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Review

Groundwater vulnerability to climate change: A review of the assessment methodology

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HIGHLIGHTS

- Presents a comprehensive review on methodologies for groundwater vulnerability assessment to climate change.
- Highlights the research gaps, including role of adaptive capacity in overall vulnerability.
- Proposes a new integrated methodology to assess vulnerability of groundwater resources to climate change.

GRAPHICAL ABSTRACT

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ABSTRACT

Impacts of climate change on water resources, especially groundwater, can no longer be hidden. These impacts are further exacerbated under the integrated influence of climate variability, climate change and anthropogenic activities. The degree of impact varies according to geographical location and other factors leading systems and regions towards different levels of vulnerability. In the recent past, several attempts have been made in various regions across the globe to quantify the impacts and consequences of climate and non-climate factors in terms of vulnerability to groundwater resources. Firstly, this paper provides a structured review of the available literature, aiming to critically analyse and highlight the limitations and knowledge gaps involved in vulnerability (of groundwater to climate change) assessment methodologies. The effects of indicator choice and the importance of including composite indicators are then emphasised. A new integrated approach for the assessment of groundwater vulnerability to climate change is proposed to successfully address those limitations. This review concludes that the choice of indicator has a significant role in defining the reliability of computed results. The effect of an individual indicator is also apparent but the consideration of a combination (variety) of indicators may give more realistic results. Therefore, in future, depending upon the local conditions and scale of the study, indicators from various groups should be chosen. Furthermore, there are various assumptions involved in previous methodologies, which limit their scope by introducing uncertainty in the calculated results. These limitations can be overcome by implementing the proposed approach.

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Contents

1. Introduction

Groundwater is a valuable resource for healthy living, ecosystems and sustainable development. At the global scale, it supplies one-third of total water withdrawal to cater for nearly 85 and 50% of rural and urban needs, respectively (Kumar and Shah, 2006). It is available in large reservoirs underneath the earth's surface that provide access or buffer storage during periods of shortage from surface resources (Lapworth et al., 2013). This ability further increases its importance at regional (e.g., Asia, Africa, Central and South America) as well as at national level, more specifically in semiarid countries.

Groundwater satisfies the drinking water requirements of about 2.5 billion of the global population (WHO (World Health organization), 2014). It also serves to sustain baseflow in wetlands, lakes and rivers during periods of low or no precipitation. Despite these indispensable contributions to human welfare and natural ecosystems, the resource is being developed in a haphazard manner, leading to its depletion and degradation. Climate variability/change has further worsened the situation by changing groundwater recharge in terms of timing, duration and magnitude (Hiscock et al., 2012; Taylor et al., 2012).

Since the beginning of the modern era, there has been an increasing threat to the quantity and quality of groundwater both from climatic and non-climatic factors solely and jointly. The former is associated with changes in climate over the twentieth century. During the latter part of twentieth century, air and ocean temperatures have escalated giving rise to hot days, hot nights and heat waves. Similarly, average precipitation totals have increased over high latitudes and decreased over subtropical, middle and lower latitudes (Bates et al., 2008). Precipitation intensity, duration and frequency are also likely to change. As projected by various studies, these trends will continue during the twenty-first century (Bates et al., 2008). The aforementioned changes have impacted on groundwater recharge (Okkonen and Kløve, 2011), sea levels and snow packs, which are key processes for the sustainability of groundwater resources (Taylor et al., 2012). It is likely that groundwater vulnerability will increase if the change in climate continues at current trends (IPCC, 2007). The non-climatic factors have the propensity to stress groundwater include population growth, urbanisation, deforestation and industrialisation, as well as increasing demands from the domestic and agriculture sectors, amplified by climate change (Mato, 2002; Taylor, 2014; Van der Gun, 2012). In some situations, the impact of non-climatic factors dominates those of climatic factors (Scanlon et al., 2007).

From the perspective of translating the impact information into relevant policy formulation and practice guidelines, it is imperative to assess groundwater vulnerability to climate change. This is because knowledge of its vulnerability can help explore the risks posed by climate change and identify/develop/implement feasible adaptation measures. Groundwater vulnerability to climate change refers to its sensitivity to current and potential threats from climatic stressors. It is a function of exposure, sensitivity and adaptive capacity (Fig. 1), representing the level up to which a system cannot withstand the potentially damaging impact of climate change. Exposure is the change in climate stimuli to which a system is exposed. Whereas sensitivity refers to the degree of impact on a system as a result of exposure to climate related stimuli, which is an intrinsic property. Adaptive capacity, on the other hand, is its ability to adjust to the potential damaging impacts of climate change. Therefore, groundwater reservoirs with insufficient capacity to withstand damaging impacts are vulnerable to climate change (IPCC, 2007; Vrba and Zaporozec, 1994).

To date, a number of investigations have been undertaken at different geographical locations and at different spatial scales to assess the vulnerability of groundwater resources to direct and indirect impacts of climate change. It is generally agreed that global climate change is posing a great challenge on human and natural systems (IPCC, 2007). As a result, there has been an increasing demand for dependable methods to assess the relative vulnerability of systems to likely impacts of climate change (Carter et al., 2007). However, as vulnerability to climate change is highly dependent on the context and scale, varying

