Water resources of Pacific atolls: evaluating sensitivity to climatic change and variability

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Abstract

Sensitivity approaches address the problem of uncertain projections of future climates and climate variability and provide useful results for decision-makers. In light of this, a scheme is developed to quantify sensitivity of freshwater resources of atolls in the tropical Pacific to climate variability and change on a regional scale. Results refer to soil moisture availability relevant to rain-fed agriculture and to groundwater recharge rates applicable to freshwater storage amounts and extraction rates. This sensitivity approach is suitable for a variety of climate studies and represents a powerful tool to gain essential information on the influence of climate on freshwater resources of atolls.

1. Introduction

Freshwater storage capacity on most atolls is limited as these small, low-lying islands have small water catchments. Surface water resources are extremely rare on atolls and groundwater exists only as a shallow freshwater lens floating on salt water (de Freitas, 2009). They are particularly vulnerable to extended droughts or periods of below average precipitation because of their limited storage capacity. The size and surface area of the island and the aquifer geology determine the upper limit of the freshwater lens (White et al., 2007), whereas the climate determines mainly the replenishment of the lens. This means the climate defines the sustainable yield of water that can be pumped out of the freshwater lens. But only a few islands hold reliable information and data about their groundwater resources, which hinders a realisation of sustainable water management (Falkland, 1999).

Freshwater resources of atolls depend on inter-annual variability of climate and by long term climate trends. Long term changes that might be expected in the future cannot be predicted without large uncertainties on the regional scale and these uncertainties are likely to persist in the near future (Barnett, 2001). One approach to cope with these uncertainties is to identify regions of high sensitivity to change, if a change in climatic conditions were to occur (de Freitas & Fowler, 1989). In light of the above, this study critically evaluates a simple methodology to assess freshwater resources and their sensitivity to climatic change and variability on atolls in the Pacific. It focuses on the groundwater resources as well as on the soil water availability which is crucial for plant growth and thus for rain-fed agriculture on these islands.

2. Method

Atolls have little or no influence upon cloud and precipitation patterns due to their low elevation (Lavoie, 1963), thus, synoptic climatic conditions of an atoll are almost identical with that over the surrounding ocean (Giambelluca et al., 1988). Because of this, datasets based on areal projections of satellite and surface observations and extended over large areas for latitude-longitude grid squares may be used (Uppalla et al., 2004). The ERA-40 reanalysis data that provides a consistent set of climate variables for the time period 1962 to 2000 is used here. Variables used include solar and longwave radiation, air temperature and precipitation.

The water balance for an atoll is given as

$$SD = P - EA + \Delta SM \quad (1)$$

where S_D is water surplus or deficit, P is precipitation, E_A is actual evapotranspiration and ΔS_M is change in soil moisture storage. P is given by the ERA-40 data sets. If E_P is available water balance models based on the Thornthwaite bookkeeping method (1955) can be used to estimate E_A. Priestley & Taylor (1972) estimate E_P using net allwave radiation (Q^*) and the slope of the saturation vapor pressure curve (**Δ**) as determining factors. Data on solar radiation downwards and net longwave radiation together with estimated albedo values (r) for atoll surfaces allow an estimate of Q^*. McAneney & Itier (1996) confirmed the suitability of this approach to estimate E_P in the humid tropics. The Priestley-Taylor method has been successfully used in other studies for Pacific islands as well (Giambelluca et al., 1988; Nullet, 1987). To run the simple regional water balance model assumptions have to be made on the available water capacity (*AWC)* of the predominant soil. Based on literature values (Nullet, 1987) r is assumed to be 0.25 and *AWC* to be 80 mm. Alley (1984) confirmed the accuracy of the model's estimated annual flows, but he notes problems in simulating accurate monthly flows.

Employing the above approach, one can estimate the mean monthly freshwater conditions under average climatic conditions for atolls (Figure 1). Freshwater resources can be assessed from two different points of view that require different approaches. To assess groundwater resources from a climatological viewpoint one has to examine recharge (S) rates and amounts. If impacts on agriculture are to be assessed soil moisture deficit (D) represents the crucial variable. Soil moisture availability is a key factor for agricultural planning (Giambelluca et al., 1988). D can serve as an indicator of plant water stress and agricultural drought. The sensitivity of these to climate variability or change may be used as a measure of the threat to the availability of freshwater resources. A definition of the areas of high sensitivity is given on the basis of an understanding of the interactions between freshwater resources and climate. The modified approach consists of four steps listed in Table 1.

The critical level for S varies depending on the state of development of the water management systems, population size and water using activities, which in the present circumstances is set at 100 mm. In the case of D, the critical level is assumed to be three months per year of severe deficit, which is defined in the current research as D being larger than 50% of the monthly P. This is to take into account that the negative impact on plant growth depends on the magnitude of D and varies between different plant types (Jackson, 1989). The impact of changed climatic conditions is assessed by running the water balance model under different climatic conditions. The results are mapped as shifts of isopleths on maps accounting for different freshwater resource questions. The areas of high sensitivity of freshwater resources on atolls are simulated using the water balance model and regional climate data from ERA-40.

