Reg Environ Change (2016) 16:827–839
DOI 10.1007/s10113-015-0794-1

ORIGINAL ARTICLE

Risk to water security for small islands: an assessment framework and application

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Received: 20 September 2014 / Accepted: 27 March 2015 / Published online: 30 April 2015

Abstract The freshwater resources of small islands are particularly vulnerable to the impacts of climate change and human stressors due to their limited extent and adaptive capacity. A water security approach is useful for effective management of the water resources; however, understanding risk to water security is critical in order to effectively plan and adapt to future changes. Currently available assessment tools generally do not incorporate risk and are not suitable for application on small islands, where the hydrogeological setting has unique vulnerabilities. The aim of this work is to provide a framework to characterize risk to water security for small islands. The risk assessment was developed using Andros Island, the Bahamas, as a case study area. Numerical modelling characterizes the response of the water system to potential future stressors related to climate change and human development, the results of which are integrated into the assessment framework. Based on risk assessment principles, indicators are determined for susceptibility, hazard threat, vulnerability and loss, in order to define the risk to water security. The resulting indicators are presented in geospatial maps that rank areas of risk to water security. These maps were provided to local water managers and policy-makers in the Bahamas as a tool to identify high-risk areas for near-term action and to inform long-term planning. The maps have also been used as a platform to engage local residents and raise awareness about the impact climate change and land-use activities may have on water security.

Keywords Small islands · Water security · Risk assessment · Climate change · Land use

Introduction

There is strong consensus that the impacts of climate change will have substantial consequences on small islands (Intergovernmental Panel on Climate Change (IPCC) 2014). In addition, small islands are susceptible to non-climate-related impacts because the availability of freshwater depends on human (water use), hydrogeological and physiographic factors, such as island shape and topography (White and Falkland 2010; IPCC 2014). Despite the increasing number of assessments related to impacts of climate change on islands, there has been little research demonstrating how this information is used in policy-making and adaptation (IPCC 2014). There is a need for assessment technologies that support decision-making in the context of climate change for small islands (Cashman 2014). Communication of risk to inform policy-makers and engage local populations is likely to increase resilience to impacts and is critical for effective adaptation (Dunn et al. 2012; IPCC 2012, 2013). In addition, climate impact research often does not incorporate concerns stemming from the local context (Barnett et al. 2008), especially those related to the outer (non-primary) islands within a given small island developing state (IPCC 2014). Therefore,

Editor: James Pittock.

Electronic supplementary material The online version of this article (doi:10.1007/s10113-015-0794-1) contains supplementary material, which is available to authorized users.

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there is often a lack of awareness at the local level about the specific threats posed by climate change (Nunn 2009), which can discourage actions that reduce vulnerability (IPCC 2012). For instance, previous studies in the Caribbean region have shown that, among other factors, increasing awareness about the risks related to tropical storms enhanced the effectiveness of adaptation and vulnerability reducing actions (Tompkins 2005; Adger et al. 2011).

This study aims to assess risk to water security for a low-lying, small limestone island to test the assessment framework and present the risk information in an accessible format for policy-makers and local stakeholders. The work was undertaken in response to local policy-makers, conservationists, resource managers and the Government of the Bahamas identifying the need to characterize risk to freshwater resources. The risk assessment presented here was completed in partnership with The Nature Conservancy Northern Caribbean Office and forms part of a larger project addressing watershed protection on several Bahamian islands. Due to the availability of data, the focus of the study is Andros Island; however, the intention is to provide guidance and transfer key lessons learned to other islands with similar hydrogeological setting within the Bahamas, and elsewhere. The components that determine risk vary in time and space so it is important to include temporal and spatial dynamics in risk assessment (IPCC 2012). Thus, this work builds a risk assessment methodology that incorporates the temporal and spatial aspects of the major stressors impacting water security on Andros Island.

Water security and risk

Water security describes the quantity and quality of water available for human use, environmental demand and economic interests (Global Water Partnership 2000; Grey and Sadoff 2007). There are varying definitions of water security across different disciplines, but essentially they represent access to sufficient quantity of water of acceptable quality to support human, environmental and economic needs (Cook and Bakker 2012). The United Nations' working definition of water security also includes aspects of political stability and prevention of water-related disasters (UNESCO-IHP 2012). Water security within the small island context generally relates to groundwater, which provides the majority of naturally occurring freshwater resources on many small islands (Falkland 1991). Although some islands utilize springs and streams or rainwater harvesting as a water supply source, groundwater tends to be the common source of sustainable water throughout the year.

Several water security assessment tools are available, most of which are based on the classification of a set of indicators that are measured at a specific point in time. Examples of indicators include: water stress as a measure of water usage versus availability (Falkenmark et al. 2007); water efficiency in food production (Rockström et al. 2007); water availability for basic human or environmental needs (Lautze and Manthrithilake 2012); water quality indicators measuring ecosystem or human health (Dunn and Bakker 2011); and the capacity for water governance (van Leeuwen et al. 2012). It can be argued that these indicator-based assessments do not assess "risk to water security" because the indicators are static in time and, as such, do not capture the potential consequences that may arise in an uncertain future (Dunn et al. 2012).

In general, risk describes the vulnerability to a hazard and the loss (sometimes also referred to as exposure or consequence) experienced if that hazard were to occur. Vulnerability is characterized by the predisposition (or susceptibility) to a hazard and the characteristics of the hazard itself. Different risk assessments identify the principal components of risk using different terminology or meanings, which can lead to confusion. For the purpose of this study, previous work (discussed below) is presented using a consistent terminology based on the following definitions, as used by Simpson et al. (2013) in a groundwater quality risk study:

$$\begin{aligned}\text{Risk} = {} & \text{Vulnerability to hazards} \\ & \times \text{Loss due to hazard occurrence}\end{aligned} \tag{1}$$

where

$$\begin{aligned}\text{Vulnerability} = {} & \text{Susceptibility} \\ & \times \text{Hazard characteristics and presence}\end{aligned} \tag{2}$$