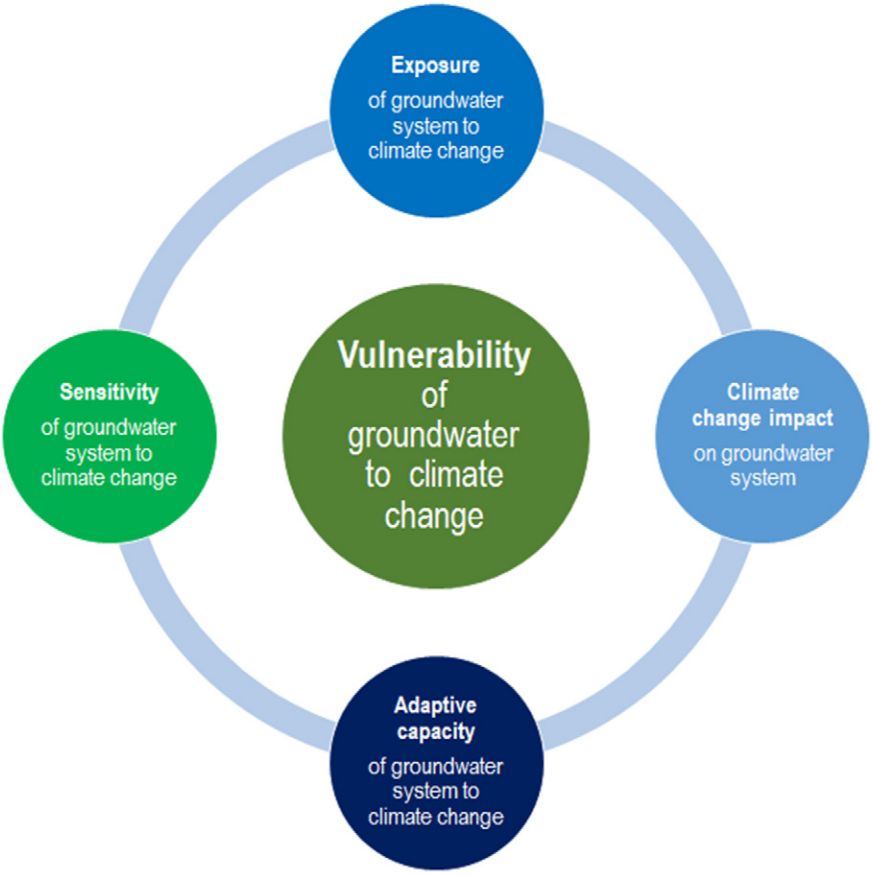


Fig. 1. Vulnerability of groundwater to the impacts of climate change (modified from Schröter et al., 2004).

largely across systems, there is substantial variation in the approaches that have been used to measure vulnerability (Downing et al., 2005). In addition, vulnerability to environmental change has discerned differently among research disciplines (Füssel and Klein, 2006). In the past, the concept of vulnerability was widely been used to evaluate groundwater quality issues posed by numerous pollutants.

The concept of vulnerability was first introduced by Margat (1968). It has then been defined differently as per context in various literatures. Vrba and Zaporozec (1994) defined intrinsic vulnerability as “an intrinsic property of a groundwater system and one that depends on the sensitivity of that system to human or natural impacts” whereas specific vulnerability was defined as “the risk of pollution due to the potential impact of specific land uses and contaminants”. Other than these, vulnerability of groundwater is also recognised as vertical (contamination from land surface activities) (Li and Merchant, 2013), and horizontal vulnerability (due to salt-water intrusion from sea), (Abd-elhamid et al., 2016; Chang et al., 2016; Sherif and Al-rashed 2001). Since climate change represents changes in numerous meteorological parameters, most importantly temperature and precipitation, changes in these parameters affect groundwater storage and levels and therefore cause groundwater vulnerability in vertical direction (vertical vulnerability) (Stuart et al., 2011).Therefore, IPCC (2007), proposed a framework to assess vulnerability of humans and ecosystems to climate change and defined vulnerability as the resultant of impacts of climate change and adaptive capacity of the systems.

This paper aims to analyse the approaches used, their relative merits/demerits, importance of indicator selection in vulnerability assessment, and proposes an integrated and generic approach which could be applied at different spatio-temporal scales for groundwater vulnerability assessment. A very concise summary of the reviewed literature is also presented to easily visualise/identify the various aspects considered in earlier studies of groundwater vulnerability assessment to climate change. Section 2 presents a detailed analysis of the methodologies, tools and techniques, followed by Sections 3, 4 and 5, each briefly presenting the vulnerability components and an in-depth analysis of the significance of indicators choice. Section 6 highlights the research gaps as well as proposing integrated approach, and Section 7 presents useful conclusions. This is the first study attempting to highlight the significance of indicators choice in groundwater vulnerability assessment to climate change.

2. Approaches to groundwater vulnerability assessment

During recent years, the vulnerability of groundwater to climate change has been assessed by various researchers at different spatial and temporal scales across the globe (Fig. 2). In fact, it is not easy to recognise the resemblances and dissimilarities inherent in these studies, or to determine whether any knowledge gaps exist. This section details the methodology, assumptions and measures of climate change vulnerability to groundwater.

2.1. Methodology

As discussed in the earlier sections that vulnerability is the resultant of exposure, sensitivity and adaptive capacity. There are substantial variations in the approaches and methods used to measure vulnerability, mainly because, vulnerability to climate change is highly dependent on the context and scale, varying largely across systems. Among them, very recent publications (after 2008) are considered on each topic to characterise various aspects of groundwater vulnerability assessment to climate change.

Various methods have been proposed for quantifying intrinsic and specific vulnerability of groundwater to contamination. These methods can be categorised into overlay/index (Li and Merchant, 2013),

