An indicative index of physical susceptibility of small islands to coastal erosion induced by climate change: an application to the Pacific islands

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ABSTRACT
An objective method is proposed to evaluate the susceptibility of islands to climate change. As used here, susceptibility is an estimate of the potential for physical change of an island coast in response to likely changes in climate–ocean boundary conditions. The evaluation is based on an assumption that the intensity of impact due to climate and ocean processes can be typically related to four physical and quantifiable variables: island rock-type (lithology), island shape (circularity), maximum elevation and area. These four physical variables were used to determine a dimensionless index for each of 1779 islands across 26 countries and 8 island types in the Pacific Ocean. Most islands fell in the high (29%), moderate (23%) and low (23%) susceptibility classes, whilst the remainder were split between the extremes of very high (12%) and very low (13%). Eleven countries had islands with all five levels, while eight had islands with mostly high and very high ratings. The index may be used as a tool for rapid appraisal by international and regional agencies as well as national governments for prioritization of adaptation measures to a changing climate, particularly when combined with climatic and oceanic process variables, together with knowledge of population and infrastructure.

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1. Introduction

Each island in the Pacific Ocean has unique physical characteristics and geographical attributes, and is subject to climatic and oceanographic conditions particular to its location and tectonic setting. Despite the physical differences between islands, management decisions relating to the vulnerability of islands are made at a variety of spatial scales that encompass a hierarchy of landforms, an overview of the processes affecting them and the time scales over which they change. Spatial scales in common use for management of extensive continental and sub-continental areas are less relevant in the Pacific where management commonly is focused on small individual islands (Hay and Mimura 2013).

Nevertheless, a hierarchy of scales is apparent in the variety of literature addressing the management of Pacific islands and archipelagos. Management decisions range from fine scales (small proportions of an island area) appropriate for site-specific locations (such as those recommended in
Nunn (2000)) to broader scales used in formulation of policy and strategic decisions for countries or regions encompassing numbers of islands and archipelagos (for example Lane (2006); Lane et al. (2013)). Each management scale in the hierarchy accords with the geographic area to be managed as well as the climatic and oceanographic processes most relevant at that scale. Ultimately, local management problems with specific objectives will be those requiring direct action; for example, improvements to reduce leakage in water supply systems (White and Falkland 2010) or establishment of shore protection measures at a particular place (Duvat 2013).

In contrast to local and sector specific issues, there have been few regional assessments spanning all of the islands within the Pacific region. Regional-scale problems are of a more general nature and relate to the governance of large administrative areas or regions, similar to those considered by organizations such as the Caribbean Community (CARICOM) and the Secretariat of the Pacific Community (SPC) as well as international agencies like the World Bank and the United Nations Development Programme. For instance, at a regional level, intergovernmental decisions may lead to region-wide adoption of a procedure for responding to impacts caused by catastrophic events such as tropical cyclones or tsunamis (CCRIF 2008). In this paper, regional-scale strategic information is used to estimate the relative susceptibility of islands in the central Pacific to climate change based on a comparison of their lithology and form. Examples provided herein focus on the comparative susceptibility of whole islands in response to potential changes in climate and ocean conditions. However, the estimate of island susceptibility is essentially a comparative index which could be linked to coastal and terrestrial issues such as those associated with coastal erosion and inundation, water supply, land degradation and island habitation patterns.

At a regional scale, analyses of where landforms fit in an observed or conceptual sequence of natural change indicates whether an island, compared to another island, or a substantial part of an island, is likely to be susceptible or resistant to changes driven by external environmental processes. Clearly some island types are inherently more susceptible to long-term physical change than others (Campbell 2006). However a regional-scale study identifying the susceptibility of Pacific islands to risks associated with climate and ocean processes has been lacking to date. An index of indicative susceptibility of islands has potential for expedient identification of islands most susceptible or most resistant to such processes. In that context, the index may be used as a tool for rapid appraisal by international and regional agencies as well as national governments for prioritization of adaptation measures.