Risk assessments are used in a wide variety of disciplines, from natural hazard management and engineering to actuarial finance and public health. There is a multitude of different risk assessment approaches and frameworks to address different purposes and objectives (e.g. Adger 2006; Birkmann 2006; IPCC 2012). Common to all risk assessments is the evaluation of the likelihood of adverse consequences occurring (Zwahlen 2004). Few water security assessments, particularly groundwater assessments, have characterized risk. Instead, most assessments have focused on characterizing the susceptibility (commonly referred to as the intrinsic vulnerability) of the aquifer, which does not require characterization of the specific hazards. Rarely are specific hazards included except in the context that such hazards exist and can be expected to enter into the aquifer system and move through the system in a particular way. The term specific vulnerability has been used to assess the behaviour of a specific contaminant along its flow path. Moreover, few approaches consider the loss component. Notable examples of water security assessments that evaluate risk include those developed under the European Commission COST Action 620, such as COPK, LEA, VULK and time-input (Zwahlen 2004), as well as a groundwater quality risk assessment framework developed to support source-water protection strategies (Simpson et al. 2013).

There are several popular methods that characterize "aquifer vulnerability" (noting that this is intrinsic vulnerability and thus is termed susceptibility in this paper), such as DRASTIC (Aller et al. 1987), GOD (Foster and Hirata 1988), AVI (Van Stempvoort et al. 1992), SINTACS (Civita and De Maio 1997) and EPIK (Doerfliger and Zwahlen 1997). Other assessments of aquifer susceptibility generally rely on the principles developed in the preceding examples, whereby a series of indicators are assigned weighted values and are combined to produce an overall index of aquifer susceptibility. Modifications may be made to represent unique aspects of a particular system, such as karst; however, the overarching principles remain the same.

Existing groundwater susceptibility assessments are generally based on a scenario of chemical (or biological) contamination derived from land-use activities, whereby hazards are introduced at the land surface and travel vertically down to the water table. However, such assessments are not fully suitable for an island context where the pathways for contamination are not exclusively vertical (Chui and Terry 2013). Freshwater on islands is contained within in a freshwater lens (FWL) that is replenished by fresh rainwater recharge (Fig. 1a). The lens is susceptible to contamination introduced at ground surface, similar to other aquifers. However, the FWL is surrounded by saltwater on the ocean boundary and is also underlain by saltwater, which may contaminate the aquifer. Storm surge may lead to overtopping of the island, thereby introducing saltwater at surface (Anderson 2002; Terry and Chui 2012). Over-extraction of groundwater may cause upconing of the saltwater from below the lens or lateral saltwater intrusion from the coast (Falkland 1991; Bobba 2002). In addition, a reduction in recharge or a rise in sea level can also compromise the FWL, leading to salt contamination or loss of lens volume (Falkand 1991; Oude Essink 2001). Thus, the water system on an island is susceptible to a range of hazards from all directions that can impact water quantity and quality (Fig. 1b).

Climate change is expressed by multiple stressors acting on a variety of spatial and temporal scales (Adger 2006). Increased temperatures and changes in the spatial distribution, frequency and magnitude of precipitation are expected to impact groundwater recharge (Green et al. 2011). Sea level rise will result in inundation and potentially a landward shift of the saltwater interface, particularly on low-lying islands. Water demand may increase with warmer temperatures or changes to land use. There is increasing research in risk assessment related to climate change impacts, particularly in support of adaptation and mitigation efforts (McCarthy et al. 2001). However, there are no risk assessment methodologies that address the unique scenarios encountered on small islands, where the freshwater resources are susceptible to hazards from numerous directions as described above. As such, a different approach for assessing vulnerability, and risk to water security, is needed for an island context. The specific objectives of this study are to: (1) develop a risk assessment methodology that is tailored to evaluate risk to water security for a small island that includes both the temporal and spatial aspects of risk and (2) present risk in an accessible format for use in policy development by policy-makers and local stakeholders.

Methods

The risk assessment was developed using Andros Island, the Bahamas, as a case study area. Andros Island is a low-lying limestone island with the highest elevations of approximately 20 m above sea level (masl) along the east coast and the lowest elevations (<1 masl) along the west coast. Due to limited land development, such as paving and buildings, recharge occurs across much of the land surface. The depth to water is relatively shallow, ranging from 1 to 5 m below ground surface (mbgs) (Little et al. 1973). A comprehensive summary of the hydrogeological setting of Andros Island is provided in Holding (2014).

The basic methodology of the risk assessment, including the identification of components that represent the island hydrogeological context (such as coastal hazards and upconing), is likely to be widely applicable to small islands, although the detailed framework presented in this study is influenced by the data that were available for Andros Island. Some components of the assessment are unique to Andros, such as the morphology of the FWL, and these components would need to be tailored to local specifications if the methodology is applied elsewhere. However, the methodology described in this paper is intended to provide guidance for application to other similar islands.

The approach relied on a solid understanding of the hydrogeology of Andros Island, which was gained through numerical groundwater modelling. Numerical hydrological models provide a key tool to understand the groundwater system and enable prediction of the hydrological response to various future stresses. There are numerous examples of previous modelling studies that have investigated aspects of FWLs and coastal aquifers. Modelling the impacts of

