Nevis. Dark green line represents annual mean groundwater recharge

4 Results and discussion

Based on all datasets of precipitation, evapotranspiration and surface runoff, with estimated groundwater recharge, the water balance equation can be solved for moisture losses. Similar to the groundwater recharge calculation, when higher values of ET produce negative values of moisture loss, these are equated to zero. Figure 4.1 shows a monthly timeseries and yearly averaged values of moisture losses for both St. Kitts and Nevis. Results show a relative regular pattern, with slightly increasing losses from 2016 to 2021. This follows the same pattern with the ET rates and is very consistent and similar for both islands (Figure 3.7).

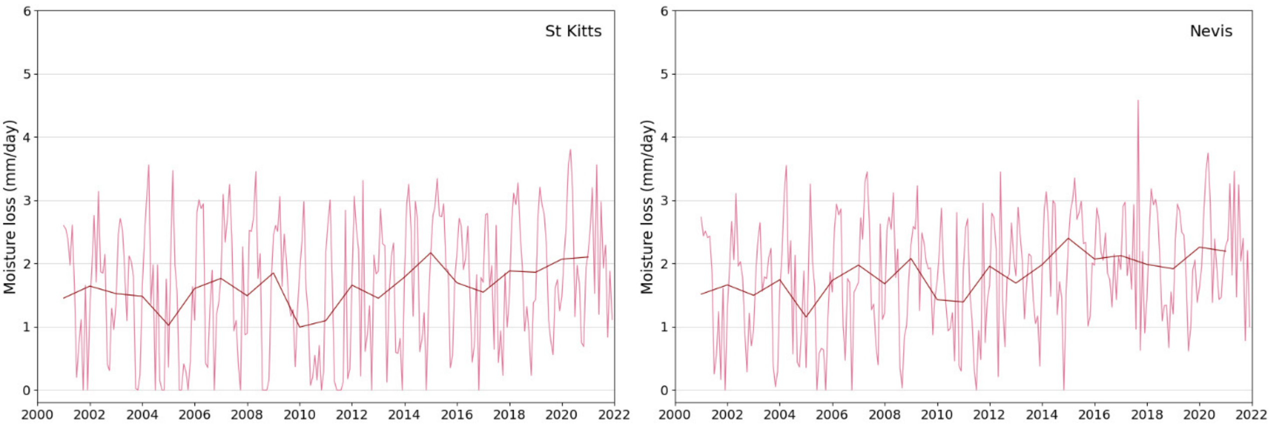

Figure 4.1: Estimated moisture losses for St. Kitts and for Nevis. Dark red line represents annual mean moisture loss

A common outcome observed in both islands is that ET is the largest component of the water balance when compared against the other parameters, which is easily observed when the sum per year is calculated. Results of the sum annual water balance for both islands and for the period of available data (2001-2022) are shown in Figure 4.2 too. The sum of monthly values per year approximates to a total of between 83.85 mm and 109.77 mm for St. Kitts (Figure 4.2c) and 83.5 mm/day to 114.85 mm/day for Nevis (Figure 4.2d).

Results of the mean annual water balance were calculated, as well as the percentages of each component to the water balance. These calculations are shown in box plots (Figure 4.3). The boxes in these figures represent the middle 50% of all the datapoints. The bottom and top of the boxes represent the 25% and 75% percentiles respectively, and lines the median or middle quartile of the data. The whiskers extend to all data available representing the lowest and highest points in each dataset. Table 4.1 and Table 4.2 show the respective mean annual water balance values for each of the two islands. These results confirm the previous statement that ET accounts for the majority of the water balance, and precipitation is the most varied parameter, with values that range from approximately 1.4 to 3.6 mm/day for St. Kitts and Nevis. Surface runoff is the parameter with lowest and more constant values for St. Kitts, with values that range from 0.1 to 0.4 mm/day, however these annual averages are higher for Nevis, reaching 0.7 mm/day. Estimated values of groundwater recharge and moisture loss differ between both islands with values in the range of 0 to 0.6 mm/day (groundwater recharge) and 1 to 2.4 mm/day (moisture loss). The same pattern is observed for the percentage of water balance for each component (Figure 4.3c and d). In St. Kitts, ET (for the period 2001-2021) on average accounts for 45.9%, and is the largest component of the water balance, followed by precipitation with 29.5% on average. The smallest component is surface runoff with 1.2% on average. In Nevis, ET (for the period 2001-2021) on average accounts for 45.6%, and is the largest component of the water balance, followed by precipitation with 27.2% on average. The smallest component, differing from St. Kitts, is groundwater recharge with 1.7% on average.