The measure of susceptibility developed in this paper is based on the physical composition and geometry of whole islands. Herein, the measures used to define an island coast are the four primary variables common to all islands: lithology, elevation, area and shape. These coastal attributes can be described independently of coastal dynamics, and considered separately from people and their use of land or nearshore waters. In this context, identification of the unique characteristics of an island’s morphology determines its susceptibility, its physical resilience to natural environmental change and is a fundamental first step in hazard or risk assessment. This approach treats descriptors of landforms, dynamics and people as discrete sets of variables. It acknowledges that islands are separately subject to different climates according to their geographic location as well as the oceanographic conditions particular to their tectonic and oceanographic setting.

Subsequent steps in broad-scale vulnerability assessment of island coasts involve two further steps: first, determination of the primary attributes of extreme weather events and ocean processes and their probable impact on the particular physical attributes of each island, especially their coastal margins; and second, the degree to which the impacts of extreme weather events and ocean processes threaten the well-being of island populations and the infrastructure supporting them. These steps are not considered in this paper.

2. Methods

A regional-scale susceptibility index was developed for 1779 islands across 26 Pacific island countries (‘countries’ used here to include sovereign states, territories and island groups) between
latitudes of 30° S and 30° N and longitudes 127° E and 83° W (Figure 1). The first stage for creating the index was compilation of a database of islands to form the basis for the analysis and to categorize the island types that was based on lithology and elevation; two characteristics that have been used in other vulnerability and sensitivity studies (Gornitz 1990; Shaw et al. 1998). The second stage required identifying and quantifying variables to develop the index. Variables selected for the susceptibility index had to be readily available for every island or easily calculable as well as quantifiable. The physical composition and geometry of the islands were described by four variables that satisfied these selection criteria: lithology, circularity, maximum elevation and area. Geometric characteristics of circularity, maximum elevation and area are quantitative measures and the lithological divisions are subjective with a relative ranking applied. The variables were ranked and the ranks combined to determine a relative measure of resistance and susceptibility of a whole island to change in structure with changing climate–ocean processes.

The database created included information on island name, island type, country, area, perimeter and maximum elevation for each of the 1779 islands. This is the first compilation of an overarching record of Pacific island characteristics, although substantial descriptions of single attributes have been collated for parts of the region. Motteler and Bryan (1986) was the main reference for island names, supported by data from Google Earth and country reports. The geographic location of islands and polygons of their shorelines were mainly derived from the World Vector Shorelines (WVS) (Soluri and Woodson 1990), augmented by manual digitization from satellite imagery and topographic maps where data were not available from WVS or its accuracy was questionable, in that they did not align with a background map.

The index required categorization of the islands into island types; the objective being to capture the diversity of physical and natural attributes of islands to assess their relative susceptibility. The classification is intended to be valid at a regional scale and is based on two attributes: geological composition (lithology) and elevation. The choice of these two variables reflects the dominant controls on a broad range of characteristics of Pacific islands, including their erodibility and resistance to erosion, their drainage (surface or subterranean) and their landscapes. Whilst recognizing that

![Figure 1. Pacific region with the 26 countries studied.](image)
few islands comprise just one lithology, those identified here are similar to those in several other schemes (Campbell 2006). Islands were classified into eight categories based on criteria developed by Nunn et al. (2015). The criteria included lithology and elevation; namely continental, volcanic high, volcanic low, composite high, composite low, limestone high, limestone low and reef islands. The division between high and low islands was taken at 30 m, an arbitrary elevation though one that provides a reasonable upper limit to the insular coastal zone that includes for example coastal cliffs, scarps, slopes and valleys as well as coastal vegetation that receives salts from sea spray blowing inland from the ocean (McLean 1980) and storm surge run-up from tropical cyclones (Ferry et al. 2010). Using these two criteria applied to 1779 islands, two types stood out; reef islands (36%) and volcanic high islands (31%). These eight categories were used, in conjunction with national borders, as the basis for considering the geographic distribution of indicative susceptibility values.