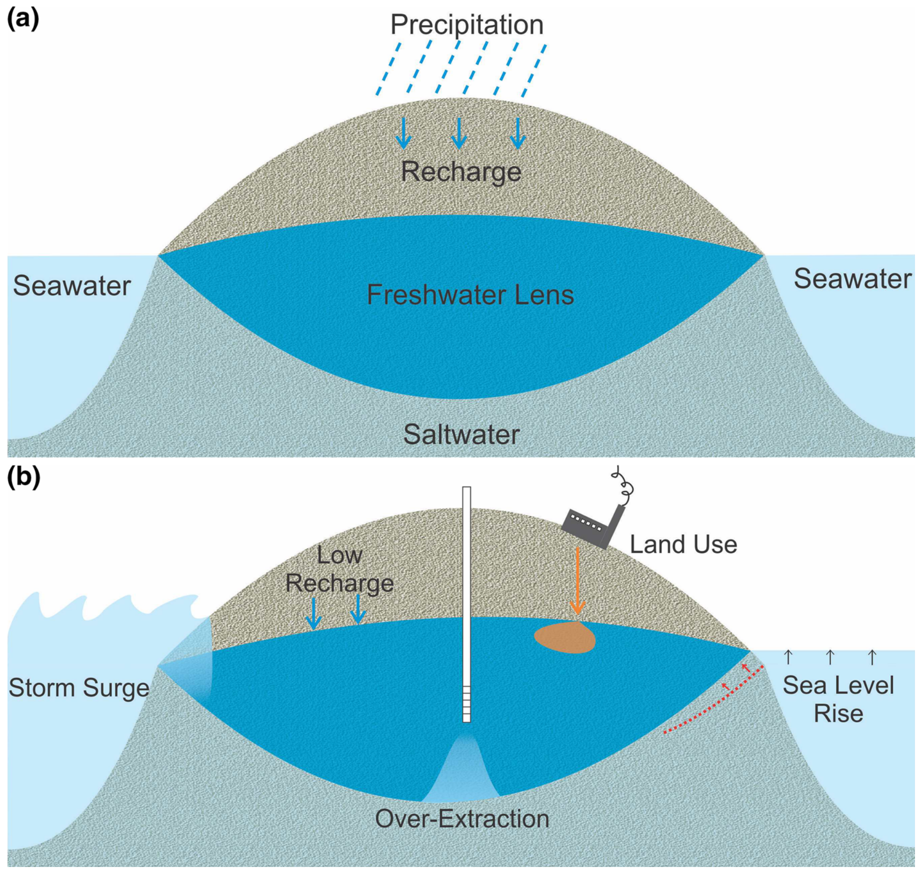


Fig. 1 **a** Freshwater lens; **b** hazards to water security in an island setting

climate change on small islands (and indeed coastal aquifers more generally) requires density-dependent flow and solute transport models to account for the density differences and concentration gradients between freshwater and salt water.

Models of the freshwater lens on Andros Island were developed using the density-dependent flow and transport code SEAWAT (Langevin et al. 2007). Modelling was undertaken at an island-wide and small scale to: (1) simulate the current location and thickness of the FWL on Andros and (2) assess the spatial and temporal response of the FWL to various human and climate change stressors. Details of the SEAWAT model setup for Andros are provided by Holding and Allen (2015). The model study focused on areas of the lens that are thick enough to provide a sustainable water supply, defined as a lens thickness greater than 2 m. The FWL thickness is defined in this study by a threshold concentration of 0.4 grams per litre (g/L) or less of salt. This threshold concentration is based on the water quality guidelines for salinity in the municipal supply on Andros Island and also falls within common definitions of freshwater containing less than 1 g/L of total dissolved solids (Freeze and Cherry 1977; Barlow 2003). Figure 2 shows the model generated FWL, which is consistent with historical observations of lens location and thickness (Little et al. 1973). There are multiple FWL on Andros Island; the thickest lens is situated in the northern region of Andros Island, and relatively thinner lenses are present in the southern region. The results are presented and discussed in detail in Holding and Allen (2015).

The risk assessment methodology is based on the basic risk equations (Eqs. 1, 2). Indicators were developed using an assessment framework to assign scores to each of the components of risk and, ultimately, to derive a risk index. The assessment framework was built within a geographical information system (GIS) platform to represent spatial variability. Temporal aspects of risk are reflected in the ranking of indicator scores that affect the overall risk index. Susceptibility is assessed to represent the current and potential future conditions of the lens, based on projections of climate change for the year 2100 (e.g. sea level rise, changes in recharge). In this way, the susceptibility indicator captures the potential temporal changes in susceptibility over this time period (i.e. present to 2100). Climate-related hazards are also assessed based on projections for the year 2100, whereas the assessment of human-related hazards incorporates the temporal aspects of hazard threat in terms of hazard duration or longevity. Therefore, the resulting risk indicators represent current conditions and the temporal variability of potential future conditions. The

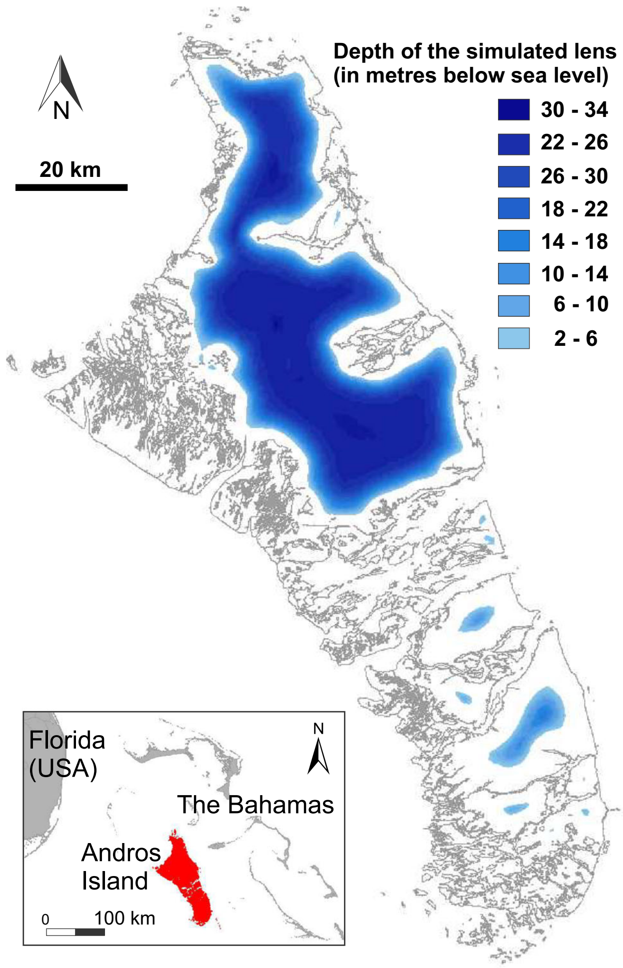


Fig. 2 Simulated freshwater lenses (FWL) on Andros Island

approach used to assess each component of risk is described in the following sections. A detailed outline of the methodology is provided in the Supplementary Material, alongside the scoring schemes (Tables 1, 2, 3).