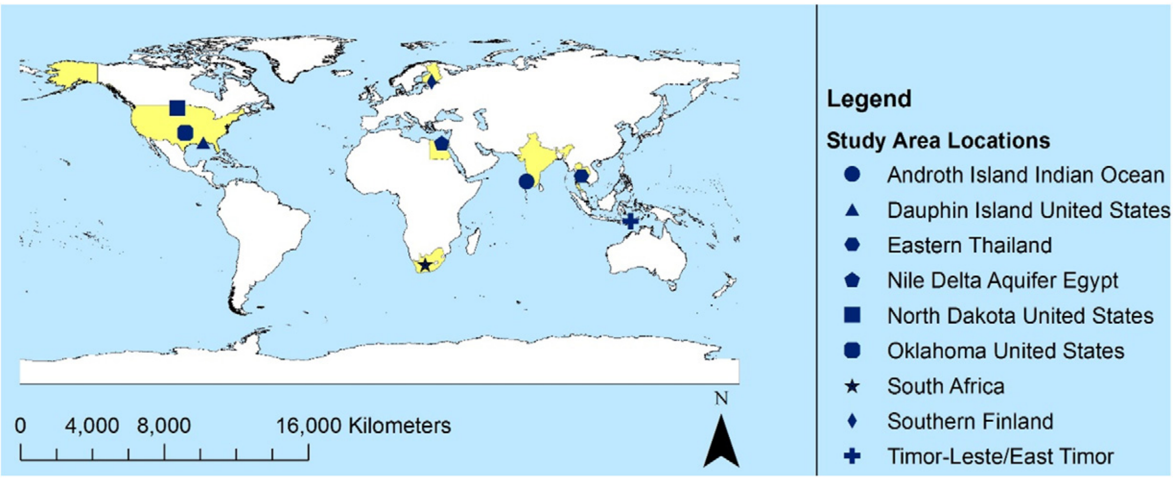


Fig. 2. Spatial distribution of the studies reviewed.

statistical and process/model-based methods. Within these, the DRASTIC (Aller et al., 1987), GOD, AVI, SINTACS, modified SINTACS, DART and GALDIT etc. are the most common methods used internationally to evaluate the intrinsic and specific vulnerability (Arauzo and Valladolid, 2013; Augé, 2004; Dennis and Dennis, 2012; Luoma et al., 2016; Seeboonruang, 2016). These methods have also been used in combine (hybrid methods) such as PATRIOT (Focazio, 2002). Process/model-based methods have been in use to quantify specific vulnerability of aquifers to pollutants and sea water intrusion from sea level rise (Abd-elhamid et al., 2016; Adams and Thomas, 2004; Chang et al., 2016; Chattopadhyay and Singh, 2013; Leterme and Mallants, 2011; Myers et al., 2011; Roosmalen et al., 2009; Wallace et al., 2012; Zume and Tarhule, 2011), however, such methods do not provide an output as simple relative values. Unlike to overlay/index and process/model-based methods, statistical methods have found limited use (Evans, 1995a; Troiano et al., 1999), and therefore, not included in this review. Instead, these methods estimate contaminant concentrations, time of travel, and duration of contamination to quantify areas of low and high vulnerability. These methods may include analytical solutions (e.g., Dupuit approximations) or numerical models (e.g., SAAT, SWAT, MIKE-SHE, MODFLOW) (Liggett and Talwar, 2009). Both overlay/index and process/model-based methods have been used (most commonly) to assess vulnerability of groundwater to climate change (Table 1).

Overlay/index methods have always been arguable due to the subjectivity involved in the selection of indicators, their functional relationship to vulnerability, and assigning weights to the indicators (based on expert opinion). Since there always exists a difference in opinion and perception among various people. Alternative interpretations of the results may occur (Meeks and Dean, 1990), depending on the indicators selected and weights assigned to those indicators. Therefore, the choice of an appropriate technique is extremely critical. In this regard, an approach such as the Modified-DRASTIC-AHP (Sener and Davraz, 2013) can be a convincing alternative, since it involves assigning weights for developing a hierarchy of the indicators based on the experience. This is followed by the construction of a pairwise matrix of the indicators for assigning the score (1 through 9) by evaluating the off-diagonal relationship between them. The pairwise comparison makes the whole process relatively easier and more reliable (Abd-elhamid et al., 2016; Chang et al., 2016; Chattopadhyay and Singh, 2013; Rezaei-Moghaddam and Karami, 2008; Sener et al., 2010; Sener and Davraz, 2013).

Analytical methods, on the other hand, involve the simplification of important parameters such as the consideration of constant hydraulic conductivity, transmissivity and uniform thickness of the aquifer (Chang et al., 2016; Dennis and Dennis, 2012). Analytical methods also involve uncertainties in projecting climate change using climate models (de Sherbinin, 2014) and in projecting the impacts of climate change on systems (i.e., groundwater) and processes (i.e., pollution transport to groundwater and recharge to groundwater) using impact models, due to the large dispersion in model outputs (Bloomfield et al., 2006). In addition, resampling of the coarse resolution climate data introduces uncertainty in the results (Li and Merchant, 2013). Uncertainties are further discussed in Section 2.3.

Furthermore, a top-down approach from global to downscaled basin level projections has been implemented in the impact studies (Fig. 3). This approach oversimplifies the role of adaptation. However, this is the only approach feasible for assessment of a system's physical vulnerability to climate change (Füssel and Klein, 2006).

There is a general consensus concerning the approaches available for vulnerability assessment in that no one is superior to another or mutually exclusive. Instead, the choice of method depends on the objectives, availability of resources and data, as well as the time frame for the study (Kelly and Adger, 2000; de Sherbinin, 2014).

2.2. Assumptions and simplifications

Various assumptions are made in several earlier studies. The relevant key assumptions are described hereunder.

2.2.1. Instant sea level rise

This assumption has been considered in certain earlier studies (Abd-Elhamid et al., 2016; Luoma and Okkonen, 2014). It introduces simplification to the modelling techniques and may result in more rapid sea water intrusion rather than being due to a gradual sea level rise (Watson et al., 2010). However, it is valid merely for assessing the impact of the last interglacial period during which the rise in sea level was 4 to 6 m. In fact, this is not a valid assumption to simulate the impact of future sea level rise (Chang et al., 2011), because sea level rise is a slow phenomenon, projected to rise on a yearly basis from 0.2 to 4.0 m over a period of more than a hundred years from 1990 to 2100 (IPCC, 2007). Furthermore, the simulated behaviour of saltwater intrusion varies with assumptions of instantaneous and gradual sea level rise, later representing the intrusion process in a more natural way (Chang et al., 2011). Therefore, to address the implications of sea level rise on groundwater resources in a more accurate way, the gradual rise in sea level has to be considered.