Each of the four variables—lithology, circularity, maximum elevation and area—was ranked on a four-point scale, from lowest to highest, where rank 1 is the least susceptible (most resistant) to change and rank 4 the most susceptible (least resistant) to change. The four rankings were summed to obtain the indicative susceptibility index.

Lithology refers to relative hardness or softness of the dominant rock-type that comprises over 80% of the island area and provides a measure of erodibility or resistance of the island fabric to change through weathering or erosion. For example, an island comprised of unconsolidated sediments is likely to change its form more readily than a hard-rock volcanic or limestone island, although the effects of infrequent abrupt events such as mega-landsliding of volcanic soils (Clouard et al. 2001; Coombs et al. 2007) can be locally important. Lithology of islands was ranked on a comparative basis from lowest to highest susceptibility order as: (1) continental and volcanic, (2) composite, (3) limestone and (4) reef islands (Table 1). Continental and volcanic islands were combined for this index as these are mainly hard-rock islands. Composite islands are comprised of both volcanic rock and limestone with each separately contributing <80% of the lithological composition of a particular island. Any composite, volcanic or limestone island will have lower susceptibility than limestone due to their hard-rock component and higher resistance to change. Reef islands are mainly comprised of loose or unconsolidated material and are therefore most susceptible to change. The high and low classifications for volcanic, composite and limestone island types were combined for lithology because maximum elevation is included as a separate criterion, avoiding the inclusion of a geometric parameter twice.

Island shape is the most difficult of the criteria to interpret in susceptibility terms. Arguably, circular islands are less susceptible to change in structure with changing climate–ocean processes than irregular shaped islands because of their greater capacity for landform adjustment. A circular island is one with the smallest possible perimeter for a given area, compared with an island that has promontories and bays, a longer coastline and greater potential to change. Circular islands potentially have less impeded coastal alongshore sediment movement than islands with more complex and intricate margins.

### Table 1. Criteria for variable classes to determine indicative susceptibility.

| Material                                           | (1) LITHOLOGY | (2) CIRCULARITY | (3) HEIGHT | (4) AREA |
|-----------------------------------------------------|---------------|-----------------|------------|----------|
|                                                     | Rank          | Roundness index | Rank       | Maximum elevation (m) | Rank | Area (km²) | Rank |
| Continental or volcanic high or volcanic low        | 1             | Round           | 1          | >100     | 1     | >100     | 1 |
|                                                     |               | 0.75 to 1       |            |          |       |          |    |
| Composite high or composite low                     | 2             | Sub-rounded     | 2          | 30 to 100| 2     | 10 to 100| 2 |
|                                                     |               | 0.5 to <0.75    |            |          |       |          |    |
| Limestone high or limestone low                     | 3             | Sub-angular     | 3          | 10 to <30| 3     | 1 to <10 | 3 |
|                                                     |               | 0.25 to <0.5    |            |          |       |          |    |
| Reef Island                                         | 4             | Angular         | 4          | <10      | 4     | <1       | 4 |
|                                                     |               | 0 to <0.25      |            |          |       |          |    |
Circularity was the shape measure used and was calculated as a ratio of the shape of a circle to the shape of the island polygon, where shape equals perimeter ($P$) divided by the square root of the area ($A$). A circle has a shape factor of 3.54 ($P_{\text{circle}} / \sqrt{A_{\text{circle}}} = 2\pi r / \sqrt{(\pi r^2)} = 3.54$), with the circularity of an island calculated as $3.54(P_{\text{island}} / \sqrt{A_{\text{island}}})$. If an island was perfectly circular, the ratio would be 1, and for all other islands it would be less than 1, approaching 0 for the least circular islands. This index was then divided into four classes in 0.25 intervals and ranked from lowest to highest susceptibility according to: (1) $>0.75$, (2) 0.5 to $<0.75$, (3) 0.25 to $<0.5$ and (4) $<0.25$ (Table 1).