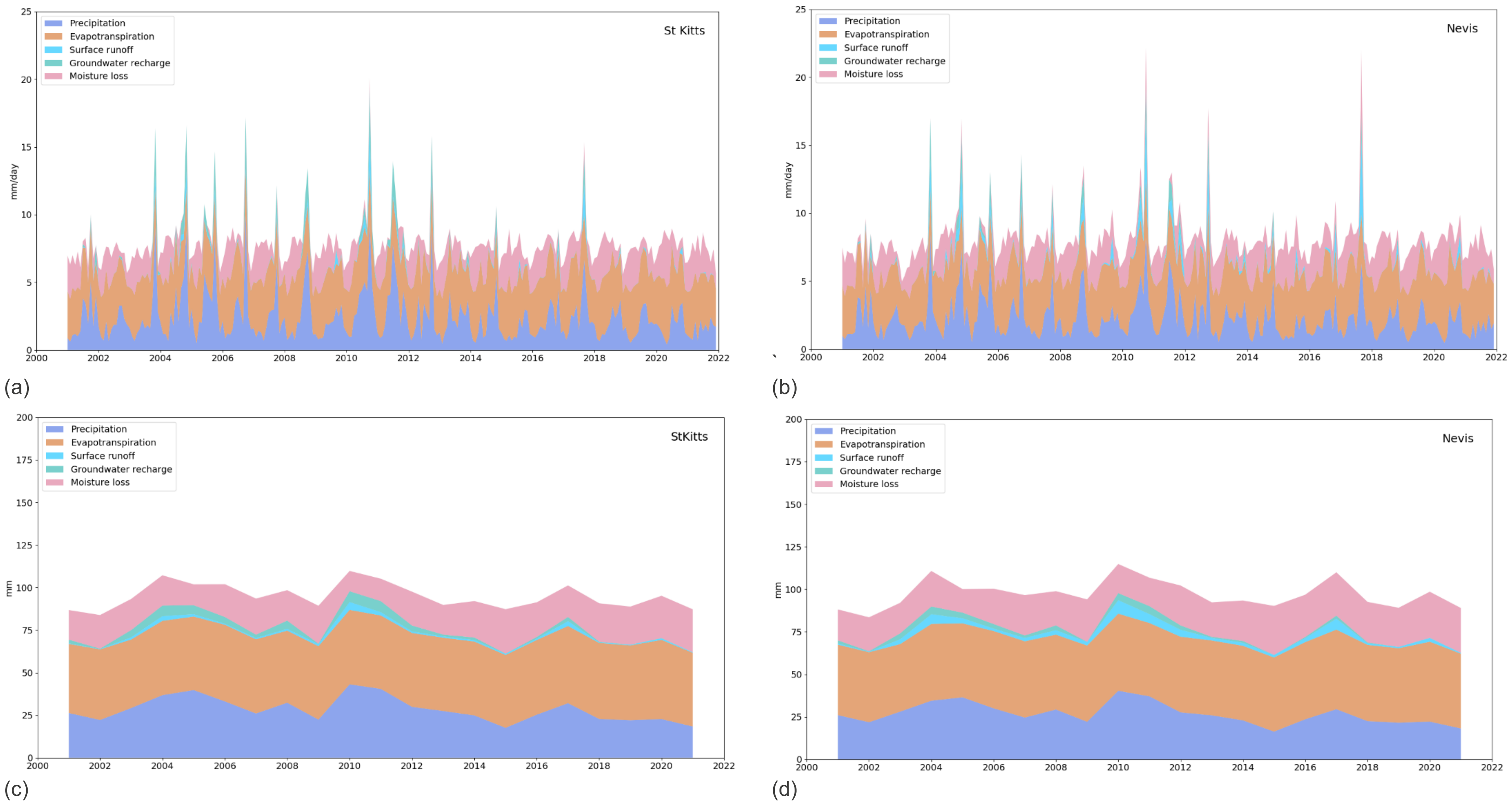

Figure 4.2: Stack areas for monthly values of the water balance in St. Kitts and in Nevis (a and b respectively). Yearly sum of water balance values for both islands (c and d)