2.2.2. Constant or average values of parameters related to soil or aquifer properties

Many studies (e.g., Dennis and Dennis, 2012; Seeboonruang, 2016) have adopted this assumption. It holds true in cases where the soil

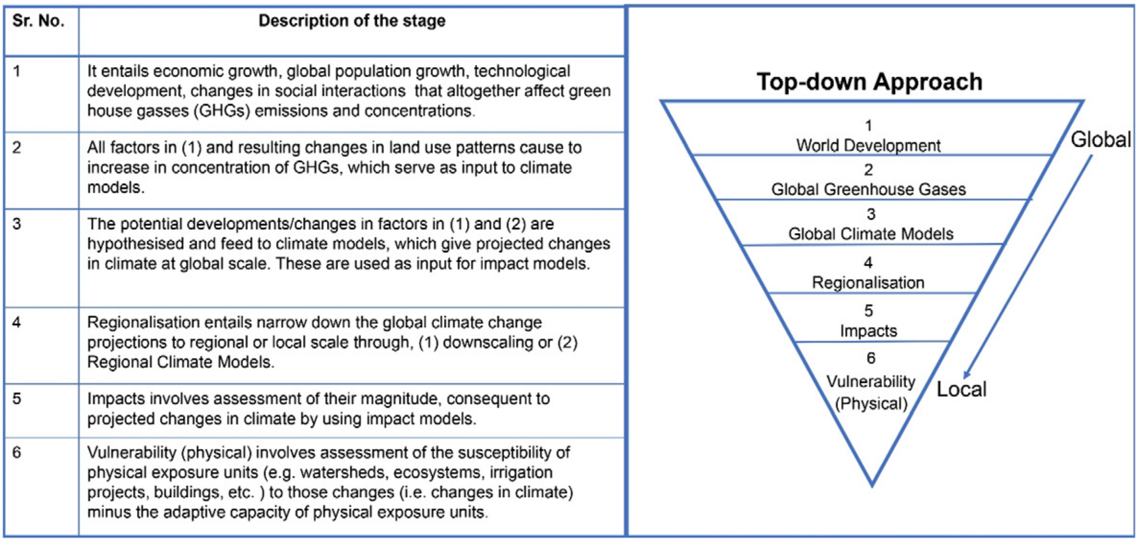
Table 1
A comprehensive summary of various aspects considered in the literatures related to groundwater vulnerability assessment to climate change.

Reference	Assessment Type	Geographical Scale	GCM(s)/RCM(s)	Downscaling Technique	Scenarios	Exposure technique & (indicators)	Sensitivity technique & (indicators)	Technique for adaptive Capacity & (indicators)	Vulnerability technique
Abd-Elhamid et al. (2016)	Analytical	Regional	N/A	N/A	N/A	(Scenario1: SLR, Scenario2: Increasing abstraction (IA), Scenario3: SLR + IA, Scenario4: Decreasing abstraction by 50%, Scenario5: Increasing recharge by 50%).	N/A	N/A	N/A
Chang et al. (2016)	Analytical	Local	GFDL_cm2_0, GISS_model, NCAR_ccsm3_0, UKMO_hadcm3	Quantile Mapping, Interpolation of monthly bias-corrected GCM anomalies onto a fine-scale grid of historical climate data	A2, A1B, and B1	Impact modeling and mapping, (Scenario1: Baseline scenario, Scenario2: LU/LC change, Scenario3: dry climate + LU/LC change, Scenario4: wet climate + LU/LC change, Scenario5: dry climate + LU/LC change + pumping increase).	Impact modeling and mapping, (Scenario1: Baseline scenario, Scenario2: LU/LC change, Scenario3: dry climate + LU/LC change, Scenario4: wet climate + LU/LC change, Scenario5: dry climate + LU/LC change + pumping increase).	N/A	N/A
Luoma et al. (2016)	Empirical	Local	CLM (RCM) nested into ECHAM5/MPI-O	Dynamic	A1B, B1 Considers climate change	The rating and weighting was performed for each parameter using the map overlay analytical function in the Spatial Analyst module of the ArcMap program (rainfall change/recharge change, sea level rise)	The rating and weighting was performed for each parameter using the map overlay analytical function in the Spatial Analyst module of the ArcMap program (depth to g/w level, recharge)	N/A	SINTACS, GALDIT: index weight rating and overlay analytical function using the ArcMap program (for combining all indicators)
Seeboonruang (2016)	Empirical	Regional	MRI-AGCM3. 1S	The Bias Correction and Spatial Disaggregation (BCSD) method	A1B Considers only climate change	The climate change exposure index is calculated by the difference between the future and baseline rainfalls and then scaled by the baseline one. These values are then classified into 4 categories as will be described under "Climate change exposure indicator".	Calculation of indicators using DRASTIC, rating, weighting of sensitivity indicators (depth of groundwater (D), aquifer media (A), soil media (S), topography (T), impact of vadose zone (I) and hydraulic conductivity of aquifer (C).)	Rating, weighting and ranking based on drought persistence.	Rating, weighting and ranking. Simple overly technique to highlight vulnerable areas (hotspots).
Chattopadhyay and Singh	Analytical	Regional	N/A	N/A	Two hypothetical	N/A	N/A	N/A	Hydro-Chemical Analysis for

(continued on next page)

Table 1 (*continued*)