Susceptibility

Susceptibility refers to physical characteristics of the island that either promote or minimize damage from hazards; susceptibility is irrespective of whether hazards are present or not. In this study, susceptibility of the FWL was considered, rather than the entire island or aquifer. For continental settings, aquifer susceptibility is assessed based on the premise that the entire aquifer is of concern. However, on an island, freshwater resides in a FWL; therefore, the FWL will only be susceptible to hazards where it is present. The susceptibility of the FWL to hazards was evaluated according to four categories:

S_{I}—Intrinsic susceptibility: the intrinsic susceptibility relates to the thickness of the FWL and the robustness of the lens to accommodate changes or buffer stressors, specifically the stressor of reduced recharge.

S_{PP}—Preferential pathways: the susceptibility of the FWL may be enhanced due to preferential pathways, where the FWL may be exposed or hydraulically connected to the surface. The FWL in these areas is therefore more susceptible to contamination either from chemicals or pathogens introduced at surface, or from overtopping by seawater following a storm surge.

S_{CT}—Coastal topography: the influence of coastal topography on susceptibility is represented by areas that are susceptible to saltwater inundation from sea level rise.

S_{OT}—Overall topography: the influence of overall topography on susceptibility is represented by areas of the island that are susceptible to storm surge overwash.

The scoring scheme is described in detail in the Supplementary Material. Separate susceptibility category maps were prepared in the GIS. The maps were then overlain, and the susceptibility scores summed to produce a total susceptibility value that varies spatially across the island. This value was normalized on a 1–10 scale, resulting in a total susceptibility (S_{Total}) indicator map illustrating the range of susceptibilities from low (1) to high (10). Each category was mapped as having either no susceptibility (0), or a ranking of low (1), moderate (5) or high (10) susceptibility. The scores were assigned to determine relative susceptibility within each category. The resulting scores were then weighted equally among the different susceptibility categories in order to determine the final susceptibility indicator. The equal weighting of each category and standard application of low, moderate and high ranking ensure that the S_{Total} indicator equally represents the susceptibility from each category.

Hazard threat

Hazard threat was defined based on the major stressors impacting the freshwater resources on Andros Island. These include stressors related to human activities (contamination and pumping) as well as climate change (sea level rise and storm surge); note that the reduction in recharge was accommodated in the susceptibility modelling as described above. Hazards related to human activities were identified on Andros Island from the results of a door-to-door hazard survey conducted by a local Bahamian organization (MCK Environmental) in partnership with The Nature Conservancy, a non-governmental conservation agency (MCK Environmental 2013). The objective of the survey was to collect geospatial data for residents and businesses on Andros Island related to practices that have the potential to impact water security, such as chemical use, waste disposal, wastewater management and water supply. Hazards related to climate change were based on the modelled impact of sea level rise and storm surge on the FWL.

Human activities

The hazard threat from human activities was determined based on the spatial data associated with each property identified in the door-to-door survey. Hazard threat indicators were assigned based on four hazard categories related to the specific hazardous activity:

H_w—Water supply and pumping: this hazard describes activities related to the extraction of groundwater from the FWL, which may lead to upconing of the saltwater from beneath the FWL.

H_{CS}—Chemical storage: this hazard describes the potential chemical contamination from activities related to the storage of chemicals.

H_{SS}—Septic systems: this hazard describes the potential pathogen contamination related to septic system usage. Due to the absence of municipal sewerage, the majority of properties on Andros Island use a septic system, although a small number of properties use composting toilets.

H_{AP}—Agricultural practices: this hazard describes the potential pathogen and chemical contamination related to agricultural practices, such as fertilizer/pesticide application and livestock rearing.

Each hazard threat from human activities was assessed according to its magnitude (quantity), the potential for release or occurrence and the strength/longevity of the hazard, with a score assigned to each. These scores were then multiplied to result in a value for each hazard. The magnitude of the hazard was based on the scale of the hazard, for example, the level of pumping or quantity of contaminants present. The potential for release or occurrence of the hazard was based on the storage or use of the chemical/pathogen so as to describe the potential of that hazard being released to the environment. The strength/longevity of a hazard was based on the degree of damage to the FWL, duration of the expected damage or ability of the FWL to recover and the persistence and mobility of the chemical/pathogen. The hazard fields were assessed based on a low (1), moderate (5) and high (10) score to provide a relative ranking amongst the hazards. The only exception was the magnitude/quantity field, which was assigned to reflect the range in magnitude of the potential hazard present. The scores for this field were assigned so that large magnitude/quantities were ranked relatively higher than smaller magnitudes within the hazard category (i.e. a large quantity of fuel ranked proportionally higher than a small quantity). The scoring scheme is described in detail in the Supplementary Material.

The total hazard for an individual property was determined as the sum of each category value (i.e. $H_W + H_{CS} + H_{SS} + H_{AP}$). The total hazard value was then normalized on a 1–10 scale resulting in a hazard threat from human activities (H_{HA}) indicator. The rankings are relative within each category, and each category is weighted equally to determine the final H_{HA} indicator. As a result, the hazard threat indicators represent the relative ranking of the cumulative hazard threat from each different hazard category. The score assignment for fields within each hazard category has a large impact on the final hazard threat indicator. Therefore, the scoring scheme was validated by checking that each property was appropriately ranked relative to the other properties. For example, a property with significant pesticide application ranked higher than a property with a small quantity of fuel storage or a moderately small septic system. The relative ranking approach removes some of the uncertainty in the score assignment and determination of total hazard threat.

Climate change

Hazard threat indicators for climate change were assigned within a similar assessment framework as used for hazards related to human activities. The principal difference is that hazards related to climate change are not related to individual properties or specific geospatial extents; therefore, the hazard threat is represented as equally present across the island (i.e. climate change impacts the entire island).

The hazard threats from climate change include:

H_{SLR}—Sea level rise: this hazard relates to the occurrence of sea level rise and associated land-surface inundation.

H_{STS}—Storm surge: this hazard relates to the occurrence of a storm surge, whereby high waves may cause inland flooding with saltwater.