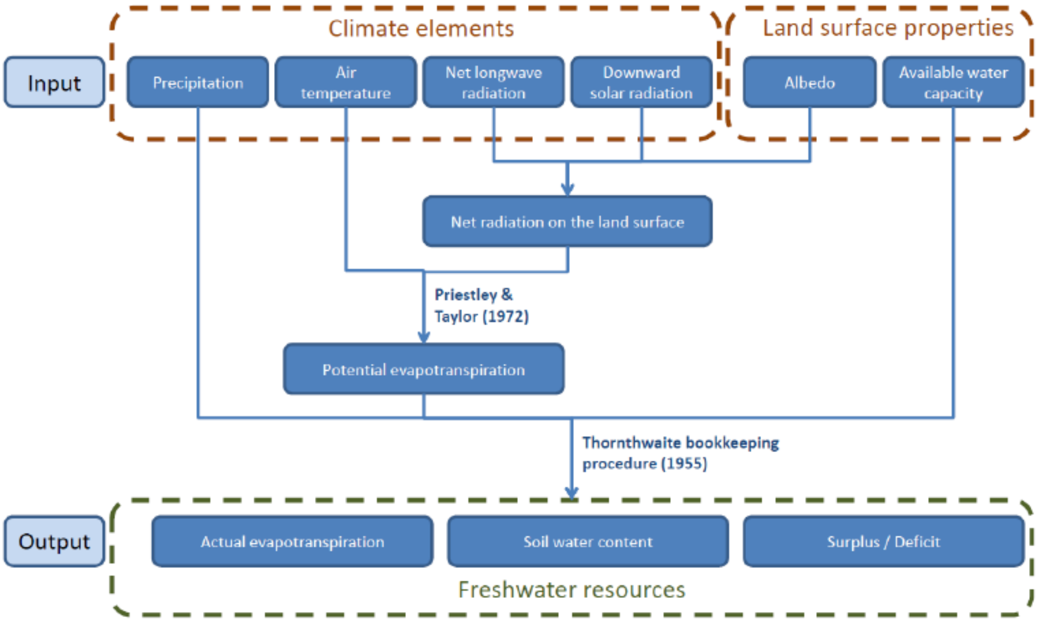

Fig. 5: Description of the water balance model with overview of the input variables, model parameters and output variables including intermediates

Tab. 1: Steps of procedure to assess areas of high sensitivity to climatic change and variability (modified after Parry 1985)

Step 1	Isolating the important climatic variables by modelling freshwater resources/climate relationships
Step 2	Establishing critical levels of freshwater resources by relating them to the use of freshwater resources on atolls
Step 3	Resolving climatic fluctuations and changes into fluctuations of the critical levels
Step 4	Mapping these as shift of isopleths to identify areas of high sensitivity

3. Results

The results focus on change and variability in P and Q^* and are divided into two sections: a) soil moisture conditions relevant for rain-fed agriculture purposes; and b) groundwater resource conditions relevant for all water extraction activities to supplement rainwater use. Some regions are not threatened by possible changed conditions, either because they exhibit a large excess of P or because the climatic conditions are too dry to benefit from variability or climatic change. Regions of interest therefore are located between very wet and very dry regions. The high sensitive areas to changing P conditions regarding the soil moisture conditions are shown in Figure 2. The results show that the islands of New Caledonia are highly sensitive to an increase in P of 20% and the Phoenix Islands to a decrease in P of 20%. Other locations, such as parts of Vanuatu and Fiji, Tonga, Niue, the Cook Islands and Kiribati, would experience deteriorated soil moisture conditions in years with 40% less P than in an average year or if average precipitation decreased by 40%.

Figure 3 illustrates the shift of the isoline representing an S of 100 mm per year assuming an increase or decrease in Q^* of 10% and 20%. Areas of high sensitivity are mainly of smaller extent than for the same change in P indicating a smaller influence of Q^* on the *S* rates. The area of high sensitivity in the northern part of the study area has a larger extent than the narrow belts at the Phoenix Islands and New Caledonia in the southern part.