Reference	Assessment Type	Geographical Scale	GCM(s)/RCM(s)	Downscaling Technique	Scenarios	Exposure technique & (indicators)	Sensitivity technique & (indicators)	Technique for adaptive Capacity & (indicators)	Vulnerability technique
(2013)					Scenarios accounting for ±30% variation from annual mean equivalent to 1600mm were considered				measuring concentrations under two rainfall scenarios, use of GIS for mapping and highlighting aquifer areas vulnerable to intrusion.
Li and Merchant (2013)	Empirical	Regional	16 fully-coupled atmosphere–ocean general circulation models (AOGCMs)	N/A	B1, A2 and A1B Considers only climate change	Mapping, indicators (Change in g/w recharge, land use change) for representing hotspots	Mapping, indicator (pollution concentration) for highlighting hotspots	N/A	Overlaying maps of all indicators and highlighting vulnerable areas
Dennis and Dennis (2012)	Empirical	National	HadAM3, ECHAM4.5, CSIRO Mk2	Self-organizing Map based Downscaling (SOMD),	A2 Considers climate change	Mapping, ranging, rating and weighting of exposure indicators (recharge, depth to water level change, transmissivity, aquifer type)	(Depth to water level change)	N/A	DART index calculation by Overlying and adding up weights for all indicators
Wallace et al. (2012)	Empirical	National	18 GCM CMIP3	Dynamic	B1, A1B and A2 Considered only climate change	Weighting, rating and Mapping (sea level rise and change in rainfall)	Weighting, rating and Mapping of indicator (aquifer yield)	Weighting and rating of adaptation options (area of aquifer, Managed Aquifer Recharge)	Modeling, Questionnaire survey, Overlay(GIS)
Leterme and Mallants (2011)	Empirical	Local	Analogue Stations	N/A	N/A	Climate change Land use change	Climate change Land use change	N/A	N/A
Myers et al. (2011)	Empirical	National	18 GCM CMIP3	Dynamic	B1, A1B and A2 Considered only climate change	Weighting, rating and Mapping (Change in rainfall and aquifer yield)	Weighting, rating, overlying and Mapping (Population pressure	Overlying aquifer recharge and annual rainfall, weighting and rating	Modeling, Questionnaire survey, Overlay(GIS)
Zume and Tarhule (2011)	Analytical	Local	N/A	N/A	N/A	Impact Modeling and Mapping, Scenario-1: Projected pumping Scenario-2: Severe drought Scenario-3: Prolonged wet period Scenario-4: Human adjustment (25% reduced pumping)	Impact Modeling and Mapping, Scenario-1: Projected pumping Scenario-2: Severe drought Scenario-3: Prolonged wet period Scenario-4: Human adjustment (25% reduced pumping)	N/A	N/A
Roosmalen et al. (2009)	Empirical	Local	HIRHAM (RCM) HadAM3H (GCM)	Dynamic	A2, B2	Precipitation + Temperature Precipitation + Temperature + Abstraction + Irrigation	Precipitation + Temperature Precipitation + Temperature + Abstraction + Irrigation	N/A	N/A



Sr. No.	Description of the stage
1	It entails economic growth, global population growth, technological development, changes in social interactions that altogether affect green house gasses (GHGs) emissions and concentrations.
2	All factors in (1) and resulting changes in land use patterns cause to increase in concentration of GHGs, which serve as input to climate models.
3	The potential developments/changes in factors in (1) and (2) are hypothesised and feed to climate models, which give projected changes in climate at global scale. These are used as input for impact models.
4	Regionalisation entails narrow down the global climate change projections to regional or local scale through, (1) downscaling or (2) Regional Climate Models.
5	Impacts involves assessment of their magnitude, consequent to projected changes in climate by using impact models.
6	Vulnerability (physical) involves assessment of the susceptibility of physical exposure units (e.g. watersheds, ecosystems, irrigation projects, buildings, etc.) to those changes (i.e. changes in climate) minus the adaptive capacity of physical exposure units.

Fig. 3. Top-down approach for assessing the physical vulnerability of groundwater resources to climate change (adapted from Dessai and Hulme, 2004).

slope remains unchanged or a negligible change occurs in topographically levelled regions. However, similar assumptions may underestimate the assessment results for rugged topographies (Delin et al., 2000). Aquifer reserves generally vary from limited to extensive, and therefore the assumption of a single soil type and geology may also mislead the results. Similarly, the vadose zone, transmissivity and hydraulic conductivity are also recharge controlling factors, like other climate and non-climate indicators. For example, the vadose zone effect varies with the degree of dryness or moisture present in the soil; the role of transmissivity and hydraulic conductivity, on the other hand, changes with the geology (Dennis and Dennis, 2012; Li and Merchant, 2013; Luoma et al., 2016; Seeboonruang, 2016). There can be various geological layers overlying groundwater that differ in hydraulic properties and ultimately have a differential effect on aquifer recharge (Stigter et al., 2014; Werner et al., 2013). Therefore, lumping these properties together may lead to an overly simplified assessment.

2.2.3. Linearity in the physical processes of groundwater contamination

The physical processes of groundwater contamination through climate change and land use change actually involve complex mechanisms such as biological and chemical degradation, adsorption on soil particles and the transport and dilution of pollutants. An assumption of linearity in those physical processes may over or underestimate the actual pollution risk (Li and Merchant, 2013).

2.2.4. Spatial scale of the assessment

Except for Chang et al. (2016) and Luoma et al. (2016), the assessment scale of all studies reviewed is relatively large (i.e., national and regional). Scale affects the results by introducing simplification to complex processes. Therefore, studies conducted over a larger area (spatial scale) may omit or average site-specific processes such as hydraulic fracturing for shale oil (Mayda, 2011) and thus the effect on groundwater quality.

2.2.5. Simplification of the rainfall recharge process

It is obvious that like other processes, recharge to groundwater is also a complex phenomenon, which depends on many factors such as rainfall, land use, aquifer media, depth to groundwater table, topography, soil characteristics and hydraulic conductivity (Dennis and Dennis, 2012; Luoma et al., 2016; Seeboonruang, 2016). Therefore, bounding the recharge process to any one of those (i.e., rainfall) may introduce uncertainty in the overall results. For example, a study by Zume and Tarhule (2011) considered recharge solely as a function of rainfall (i.e., 10% of annual direct rainfall), which literally omitted other aforementioned influencing factors, leading to the over or underestimation of groundwater recharge.