The impact of reduced recharge due to climate change was not considered a hazard in this study; rather, it was assessed in terms of how reduced recharge impacts the susceptibility of the FWL (as described earlier). A score was assigned to each field: magnitude (quantity), the occurrence potential and the strength/longevity of the hazard. The scores were then multiplied to result in a value for each climate change hazard. The quantity field relates to the degree of inundation expected or amount of saltwater contamination that may occur. The occurrence potential field describes the potential for these hazards to occur. The strength/longevity of the hazard reflects the temporal variability in terms of the reversibility of impacts resulting from occurrence of the hazard. Similar to the assessment used for hazards related to human activities, the hazard fields were assessed based on a low (1), moderate (5) and high (10) score to provide a relative ranking. The scoring scheme is described in detail in the Supplementary Material.

The total climate change hazard was determined as the sum of each category value (i.e. $H_{\mathrm{SLR}} + H_{\mathrm{SS}}$). The total hazard value was then normalized on a 1–10 scale resulting in a hazard threat from climate change (H_{CC}) indicator value of 4.7. These climate change-related hazard threats are not shown on a map because the hazard threat is constant across the entire island and does not vary spatially. However, the threats posed from these hazards are included in the vulnerability assessment calculations as discussed below.

Vulnerability

The vulnerability indicator for human activities (V_{HA}) was determined based on multiplying the total susceptibility indicator by the hazard threat from human activities indicator according to:

$$V_{\mathrm{HA}} = S_{\mathrm{Total}} \times H_{\mathrm{HA}}. \tag{3}$$

As mentioned previously, the climate change hazards are constant across the whole island because they lack spatial variability. It is the geospatial distribution of the susceptibility, which provides the topographical and geospatial constraints on the hazard threats from climate change. Therefore, the vulnerability from climate change hazards (V_{CC}) was determined separately based on the coastal and overall topography susceptibilities and the hazards from sea level rise and storm surge, according to:

$$V_{\mathrm{CC}} = (S_{\mathrm{CT}} \times H_{\mathrm{SLR}}) + (S_{\mathrm{OT}} \times H_{\mathrm{STS}}). \tag{4}$$

The resulting vulnerability from climate change hazards was then added to the vulnerability resulting from human activities according to:

$$V_{\mathrm{Total}} = V_{\mathrm{HA}} + V_{\mathrm{CC}}. \tag{5}$$

The total vulnerability score map was normalized on a 1–10 scale to determine the total vulnerability (V_{Total}) indicator (Fig. 4c).

Loss

Loss describes the consequences of hazards occurring, resulting in an undesirable condition. There are many possible definitions of loss depending on the perspective of the stakeholders. Therefore, this component of the assessment framework may be modified to accommodate different perspectives on risk or updated to capture changing socio-economic and environmental scenarios (Adger 2006). In this study, the loss (L_{W}) indicator was defined in terms of access to freshwater (see Supplementary Material).

Risk

The risk to water security was determined by multiplying the total vulnerability indicator with the loss indicator according to:

$$\mathrm{Risk} = V_{\mathrm{Total}} \times L_{\mathrm{W}}. \tag{6}$$

The results were then normalized on a 1–10 scale to produce the risk to water security (R_{WS}) indicator map. A process tree is provided in the Supplementary Material (Figure A) that illustrates the steps to determine the various categories and indicators that result in the final risk indicator.

Results

Figure 3 shows the mapped scores for the various susceptibility categories. The intrinsic susceptibility of the aquifer is lowest for the thicker lens in the north and central regions of Andros Island (Fig. 3a). The smaller, thinner lenses in the southern region correspond to a large area of moderate susceptibility, where the FWL may only provide a small-scale water supply but is likely to be impacted by reductions in recharge. Areas of high intrinsic susceptibility are located along the periphery of the FWL, where the lens is anticipated to be less robust to reductions in recharge based on modelling results. These areas are defined based on projections of climate change up to the year 2100 and, therefore, reflect the potential changing conditions of the FWL for a future scenario within this timeframe. Susceptibility related to preferential pathways tends to be limited to small areas surrounding wells within the settled areas and/or near seasonal ponds, which are distributed throughout the island (Fig. 3b). High susceptibility related to coastal topography is mapped along the southwestern and northern coastlines, reflecting the greater likelihood of inundation occurring because they have low relief (Fig. 3c). However, high susceptibility related to overall topography (i.e. susceptibility to storm surge) is mapped across much of the island, with only small high topographical areas having low susceptibility along the east coast due to the high elevation of the ridge.

The four susceptibility category maps combine to produce a total susceptibility (S_{Total}) map (Fig. 4a). In general, areas of low total susceptibility are present along the eastern coastline. These low susceptibility areas are representative of where low susceptibilities for each of the components coincide, particularly where the intrinsic susceptibility is low due to the presence of a thick FWL and where susceptibility due to coastal and overall topography is low (i.e. high ground elevation).