Island height, specifically maximum elevation, provides a surrogate measure of the susceptibility of an island to marine inundation, the stability of hill slopes and complexity of river catchments for example. Maximum elevation was used because it was the most readily available information pertaining to island height. Maximum elevation data were obtained from country reports, topographic maps, inferred elevations from satellite imagery within Google Earth and, where data were not available from these three sources, the Shuttle Radar Topography Mission (SRTM) data that forms the world Digital Elevation Model (DEM) was used.

Maximum elevations ranged from 0 to 4205 m, split into four classes from lowest to highest susceptibility according to: (1) $>100$ m, (2) 30 to 100 m, (3) 10 to $<30$ m and (4) $<10$ m (Table 1). Islands with $<10$-m maximum elevation were considered to be most susceptible to marine inundation such as over-wash due to storm surge (Terry and Falkland 2010). The 30-m maximum elevation marks the normal upper limit of routine marine influences on island landforms and littoral vegetation; islands with a maximum elevation greater than 100 m are unlikely to be affected by marine processes on a whole-island scale.

Area completes the three-dimensional geometric description of the island, together with height and roundness (circularity). The latter provides the base shape of an island whereas area provides the size of the base. At a regional scale, the size of an island, its area, has relevance in combination with other variables such that, overall, the perimeter of a small island is likely to be relatively more unstable than that of a large island. Area in this case was calculated in GIS using the WVS shoreline polygons that, with atolls, often included the entire perimeter of the atoll rather than each of the islets within it. It should be clarified that area was the land area only and excluded enclosed lagoons such as in atolls. For the whole data set, area ranged from 0.013 km$^2$ to 35,780 km$^2$. Island area was separated into four classes from lowest to highest susceptibility according to whether it was (1) $>100$ km$^2$, (2) 10 to 100 km$^2$, (3) 1 to $<10$ km$^2$ or (4) $<1$ km$^2$ (Table 1). The break points in the four classes for area were based on creating a range of ranks within the dataset in a distribution strongly biased to very small islands that are more likely to be subjected to coastal changes from climate–ocean processes than those islands with a larger perimeter.

Rankings for the four variables were summed without weighting to give a final estimate of the relative susceptibility of islands to changing boundary conditions. A weighting was not applied due to lack of a defensible weighting scheme, and because the four variables define the geometry of each island. The combined index was called ‘indicative susceptibility’ because the term refers to the relative susceptibility of one island compared to others. Since each of the variables used in the assessment had a range of 1–4, the final susceptibility score had a range of 4–16. This was then divided into a five-point scale of very low (4–6), low (7–8), moderate (9–11), high (12–13) and very high (14–16) susceptibility.

3. Results

Results derived from qualitative comparison of the geological composition and geometry of islands in the Pacific are considered from two perspectives. First, variation in the geographic distribution of indicative susceptibility for whole islands is examined at a regional scale on the basis of island type. This is done without regard for administrative boundaries. Second, the diversity of outcomes for countries in the Pacific area under consideration is determined.
3.1. Regional scale

Indicative susceptibility indices are presented for all 1779 islands in Figure 2. For the region as a whole, three-quarters (1334) of the islands fall into the low (23%), moderate (23%) or high (29%) susceptibility classes, whilst the remainder are nearly equally split between the extremes of very low (13%) and very high (12%) (Table 2). Most of the islands having high and very high susceptibility occur in a central arc from Palau in the NW to the Tuamotus in the SE and include many of the islands of Micronesia and Polynesia. On the other hand, most islands with very low and low susceptibility occupy either an inner band in the SW Pacific primarily of Melanesian islands, or comprise the more isolated groups of islands in the broad Eastern Pacific (Figure 2).