2.3. Measurement of climate and climate stressors

In assessing vulnerability to future climate change, quantification of the change (i.e., exposure) is a key step, and stressor choice is equally as important since it derives from the selection of indicators. Stressor selection depends on many factors and all affect the accuracy and reliability of results. The ongoing section highlights the limitations associated with the choice of stressor and quantification methods used in previous studies.

Multiple stressors are most important and close to a system in terms of their effects. They should therefore be included in the exposure, and in turn, the vulnerability assessment (Leichenko and O'Brien, 2002; Luers et al., 2003). For example, climate change as a global phenomenon affects systems on a multi-scale (i.e., local, global, etc.) and in multi-ways (i.e., directly through temperature and precipitation variations and indirectly through changing evapotranspiration, increasing population, water demand, etc.). An understanding of multiple stressors is therefore required, together with infinitely diverse actors and multiple time scales to characterise them (Adger, 2006) Contrary to this fact, few studies have considered multiple stressors in their assessments (Abd-elhamid et al., 2016; Chang et al., 2016; Myers et al., 2011; Seeboonruang, 2016), while others have limited their work to one or two stressors. There is a lack of stressor considerations such as population pressure, groundwater abstraction (Li and Merchant, 2013) and land use/cover (Chattopadhyay and Singh, 2013; Dennis and Dennis, 2012; Myers et al., 2011; Seeboonruang, 2016; Wallace et al., 2012).

2.3.1. Climate variability and climate change

Climate variability is as important as climate change, but none of the reviewed studies has considered climate variability in their vulnerability assessments, and instead the focus has been solely on climate change. Indeed, indicators of climate vulnerability are influenced by both climate change and variability (Lavell et al., 2012). Since change represents the trend of mean climate conditions, it cannot be considered representative of the actual situation in the true sense. Thus, the inclusion of variability, which represents the range of changes in climate, at the minimum of a yearly time scale, would lead to a more robust analysis of the actual situation (Dinse, 2011; Lavell et al., 2012). On the other hand, exclusion of variability (say in precipitation) may cause overestimation of recharge in humid regions and underestimation in semiarid (Portmann et al., 2013).

2.3.2. Climate models and downscaling techniques

Among the studies reviewed, one has assessed the current vulnerability (Chattopadhyay and Singh, 2013), while others have focused both on current and future times. They employed General Circulation Models (GCMs) for future climate projection, under the Special Report on Emission Scenarios (SRES) A2, A1B and B1 (Dennis and Dennis, 2012; Elshinnawy and Abayazid, 2011; Li and Merchant, 2013; Luoma et al., 2016; Myers et al., 2011; Seeboonruang, 2016; Wallace et al., 2012). The scientific community has agreed that there are several uncertainties linked to scenarios and GCM projections (Gosling et al., 2011; Xu et al., 2011). These uncertainties are basically associated with the coarser resolution of GCMs at a scale ranging from 1 to 2°, where one degree equals almost 100 km. They cannot accurately represent some of the climate phenomena (e.g., orographic precipitation) (de Sherbinin, 2014). GCMs normally underestimate both the temporal autocorrelation and standard deviation of projected data when compared with the observed data series (Brown and Wilby, 2012). Furthermore, they do not take into account abrupt changes in the climate system (Duarte et al., 2012). Therefore, Regional Climate Models (RCMs) offer a reliable alternative since they have a spatial coverage varying from 0.1 to 0.2°. They are also capable of incorporating climate dynamics (IPCC, 2013). Another alternative is to use new generation high-resolution GCMs with a spatial coverage of 0.2 degrees, produced for the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (Kitoh, 2012).

Most researchers have used statistical downscaling techniques like Self-Organising Map based Downscaling (SOMD) (Hewitson and Crane, 2006), delta change (Döll, 2009; Li and Merchant, 2013; Loaiciga et al., 1996), and Bias Correction and Spatial Disaggregation (BCSD) (Seeboonruang, 2016). Chattopadhyay and Singh (2013) undertook an investigation under hypothetical scenarios while Luoma et al. (2016), Myers et al. (2011) and Wallace et al. (2012) corrected their data using dynamic downscaling. The downscaling techniques have a few disadvantages such as the delta change technique not taking into account climate temporal variability and inter-annual variabilities being left unaccounted for (Hagemann et al., 2011; Hempel et al., 2013; Piani et al., 2010). Whereas SOMD underestimates the number of rainy days in heavy rainfall areas, due to the limited capability of capturing temporal autocorrelation; it takes both inter-annual variability and stationarity into account (Hewitson and Crane, 2006). The BCSD has one disadvantage in that it does not effectively address the terrain effect which affects spatial variability, but this weakness comes from the GCM due to poor representation of the terrain features (Hamlet et al., 2010). Therefore, a technique like BCSD can best suit areas with levelled topography. However, for areas with rugged topography, the use of dynamically downscaled RCMs could ultimately overcome the terrain effect problem (Andréasson et al., 2003).

3. Effect of indicators

System vulnerability is the cumulative effect of both climatic and non-climatic indicators (factors). Therefore, consideration of indicator choice is of prime importance. Adger and Vincent (2005) and Preston et al. (2011), contend that the selection of indicators should be made based only on their theoretical linkages and with insight knowledge of the relative contributions of exposure, sensitivity and adaptive capacity to vulnerability. The following sections provide an insightful analysis on the effects of indicator selection (choice) (i.e., climate, non-climate or a combination of both) considered in the studies to assess the components, and in turn, the groundwater system's overall vulnerability. The following sections have been categorised into exposure to climate change, sensitivity to climate change and the adaptive capacity of the social and physical system.

3.1. Exposure to climate change

Exposure portrays the current and future climate conditions including mean and extreme variability and changes to which a system is exposed. Thus, exposure as an element of vulnerability is not merely the extent of climate variations to which a system is exposed, but also encompasses their magnitude and duration (Adger, 2006).