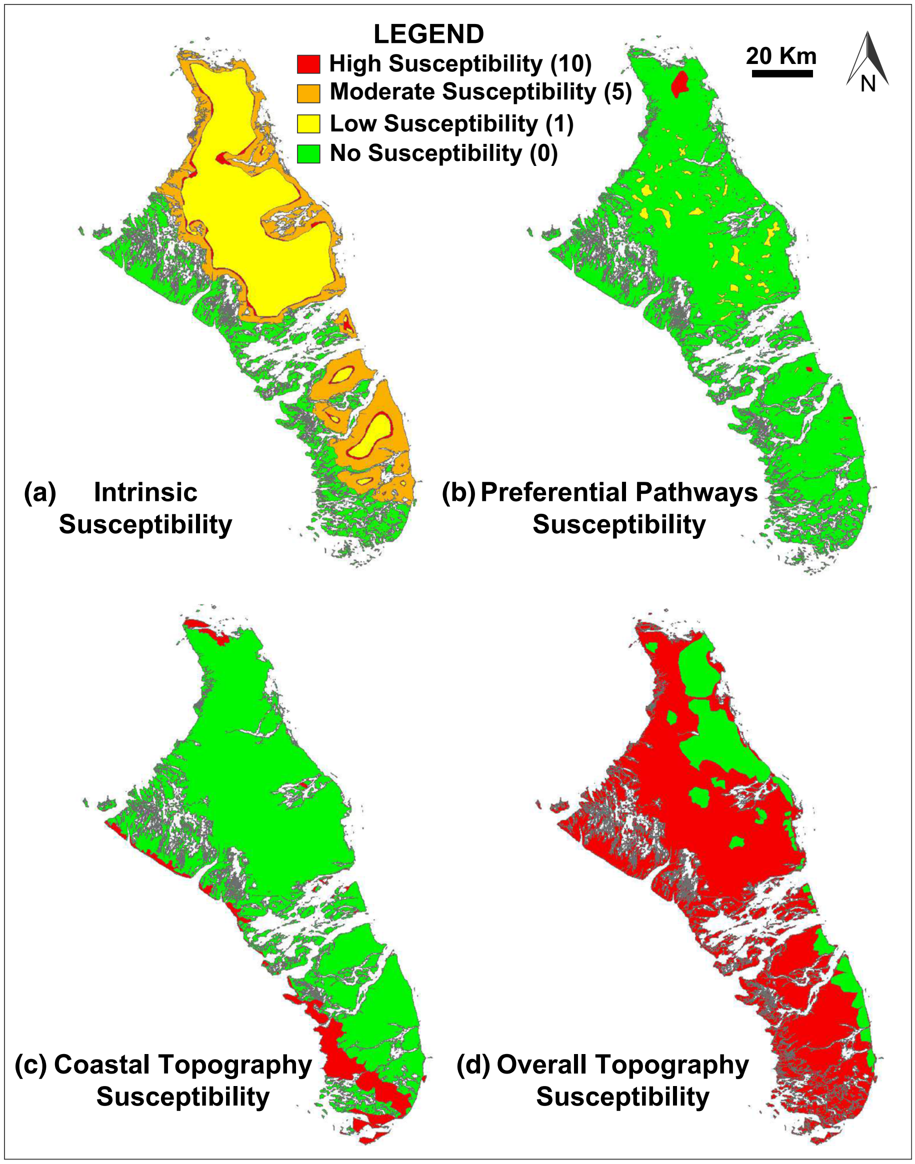


Fig. 3 Mapped categories of susceptibility: **a** intrinsic; **b** preferential pathways; **c** coastal topography; and **d** overall topography

Figure 4b shows the hazard threat from human activities (H_{HA}) indicator map. Due to the large size of the island and dispersed nature of the settlements, inset maps at a smaller scale are included to show the detail. The highest hazards are those related to chemical storage (particularly fuel), farming and waste disposal (e.g. landfills). However, the occurrence of these hazards is limited to relatively small properties within or near settlements. Hazards related to climate change (not shown), such as sea level rise and storm surge, represent a moderate hazard threat (4.7) relative to that from human activities. The hazard threat indicators represent a relative valuation (low, moderate, high) of the different hazard threat categories, where the hazard threat score is weighted equally in determining the total hazard threat indicator. This approach removes some of the uncertainty in score assignment, as the assessment framework provides the relative ranking of the cumulative score for each hazard category.

At an island scale, the total vulnerability (Fig. 4c) is largely influenced by the susceptibility, which (as mentioned earlier) is generally low in developed areas where hazard threat is high. Therefore, the vulnerability related to human activities is relatively low when viewed at the island scale, but at the local scale near settlements there are areas of high vulnerability related to human activities (not visible on the vulnerability map due to the small scale of the properties). Although the settlements cover a relatively small proportion of the island, water wells are concentrated in these developed areas. The result is that water supply systems are often in close proximity to areas of high human hazard threat, represented by the small pockets of high vulnerability within the developed areas. Areas of high