Table 2. Counts of indicative susceptibility per island type (the modal indicative susceptibility of each island type is shown in bold and colour coded).

| Island type       | Very Low | Low | Moderate | High | Very High | Total per island type |
|-------------------|----------|-----|----------|------|-----------|-----------------------|
|                   | Count    | % of island type | Count | % of island type | Count | % of island type | Count | % of island type | Count | % of island type | Count | % of island type |
| Continental       | 5        | 36%  | 6        | 43%  | 3         | 21%       | 141 (13%) |
| Volcanic high island | 218     | 40%  | 293      | 54%  | 34        | 6%        | 545 (31%) |
| Volcanic low island    | 13      | 17%  | 113      | 83%  | 1         | 1%         | 147 (8%)  |
| Composite high island | 15       | 15%  | 61       | 60%  | 26        | 25%       | 102 (6%) |
| Composite low island   | 3        | 13%  | 20       | 87%  |           |           | 23 (1%)   |
| Limestone high island  | 29       | 23%  | 97       | 76%  | 1         | 1%         | 127 (7%) |
| Limestone low island    | 77       | 42%  | 105      | 57%  | 2         | 1%         | 184 (10%)|
| Reef island           | 13       | 2%   | 404      | 63%  | 220       | 35%       | 637 (36%) |
| Total per rank       | 238      | (13%)| 405      | (23%)| 511       | (29%)     | 222 (12%)|
The distribution and modal values of indicative susceptibility for each of the eight island types are shown in Table 2 and Figure 3. Some island types are inherently more susceptible than others and, as these data show, each of the eight island types includes more than one susceptibility class. If an island is a continental, volcanic high or composite high island type, it is most likely to be in the low susceptibility category, ranging from very low to moderate. Conversely, a volcanic low, composite low or limestone high island is most likely to be in the medium susceptibility category, ranging from low to high. Limestone low or reef islands are most likely to be in the high category, ranging from moderate to very high. At this level of assessment, the majority of islands with a very high susceptibility index are reef islands.

3.2. National scale

The distribution and modal values of indicative susceptibility for each of the 26 countries are shown in Table 3 and Figure 4. The geographic distribution of the values demonstrates large variation in susceptibility, both between and within different countries, with the exception of Guam, Nauru and Niue, which are single-island countries. In Table 3, the modal indicative susceptibility rating for each country is shown in bold and colour coded. Eleven countries (Cook Islands, Federated States of Micronesia, Fiji, French Polynesia, Hawaii, New Caledonia, Palau, Papua New Guinea, Solomon Islands, Tonga, and Wallis and Futuna) have all levels of indicative susceptibility across their constituent islands. Four countries, including three single-island countries fall within one susceptibility category, with Guam, Nauru and Niue in the low susceptibility class and Tokelau in the very high susceptibility class. Other countries with islands that have mostly very high and high indicative susceptibility ratings are the Cook Islands, Federated States of Micronesia, French Polynesia, Kiribati, Marshall Islands, Tuvalu and the US Administered Islands in the Central Pacific. In contrast, 10 countries have islands that are mostly low and very low indicative susceptibility ratings, including, in addition to Guam, Nauru and Niue, the Chilean Islands (SE Pacific), Eastern Pacific Outliers, Fiji, Hawaii, Northern Mariana, Samoa and Vanuatu (Table 3).

4. Discussion

Despite the coarse nature of the indicative susceptibility measure developed here, the results provide a comparative perspective of 1779 Pacific islands on the basis of consistent diagnostic information across the entire region. The research has produced a regional-scale analysis and maps of indicative
susceptibility of whole islands that is independent of projected changes in climate and ocean forcing. It demonstrates regional and national geographical diversity in relative susceptibility (Figure 2) inherent to whole islands based on a combination of their lithology and geometry.

Notwithstanding the value of having developed a simple and defensible index, there are a number of shortcomings that also need to be acknowledged. Use of maximum elevation as a criterion is

Table 3. Counts of indicative susceptibility per country (the modal indicative susceptibility of each island type is shown in bold and colour coded).