Tables 1 and 2 present the indicators of exposure considered in the reviewed studies, including both climatic and non-climatic types. Climatic indicators include changes in rainfall and sea level rise and non-climate indicators relate to population increase and land use/cover change.

Some researchers argue that the combined effect of both categories of indicators (factors) poses a greater system threat than individually, and consideration of both will make the results more practical (Abd-Elhamid et al., 2016; Chang et al., 2016). Some indicators are interdependent; land use/cover and climate have a link of moisture sharing through precipitation and evapotranspiration. This dependence defines the nature of their interactions. Groundwater abstraction, especially for domestic and agricultural use, is partially governed by local climate conditions. Therefore, the choice of indicators is very much crucial to the climate change vulnerability assessment.

For example, Abd-Elhamid et al. (2016) in Egypt (Fig. 4) highlighted the effect of indicator selection using five hypothetical scenarios to evaluate the exposure of groundwater resources to climate change (Table 3). Under the Scenario-1, at a sea level rise of 100 cm, the model projected saltwater intrusion into the aquifer to 77 km from the shoreline for an equi-concentration of 35 and to 90.75 km for an equi-concentration of 1, respectively. Whereas consideration of a population-driven increasing abstraction in Scenario-2 extends intrusion to 79 km for an equi-concentration of 35 and to 91 km for an equi-concentration of 1. On the other hand, saltwater intrusion extends up to 81.25 km and 92.5 km from the seashore for both equi-concentrations under Scenario-3 considering both sea level rise and increasing abstraction. Scenarios-4 and 5 were management based in which the effect of a 50% reduction in abstraction and an increase of 50% recharge were evaluated to control saltwater intrusion. The study findings showed the importance of taking both climatic and non-climatic indicators into account, by highlighting their effects individually and in combination, arguing in favor of the latter case since the magnitude of intrusion is higher for Scenario-3 compared with Scenarios-1 and 2 under both equi-concentrations.

In Dauphin Island, USA (Fig. 5), Chang et al. (2016) showed that compared with baseline conditions, saltwater intrudes very little into the aquifer under Scenario-1 in which three indicators (i.e., wet/dry climate, land use/cover and increasing pumping) were kept constant. Intrusion was exceeded by 31.4 m into the aquifer under land use/cover change (i.e., Scenario-2). Consideration of the dry climate and land use/cover change (i.e., Scenario-3) caused the salt water to advance further by 20 m. The addition of an increasing pumping rate with a dry climate and land use/cover change (i.e., Scenario-5) further moved the saltwater by 26.8 m. Vertical intrusion was alike in behaviour to lateral intrusion under the same scenarios (Table 3).

Compared to the freshwater/saltwater interface location, which was around −10.9 m below the mean sea level in the year 2011, under baseline conditions it rises by −0.1, 1.1, 2.0, 0.6 and 2.0 m for Scenarios-1 to 5, respectively. The interface movement was alike for Scenarios-3 and 5 due to the same consideration of dry climate in both scenarios. Results from the study depicted that although each category of indicators, whether climatic or non-climatic, had an effect on saltwater intrusion, however the combined effects were remarkable. The results further highlight that inclusion of the combined effects of indicators may ensure that the estimation of groundwater resource exposure is more realistic.

In the USA's Southern Great Plain, (Fig. 6) an increase in groundwater drawdown of 1.95 m and a significant decrease in streamflow under the projected pumping scenarios compared to the baseline drawdown level of 0.73 m (Zume and Tarhule, 2011). Under severe drought in Scenario-2, it reaches a maximum average of 12.46 m. While under wet conditions in Scenario-3, drawdown reduced to 5 m with stream depletion equal to zero, probably due to an increased baseflow to

Table 2
Functional relationship of exposure, sensitivity and adaptive capacity indicators (used in earlier studies) with groundwater vulnerability.