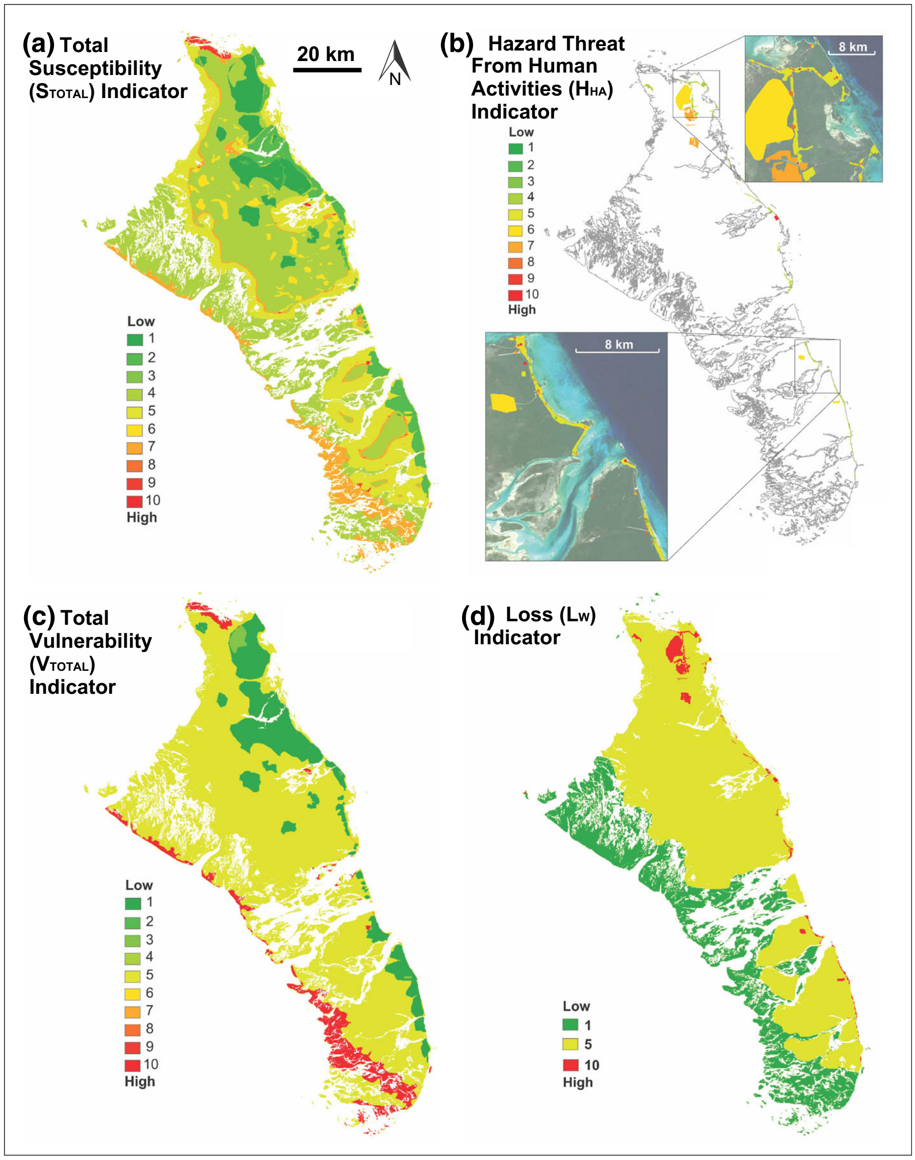


Fig. 4 **a** Total susceptibility (S_{Total}) indicator; **b** hazard threat from human activities (H_{HA}) indicator; **c** total vulnerability (V_{Total}) indicator; **d** loss (L_{W}) indicator

vulnerability are also focused along the northern and western coastlines, where the island is low-lying and thus has a high susceptibility to inundation.

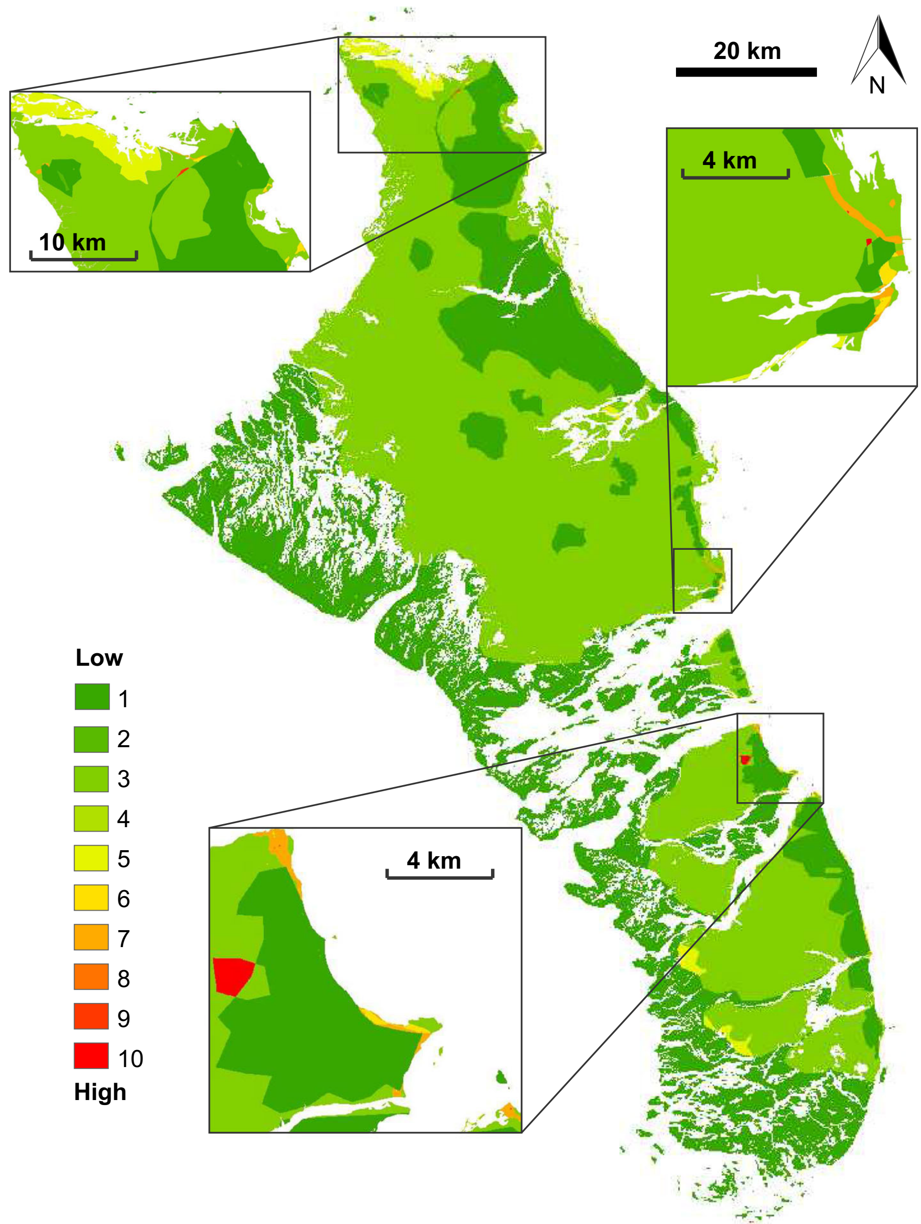
The loss (L_{W}) indicator is presented in Fig. 4d. The spatial distribution of loss is related to the presence of developed areas and the potential for future settlement. Loss is concentrated in currently developed areas where the impact of hazard occurrence would be greatest. The potential for future development is included in the loss indicator, whereby moderate loss represents areas that may support future settlements.

Risk is generally low across the island, partly because loss is concentrated around the settlements and reflects the low population density (Fig. 5). Although overall risk appears low at an island scale, there is significant risk within the developed areas, largely related to human activities resulting in high human hazard threats. In addition, areas of moderate risk, generally related to climate change, are focussed along the coastline near settlements. These areas of moderate to high risk occur where hazard threat (related to either human activities or climate change) intersects with areas of high susceptibility and high loss. For example, portions of the eastern and northern coastline have higher susceptibility and high loss due to the reliance on the FWL, resulting in high risk when hazard threats are also present in these areas.

Discussion

This assessment was performed at an island scale; however, variability at the local scale is crucial to adequately capture risk to water security for Andros Island because

Fig. 5 Risk to water security (R_{WS}) indicator for Andros Island. Most of Andros has low risk to water security; however, within the small developed areas (*inset maps*), the risk is significantly higher



much of the risk is concentrated in developed areas. Water and land-use management should consider risk within individual settlements in order to identify potential source zones or high-risk areas of concern. Areas of risk along the coastline near settlements also pose a significant threat to water security. Changing demographic patterns and tourism pressure drives more infrastructure development along the coasts, rather than at the traditional inland locations, on many small islands (Ranjan et al. 2009; Cashman et al. 2010). This concentrates hazards and loss in areas that have high susceptibility, increasing risk to water security. Therefore, risk within developed coastal areas should also be considered at a local scale and included in future development planning.