| Indicative Susceptibility | Very Low | Low | Moderate | High | Very High | Total No. Islands |
|---------------------------|----------|-----|----------|------|-----------|------------------|
| Count | % of Country | Count | % of Country | Count | % of Country | Count | % of Country | Count | % of Country |
| American Samoa | 2 | 29% | 3 | 43% | 0 | 0% | 2 | 29% | 0 | 0% | 7 |
| Chilean Is. (S.E. Pacific) | 1 | 50% | 1 | 50% | 0 | 0% | 0 | 0% | 0 | 0% | 2 |
| Cook Islands | 2 | 13% | 3 | 20% | 1 | 7% | 4 | 27% | 5 | 33% | 15 |
| Eastern Pacific Outliers | 15 | 63% | 9 | 38% | 0 | 0% | 0 | 0% | 0 | 0% | 24 |
| Fed. States of Micronesia | 8 | 6% | 19 | 15% | 10 | 8% | 65 | 51% | 25 | 20% | 127 |
| Fiji | 39 | 11% | 18 | 38% | 47 | 22% | 44 | 21% | 1 | 0% | 211 |
| French Polynesia | 14 | 11% | 23 | 18% | 2 | 2% | 14 | 11% | 73 | 58% | 126 |
| Guam | 0 | 0% | 0 | 0% | 6 | 18% | 15 | 45% | 12 | 36% | 33 |
| Hawaii (USA State) | 8 | 50% | 2 | 13% | 2 | 13% | 3 | 19% | 1 | 6% | 16 |
| Marshall Islands | 0 | 0% | 0 | 0% | 6 | 18% | 15 | 45% | 12 | 36% | 33 |
| Nauru | 0 | 0% | 1 | 100% | 0 | 0% | 0 | 0% | 0 | 0% | 1 |
| New Caledonia | 7 | 24% | 9 | 31% | 9 | 31% | 3 | 10% | 1 | 3% | 29 |
| Niue | 0 | 0% | 1 | 100% | 0 | 0% | 0 | 0% | 0 | 0% | 1 |
| N. Mariana Islands | 9 | 56% | 4 | 25% | 2 | 13% | 1 | 6% | 0 | 0% | 16 |
| Palau | 1 | 3% | 3 | 9% | 16 | 48% | 12 | 36% | 1 | 3% | 33 |
| Papua New Guinea | 61 | 14% | 93 | 21% | 126 | 29% | 130 | 30% | 29 | 7% | 439 |
| Pitcairn Islands | 1 | 25% | 1 | 25% | 0 | 0% | 1 | 25% | 1 | 25% | 4 |
| Samoa | 5 | 71% | 2 | 29% | 0 | 0% | 0 | 0% | 0 | 0% | 7 |
| Solomon Islands | 29 | 7% | 114 | 28% | 107 | 26% | 137 | 33% | 26 | 6% | 413 |
| Tokelau | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% | 3 | 100% | 3 |
| Tonga | 6 | 5% | 5 | 4% | 56 | 45% | 51 | 41% | 6 | 5% | 124 |
| Tuvalu | 0 | 0% | 0 | 0% | 0 | 0% | 5 | 50% | 5 | 50% | 10 |
| US Admin. Is. in C. Pacific | 0 | 0% | 0 | 0% | 0 | 0% | 5 | 63% | 3 | 38% | 8 |
| Vanuatu | 27 | 33% | 28 | 35% | 18 | 22% | 8 | 10% | 0 | 0% | 81 |
| Wallis and Futuna | 3 | 21% | 3 | 21% | 1 | 7% | 6 | 43% | 1 | 7% | 14 |
| Total per rank | 238 (13%) | 405 (23%) | 403 (23%) | 511 (29%) | 222 (12%) | 1779 |

Figure 4. Indicative susceptibility distribution by country.
limited because, in many places, an elevation at one point cannot be taken as representative of the whole island. For example, an island could be 95% lowland with one high peak, which would skew the calculations to lower indicative susceptibility. Ideally, modal elevation of the low-lying landforms would be more appropriate, yet such data are not available for all islands at the resolution required.

The ranking cut-offs for circularity, maximum elevation and area are arbitrary, and there does not appear to be literature supporting this categorization. Break points used for ranking were selected intuitively to provide a spread of information for each variable, and this may explain any apparent bias in results away from reasonable expectation for some islands. Additionally, none of the variables were weighted, although it is recognized that different weightings might be applied to different island lithologies. An application of weighting warrants further investigation when more robust information becomes available. At a whole-island scale, lithology is arguably the most important of the four variables as it indicates a physical resistance to change and could have a higher weighting than the three geometric variables. It could also be argued that using only the two criteria of lithology and height would lead to a similar ranking as obtained here, however, the inclusion of area and shape allowed an improved predictor of susceptibility of the islands, as explained in the paragraph below.