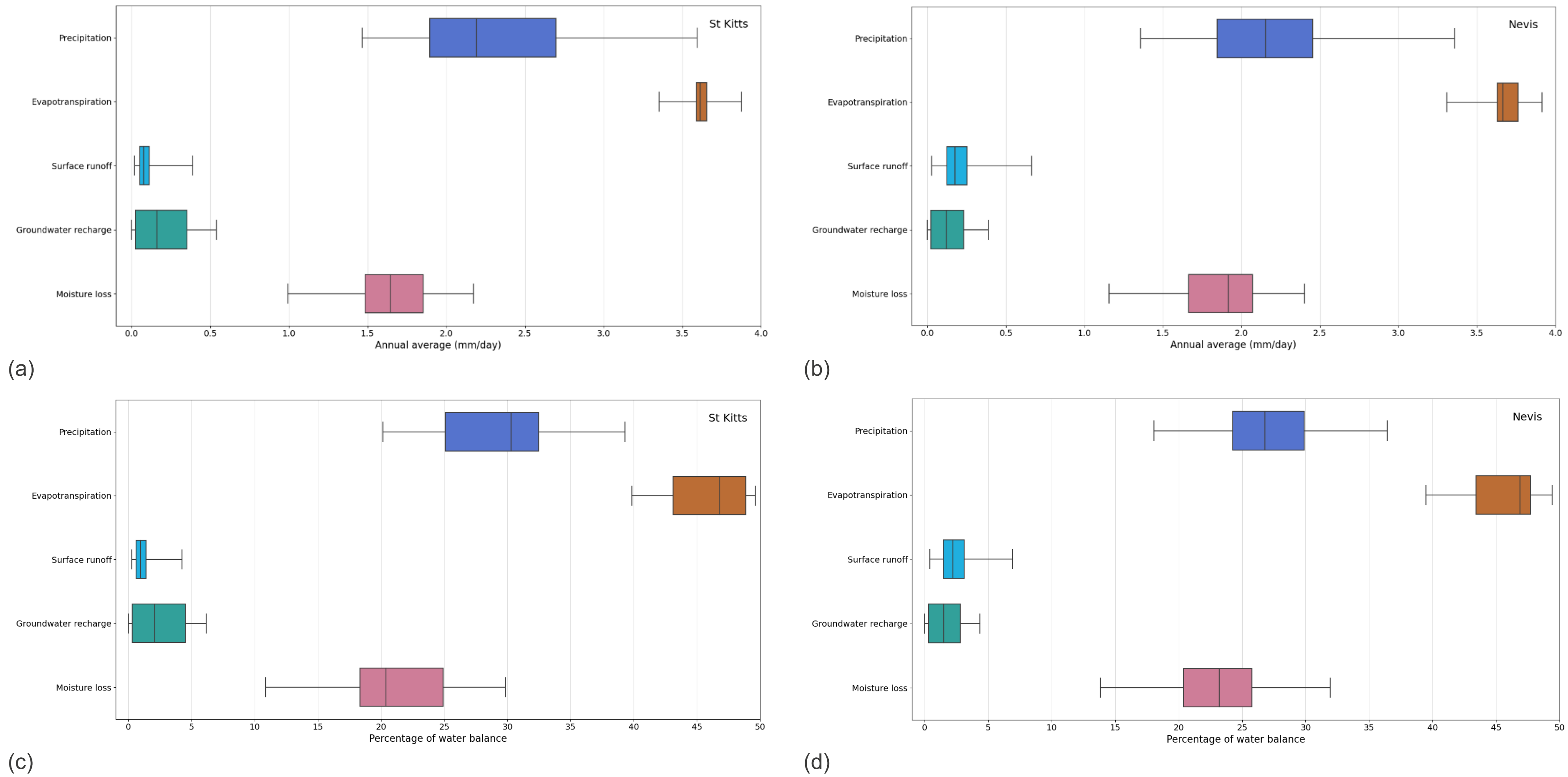

Figure 4.3: Annual average water balance components in both islands (2001–2021). Box lower and upper limits represent the lower and upper quartiles and black line the median value of the data set. Upper and lower whiskers extend to the smallest and highest values of the data

Table 4.1: Annual averages and annual percentage statistical values for St. Kitts (mm/day)

St. Kitts	Annual average					Annual percentage				
Parameters	**Min**	**25% percentile**	**50% percentile**	**75% percentile**	**Max**	**Min**	**25% percentile**	**50% percentile**	**75% percentile**	**Max**
Precipitation	1.47	1.89	2.19	2.70	3.60	20.15	25.10	30.30	32.48	39.30
Surface runoff	0.02	0.05	0.07	0.11	0.39	0.28	0.61	0.95	1.39	4.24
ET	3.35	3.59	3.62	3.66	3.88	39.84	43.11	46.82	48.87	49.61
Moisture loss	0.99	1.48	1.64	1.85	2.17	10.88	18.33	20.40	24.90	29.85
Groundwater recharge	0.00	0.02	0.16	0.35	0.54	0.00	0.31	2.09	4.51	6.16