The assessment framework is intended to be a generalized tool that can be applied to evaluate water security when datasets are limited, which is often the case for small islands (Cashman et al. 2010; Robins 2013). Data limitations for this study included a lack of current FWL morphology data and cadastral property maps that delineate property boundaries. These limitations were addressed by using numerical groundwater modelling based on historical FWL morphology data and by estimating property boundaries from aerial photographs alongside the hazard survey data. When applying this assessment framework to other small islands, it is likely that similar data limitations will be encountered. There are several data that are critical in order to effectively utilize this framework, and these data would need to be compiled from existing sources or estimated through modelling. These data include: (1) an estimate of the current FWL morphology (thickness and extent); (2) future climate change and development scenarios for the region; (3) an estimate of FWL response to projected changes in the climate; and (4) a geospatial survey of potentially hazardous land-use activities. If it is not feasible to conduct a dedicated study evaluating the FWL response to changes, it may be possible to estimate the robustness of the lens based on current FWL morphology and expert knowledge. For example, the periphery and thin areas of the FWL are likely to be less robust than the central, thicker areas because there is less freshwater volume present so that even small changes in recharge may result in loss of FWL areal extent. In addition, although this study relied on a hazard survey for each property, it would not be necessary to conduct a survey if the assessment framework is applied to another island. An alternative method would be to obtain the cadastral data, which would provide the geospatial distribution of different property types. With this information (or an estimate of property location and type obtained from another method), a reasonable estimate of the hazard threat for each property can be assigned based on common land-use practices for each property type. This approach has been successfully employed in other water security risk assessments where it was not reasonable to conduct a door-to-door hazard survey (Simpson et al. 2013).

The determination of the scores and geospatial extent of each area contain elements of uncertainty in the assessment framework. Much of the uncertainty is based on data limitations, the uncertainty associated with the modelling results and the uncertainty in future events. Within the assessment framework, uncertainty in the data was addressed by using a relative scale. Each indicator was normalized on a 1–10 scale so that the values retain their relative position (i.e. greater or less risk), although the score assigned to a specific area may not be accurate. This also allows the framework to be applied to other settings, where the resulting scores for each breakdown field are likely to be different than those determined for Andros Island, but the normalized final indicators will still represent the relative rankings. Modelling uncertainty was addressed by calibrating the model to observed field data to establish a reasonable representation of the hydrogeological system. The model results were also compared to other studies and the anticipated response of the FWL to ensure the results were probable and realistic. Uncertainty in future events was addressed by using climate change projections based on an ensemble of 15 different global climate change models (McSweeney et al. 2010). A more comprehensive risk assessment would consider the uncertainty of different potential future scenarios, perhaps using a range of GCMs and emissions scenarios and incorporating probability into the assessment. However, this was outside the scope of this study due to the computational demand involved.

Despite these uncertainties, the resulting risk assessment significantly improves previous understanding of risk to water resources on Andros Island. Climate change contributes substantial uncertainty to risk assessment; however, its imperative adaptation planning is not neglected, but instead that potential impacts are managed within the limitations imposed by uncertainty (Hallegate 2009; IPCC 2014). An appropriate initial step towards addressing uncertain risk is to undertake "low-regret" or "no-regret" measures, which can provide positive results regardless of the impacts of climate change (Hallegate 2009). Some examples include risk communication and education between policy-makers and local citizens, and informed restrictive land-use planning to safeguard resources (Hallegate 2009; IPCC 2012). Identifying risk to water security allows policy-makers to make informed plans for the future and mitigate potential impacts.

The results of this work were provided to several Bahamian government departments and non-governmental organizations to promote risk communication and education. The Bahamas Ministry of Environment is using the risk assessment results to assist with the management of Andros Island's water resources, as well as in decision-making regarding future development plans for the island, which may impact the FWL. The hazard threat assessment was used to tailor educational seminars on Andros Island, conducted by The Nature Conservancy, aimed at raising awareness about water conservation and environmental protection technologies, such as alternative wastewater treatment systems. The Nature Conservancy also presented the results of this work at public events in the Bahamas. The risk assessment for Andros Island is being used by the Bahamas Environment, Science and Technology Commission to guide scientific research permits to focus on studies impacting high-risk areas and activities. Lastly, the results of the work are integrated into ongoing projects conducted by the Bahamas National Trust, a non-governmental conservation organization, which include education activities aimed at promoting better land-use practices around areas of potential risk that may negatively impact the national parks on Andros Island. The impacts of risk identification and communication provided by this study are ongoing and have yet to be determined; however, it is a positive first step towards understanding the risks to water security on Andros Island.

Conclusions

Freshwater resources on small islands are particularly vulnerable to climate change and human impacts. Therefore, water security assessments that are tailored to the unique aspects of island hydrogeology are critical in order to effectively manage island water resources. The assessment framework outlined in this paper provides a method of incorporating the results from numerical modelling and land-use/hazard surveys into an accessible map format. The maps have provided useful tools for water managers and policy-makers in the Bahamas by identifying high-risk areas for near-term action and informing long-term planning. The maps also provide a platform to engage local residents and raise awareness about the relationship between hazardous land-use activities and the resulting impact on water security. The assessment framework is an adaptive tool that may be applied to other islands (with appropriate adjustments to account for the diversity of small island settings) and can be refined when additional data become available. Future studies implementing the assessment framework on other islands would provide useful insight into its applicability to other island hydrogeological settings.

Acknowledgments This research was supported by the Royal Bank of Canada's Blue Water Project™ in partnership with The Nature Conservancy Northern Caribbean Office and the Bahamas National Trust. The Bahamas Water and Sewerage Corporation provided field data for model calibration. Additional funding was provided by the Natural Sciences and Engineering Research Council (NSERC) through a Discovery Grant to Diana Allen.

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