Despite shortcomings of the limited number of variables used and the subjectivity in deciding the cut-off values, this first-pass assessment demonstrates a number of important points that can provide a basis for strategic planning by countries within the region and external organizations supporting adaptation to reduce the impacts of climate and ocean processes driving island change. Several observations emerge from this analyses that have relevance for regional and international agencies and national governments. First, a range of indicative susceptibility was identified for each of the eight island types (Table 2 and Figure 3); with very low to moderate susceptibility for continental and volcanic islands contrasting with mainly high to very high susceptibility for reef islands and intermediate values for the limestone islands. Second, the present analysis has shown that island type, by itself, is not an adequate predictor of susceptibility, but is considerably improved when moderated by data on island shape, size and elevation as illustrated by the following examples. Most (98%) reef islands are ranked as having high and very high indicative susceptibility because they have low maximum elevation and small area though shape is an important discriminator. Reef islands that are compact or circular in form are more stable than elongate islands (as demonstrated by McLean and Kench (2015)) that places them in a high rather than very high susceptibility category. Volcanic low, composite low and limestone high islands are of predominantly (76%–90%) moderate susceptibility with the remainder being low. Volcanic low and composite low islands are moderate because the low susceptibility attributed to hard-rock lithology and circular shape is compensated by the small area and low maximum elevation, suggesting the islands are susceptible to inundation. Limestone high islands are also moderate because the higher susceptibility attributed to lithology is compensated by a more normal distribution of maximum elevation and area, and lower susceptibility attributed to more circular islands. Continental, volcanic high and composite high islands are mainly (43%–60%) low susceptibility with the remainder being very low and moderate. These island types have lower susceptibility because their lithology and high maximum elevation are modulated by a broader distribution of circularity and area.

Third, focusing on the national results, the four countries of Marshall Islands, Tokelau, Tuvalu and the US Administered Islands in the Central Pacific have all of their islands in the high and very high susceptibility classes. This is mainly due to the geological composition of unconsolidated sediments and low elevation (<10-m maximum elevation) of the reef islands that also have a low circularity index (<0.25). The Chilean Islands (South-Eastern Pacific), Eastern Pacific Outliers and Samoa have all of their islands in the low and very low susceptibility classes. The majority of islands in these countries are of volcanic composition and have a high maximum elevation. This suggests they may be broadly resistant to erosion from changes in climate forcing. Eleven of the 26 countries have all 5 levels of sustainability across their constituent islands with the clear implication that major
differences in island susceptibility will exist and that a variety of policies, rather than an all-encompassing ‘one-size’ response, will be required.

The indicative susceptibility rankings provide a platform for broad-scale decision making at both a national and regional scales. At a regional scale, the comparative information provides international agencies with a broad understanding of where most of the susceptible islands and island types are located and our data show some surprising results. For instance, both Papua New Guinea and the Solomon Islands have numerically more low limestone and reef islands with high and very high susceptibility than the atoll island states of Tuvalu, Marshall Island and Kiribati that have been identified as ‘titanic states’ (Barnett 2005). At a national scale, the rankings provide information to national governments concerning which of their constituent islands are more susceptible relative to others. At both international and national levels, the results support prioritization for finer scale data collection and support for adaptation.

This is a first-pass assessment of indicative susceptibility of Pacific islands at a whole-island scale using four readily-available and calculable variables based on the intrinsic characteristics of all islands. There are many other processes and variables affecting the stability of island landforms and the degree to which they are susceptible to climate and ocean hazards. Some of these variables are geographical such as the proximity of other islands, while some are physical such as island topography and drainage. Others include climate–ocean drivers such as sea level fluctuations, tropical cyclones and drought as well as human induced factors. For example, Kumar and Taylor (2015) reported considerable variability in risks to infrastructure along the coasts of several islands in the Pacific. In many situations, detailed information is not readily available and was not considered at the whole-island scale. The susceptibility rank developed here is indicative because it is focused on island composition and geometry; and we acknowledge that many components of island stability will be affected by climate–ocean processes and their interaction with island landscapes.