Table 4.2: Annual averages and annual percentage statistical values for Nevis (mm/day)

Nevis	Annual average					Annual percentage				
Parameters	**Min**	**25% percentile**	**50% percentile**	**75% percentile**	**Max**	**Min**	**25% percentile**	**50% percentile**	**75% percentile**	**Max**
Precipitation	1.36	1.85	2.15	2.45	3.36	18.05	24.24	26.79	29.87	36.41
Surface runoff	0.03	0.12	0.18	0.25	0.66	0.39	1.46	2.23	3.11	6.93
ET	3.31	3.63	3.67	3.76	3.91	39.48	43.42	46.88	47.69	49.43
Moisture loss	1.16	1.66	1.92	2.07	2.40	13.85	20.40	23.21	25.76	31.95
Groundwater recharge	0.00	0.02	0.12	0.23	0.39	0.00	0.29	1.50	2.79	4.36

Conversion of groundwater recharge rate to volume

To convert the annual average groundwater recharge rate (units of mm/day) to volume of water (ML/d), the island area is multiplied by the annual average groundwater recharge rate (50th percentile). This gives the total volume of groundwater recharge.

St. Kitts area = 174 km^2

Nevis area = 92.98 km^2

St. Kitts volume of groundwater recharge = 174 km^2 x 0.16mm/d = 27.84 ML/d

Nevis volume of groundwater recharge = 92.98 km^2 x 0.12mm/d = 11.16 ML/d

5 Summary

For the current water balance calculation in St. Kitts and Nevis, the methodology proposed by Falalakis & Gemitzi (2020). Falalakis et al. (2020) was used as it included a basic calculation of groundwater recharge that most other water balance calculation methods do not. This calculation (Gemitzi et al., 2017) allows for groundwater recharge, based on an empirical relationship between precipitation and evapotranspiration, to be estimated and consequently used in the water balance equation. CHIRPS precipitation, MODIS ET, and ERA5 surface runoff data were processed and incorporated in the process. This approach was applied to both islands for the period of data available (MODIS ET was available since 2001), covering a 20-year period: 2001-2021. Monthly water balance parameters were computed (groundwater recharge and moisture loss) at the island scale to use as a representative example of each island. Several assumptions were made in this approach as the lack of data at this stage of the project does not allow for a more detailed calculation (i.e. at catchment scale). The individual monthly water balance components resulted in ET values to account for approximately 40%-50% of the water budget (yearly averages), making it the largest component of the water balance. Precipitation values accounted for approximately 20%-39% of the water budget. Surface runoff and groundwater recharge are the smallest components of the water balance calculation accounting for approximately 0.3%-4.2% and 0%-6.2% respectively. Zero values in the groundwater recharge calculation were assigned when ET surpassed precipitation values. Moisture loss accounts for approximately 11%-30% of the water budget.

This water balance calculation is the first step towards a model-based calculation and therefore it will be improved once models for both islands are set up, and calibrated with the data that are made available.

In a warming climate, higher temperatures are expected to increase evaporative demand, but how much this will induce moisture deficits and evaporative stress, as opposed to increased evapotranspiration, is partially dependent on climate (Maxwell & Kollet, 2008). Plant water availability is controlled by local precipitation and soil moisture, but soil moisture and streamflow may also be supported by shallow groundwater (Fan, 2015). Under climate change, increased evapotranspiration may shift the fraction of precipitation that runs off as surface water or infiltrates to the subsurface as recharge. Long-term shifts in recharge patterns can change groundwater levels (Portmann et al., 2013), with potentially negative consequences for availability of freshwater on the two islands.

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ISO 9001 Quality Management Systems CERTIFIED FS 516431

ISO 45001 Occupational Health and Safety Management CERTIFIED OHS 595357

ISO 14001 Environmental Management CERTIFIED EMS 558310

HR Wallingford is an independent engineering and environmental hydraulics organisation. We deliver practical solutions to the complex water-related challenges faced by our international clients. A dynamic research programme underpins all that we do and keeps us at the leading edge. Our unique mix of know-how, assets and facilities includes state of the art physical modelling laboratories, a full range of numerical modelling tools and, above all, enthusiastic people with world-renowned skills and expertise.

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