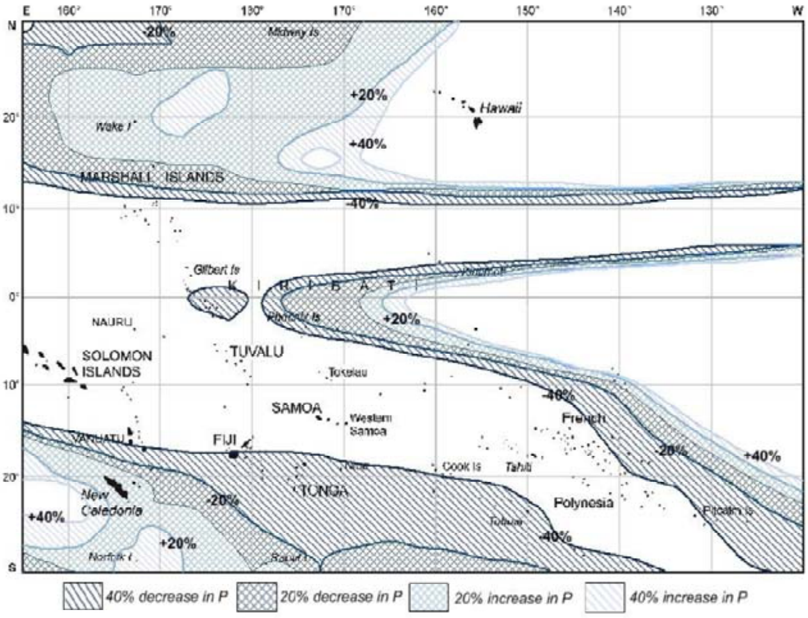

Fig. 6: Map of areas with high sensitivity to variability and change in precipitation. Shaded zones indicate the shift of the isoline of three severe deficit months assuming a specific percentage change in annual precipitation.

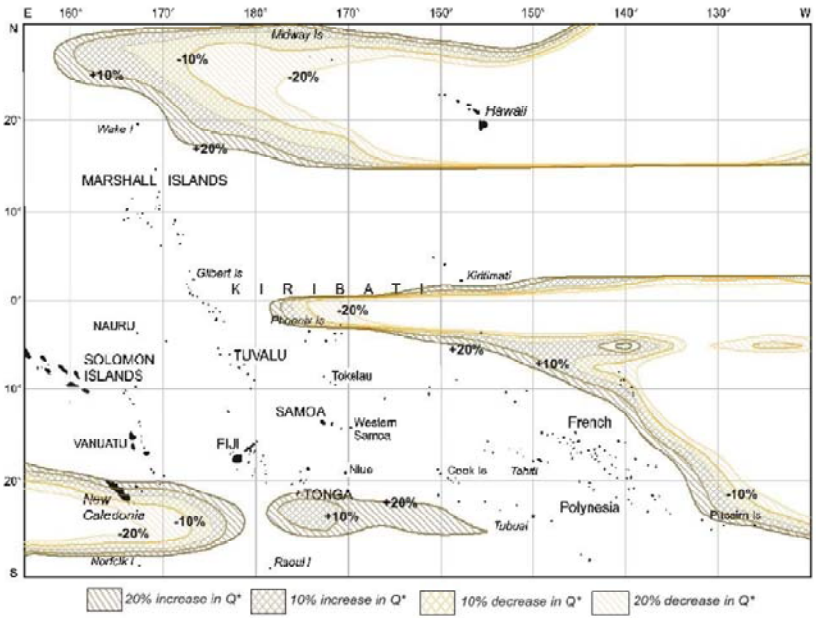

Fig. 7: Map of areas with high sensitivity to variability and change in net radiation. Shaded zones indicate the shift of the isoline of 100 mm of annual surplus assuming a specific percentage change in net radiation.

Climatic change and variability is not very likely to affect only one of both variables. Because of that a combined scenario including both variables is of greater reliability. Therefore the same procedure could be applied assuming change and variability in both variables giving more sophisticated results.

4. Discussion

The generalized nature of the method employed means that the reliability of the results needs to be carefully considered. Problems in simulating cloud properties cause an underestimation of radiation fluxes. Furthermore precipitation in tropical regions is overestimated (Uppalla et al., 2004). These biases in ERA-40 data have to be considered in the interpretation of the results of this study to avoid misleading results. Studies by Taylor (1973) and McGregor & Nieuwolt (1998) confirm the overestimation of P amounts by ERA-40 for areas near the equator, but show reasonable agreement for areas in higher latitudes of the study area. Although the various studies use data covering different time periods, it can be assumed that P is generally overestimated in equatorial areas. Only one study on E_P on atolls covering the whole tropical Pacific could be found, namely Nullet (1987), whose findings suggest E_P is largely underestimated due to an underestimation of Q^* all over the study area. In light of this, boundaries of the zones of sensitivity are very approximate. Model parameters r and AWC have to be adjusted to these to match soil and surface conditions of atolls to which the generalised result are applied. Knowledge of the patterns of change and variability of P and Q^* is also necessary to interpret the results. Change and variability of P was found to be of greater magnitude than change and variability of Q^* indicating the crucial importance of current and future patterns of P in the study area.

6. Conclusion

Possible impacts on the water budget on atolls under changed climatic conditions are examined. The approach converts changed climate conditions into impacts on freshwater resources. It provides a simple but powerful method to identify atolls that lie in areas of high sensitivity, even for regions with no data from climate stations. The results can be applied to specific atolls by adjusting model parameters to match local surface characteristics such as soil type and depth. The quality of results is not only a function of the data quality, but also of the appropriateness of the parameter setting. GPCP and ERBE data could be integrated in regional scale freshwater resource assessments based on the approach of this study. They represent more accurate datasets for the relevant climatic variables P and Q^* and thus are very likely to produce more reliable results. But for that purpose a method to adjust the different resolutions and time periods has to be developed.

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