Exposure to such factors will vary for the different islands across the region, not only because of the differences in island type and susceptibility quantified here, but also because the impacts on the islands, settlements established on them, their inhabitants, built infrastructure and land resources will be different. For example, islands with people and infrastructure distributed on coastal fringes at <30-m elevation should have a more detailed susceptibility assessment undertaken that incorporates coastal landforms, reef structures and proximity to other islands, while those above that elevation need to include relative relief, surface and subsurface drainage and proximity to river channels. The indicative susceptibility index reported here is clearly set at a broad scale. Importantly, the methodology can be further developed by using more detailed descriptors of island physiography and landforms. Indices derived from the variables may then be combined with the process drivers of topographic and coastal change to identify future vulnerabilities of islands to a range of oncoming climate–ocean processes (Nunn et al. 2015, 2016).

The susceptibility index developed here can be readily combined with the human dimension or biota information to look at vulnerability and adaptive capacities of island communities. As an example, Kumar and Tehrany (2017) combined the susceptibility index with the International Union for Conservation of Nature (IUCN) classification index of endangered, critically endangered and threatened terrestrial vertebrate species of the Pacific islands to investigate their vulnerabilities under climate change. A similar analysis can be undertaken to determine the vulnerabilities of island populations to climate impacts. The development of the susceptibility index and the accompanying large database in this research should encourage further work in this area by other researchers.

5. Conclusion

A broad-scale comparison of the geological composition and geometry of whole islands in the Pacific Ocean was made by combining measures of lithology, roundness, elevation and area for each island in an index. The four variables were selected because data were readily available or calculable for each island in the region. This enabled the development of an index suggesting the indicative
susceptibility of the whole island to possible changes driven by future climate change processes, but which was independent of those processes.

The ranking procedure provided statistics for eight island types and regional-scale maps of the indicative susceptibility of 1779 Pacific islands across 26 countries. The geographical diversity within the region and nationally was established for the broad level at which comparative information was available for all islands. A wide range of indicative susceptibility was identified for each of the island types examined; with mainly high to very high ratings for reef islands contrasting with very low to moderate susceptibility ratings for continental and volcanic islands. The dichotomy indicates a separate susceptibility assessment, perhaps using different assessment criteria, should be completed independently for the reef islands than that applied to other island types.

At a regional scale, most of the islands having high and very high susceptibility occur in a broad zone from Palau to French Polynesia, whereas those with very low and low susceptibility indices are either in the SW Pacific Ocean or the Eastern Pacific. At a national level, the geographic distribution of susceptibility values again identifies marked variation between and within different countries. Eleven countries have all levels of indicative susceptibility across their constituent islands, and eight have a majority of islands with high and very high ratings. The latter include the Cook Islands, Federated States of Micronesia, French Polynesia, Kiribati, Marshall Islands, Tokelau, Tuvalu and the US Administered Islands in the Central Pacific.

There is similarity in the island types shared between different countries and for which common problems may later be defined and addressed at a finer scale. In this respect, the results provide a basis for strategic planning by countries within the region and external organizations supporting adaptation to climate change. Nevertheless, management decisions should not be made solely on the basis of this research, although the approach used provides context and a rationale for more detailed, local-scale analyses.

**Data availability**

The data that support the findings of this study are openly available in Figshare as filename 40562_2016_41_MOESM1_ESM.csv as part of publication Nunn, P.D., Kumar, L., Eliot, I., McLean, R.F. (2016) Classifying Pacific islands. *Geoscience Letters*. 3: 7 at https://geoscienceletters.springeropen.com/articles/10.1186/s40562-016-0041-8

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