Component	Indicator	Proxy for	Functional relationship with vulnerability	Pathways	Reference(s)
Exposure	Change in groundwater recharge	Risk of reduced quantities	Inverse proportionality	Reduced recharge reduces groundwater quantity and vice versa	Dennis & Dennis, (2012); Luoma et al. (2016)
		Risk of contamination	Direct proportionality	Increased recharge at mild slope increases concentration of soluble contents	Luoma et al. (2016)
	Sea level rise	Risk of contamination/increased seawater intrusion	Direct proportionality (increase)	Rise in sea level triggers the movement of salt water from higher to lower levels thus increases contamination	Dennis & Dennis, (2012); Elshinnawy & Abayazid, (2011); Wallace et al. (2012)
	Change in rainfall	Extent of climate change and variability	Mixed proportionality (increase/decrease)		Myers et al. (2011); Seeboonruang, (2016); Wallace et al. (2012)
		Risk of contamination (surface sources)	Direct proportionality	Increased rainfall increases recharge at mild slope, which brings soluble contents in large quantities	Luoma et al. (2016)
		Risk of contamination (sea water)	Inverse proportionality	Increased rainfall increases recharge at mild slope in turn increase storage & level thus cause reduction of salt water intrusion.	Chattopadhyay and Singh, (2013); Wallace et al. (2012)
	Population growth	Risk of pressure on groundwater	Direct proportionality (increase)	Increase in population increases the demand for water and thus groundwater abstraction.	Myers et al. (2011)
	Change in slope	Risk of reduced quantities	Inverse proportionality	Steep slopes generate more runoff and reduce the recharge and quantity of groundwater reserves and vice versa.	Dennis & Dennis, (2012); Wallace et al. (2012)
		Risk of Contamination	Mixed proportionality	Steep slopes generate more runoff and reduce the recharge and thus contamination from surface sources. Mild slopes generate less runoff, more recharge and thus increase contamination from surface sources.	Dennis & Dennis, (2012)
	Change in transmissivity	Risk of Reduced Quantities	Direct proportionality	Less transmissivity means less recharge and thus less groundwater quantity.	
		Risk of Contamination	Direct proportionality	Less transmissivity means less recharge therefore, less contamination from surface sources. High transmissivity increases recharge and causes more contamination from surface sources.	
Sensitivity	Groundwater recharge/amount of recharge	Availability of groundwater to cope with domestic, industrial and agricultural needs	Inverse proportionality	Higher recharge increases groundwater quantity	Dennis & Dennis, (2012); Luoma et al. (2016)
		Groundwater contamination from surface sources	Direct proportionality	Increased recharge at mild slope increases quantities of soluble contents	Luoma et al. (2016)
	Distance from the sea	Percent of aquifer area affected	Inverse proportionality	Larger the distance from shoreline less will be the contamination from intrusion	Dennis & Dennis, (2012); Elshinnawy & Abayazid, (2011); Wallace et al. (2012)
	Amount of rainfall	Availability of groundwater to cope with domestic, industrial and agricultural needs	Mixed proportionality (increase/decrease)	More rainfall increases recharge at mild slope in turn increase storage. More rainfall increases runoff at steep slope and thus reduces storage.	Myers et al. (2011); Seeboonruang, (2016); Wallace et al. (2012)
		Groundwater contamination from surface sources	Mixed proportionality	More rainfall at mild slope triggers recharge and concentration of soluble contents and thus sensitivity. More rainfall at steep slope reduces recharge and concentration of soluble contents and thus sensitivity.	Luoma et al. (2016)
		Change in Seawater Intrusion	Inverse proportionality	More rainfall increases recharge at mild slope in turn increase storage. More rainfall reduces recharge at steep slope and in turn reduces storage.	Chattopadhyay and Singh, (2013); Wallace et al. (2012)
	Sea level rise	Type of aquifer Recharge area of the aquifer	Mixed proportionality Indirect proportionality	Intergranular aquifer with small recharge area will have high sensitivity and vice versa Fissured aquifer with steep profile in large inland area will be highly sensitive. Localized aquifer with high topographic relief from sea and less recharge will be highly sensitive.	Wallace et al. (2012)

(continued on next page)

Table 2 (*continued*)

Component	Indicator		Proxy for	Functional relationship with vulnerability	Pathways	Reference(s)
	Population pressure		Increased pressure on groundwater resources	Direct proportionality (increase)	Increase in population increases demand for water and thus groundwater abstraction.	Myers et al. (2011)
	Groundwater pollution		Percent of area affected			Dennis & Dennis, (2012); Wallace et al. (2012)
	Surface slope/geographical highs $<30\%$ or $>30\%$		Percent of area with slope $<$ 30%/ Change in groundwater quantities	Mixed proportionality	Steep slope generates more runoff and less recharge thus reduces groundwater quantity. Mild slope generates more recharge and thus more groundwater quantity.	Dennis & Dennis, (2012)
			Groundwater contamination from surface sources	Mixed proportionality	Steep slope generates more runoff and less recharge therefore, reduces contamination from surface sources. Mild slope generates more recharge and thus more contamination from surface sources.	
	Transmissivity		Change in groundwater quantities	Inverse proportionality	Less transmissivity means less recharge therefore, therefore less contribution to groundwater quantity. High transmissivity increases recharge and thus increases the quantity of groundwater.	Seeboonruang, (2016);
			Groundwater contamination from seawater intrusion	Direct proportionality	Less transmissivity reduces recharge and thus groundwater level and quantity therefore, increase intrusion and thus sensitivity and vice versa.	Dennis & Dennis, (2012)
	Aquifer media Soil media Impact of vadose zone		Availability of groundwater to cope with the needs Groundwater contamination from surface sources	Mixed proportionality (increase/decrease)		Li & Merchant, (2013); Myers et al. (2011); Seeboonruang, (2016)
Adaptive Capacity	Droughts persistence		Percent of drought free area (Less groundwater reserves/Increased dependence on groundwater resources	Direct proportionality	More the number of droughts, less will be the availability of surface water and more dependence on groundwater resources means therefore, less will be the adaptive capacity.	Seeboonruang, (2016)
	Wealth	Poverty	Percent of population in two lowest wealth quintiles	Direct proportionality	More the income at household level, more will be the adaptive capacity.	Myers et al. (2011)
		Radio	Percent of households owning a radio			
		Mbike	Percent of households owning a motorcycle			
		Floor	Percent of houses having tiled or concrete floor			
		Roof	Percent of houses having corrugated metal roof			
		Light	Percent of houses with electric light			
		Wood	Percent of households that use wood as a fuel for cooking.			
		Water	Percent of households with access to drinking water supplies (indoors or outdoors)			
	Education	NoEd	Percent of individuals 5 years or older who have never attended school	Direct proportionality	Higher levels of education increase understanding for causes and effects and thus adaptive capacity.	
		Vacc	Percent of anemia affected children who have received the four main vaccinations, i.e. DPT, polio, hepatitis B, measles			
		NoVacc	Percent of children who have not received any of four vaccinations			
	Health	Mal	Measure of malnutrition. Percent of children with height for age $>$ 3 standard deviations below average	Direct proportionality	More the medical facilities, more will be the capacity to cope the health effects.	
		Wt4Ht	Percent of children with weight for height $>$ 3 standard deviations below average			

Table 2 (*continued*)

Component	Indicator		Proxy for	Functional relationship with vulnerability	Pathways	Reference(s)
		Wt4age	Percent of children with weight for age > 3 standard deviations below average			
		Anaem	Percent of children with anemia			
		NetK	Percent of children who slept under any kind of mosquito net the night before the survey			
		NetW	Percent of pregnant women who slept under any kind of mosquito net the night before the survey			
		W4Dec	Percent of women who participate in decisions relating to four areas, i.e. own healthcare, major household purchases, daily needs, visit to friends & family			
	Water management potential	Potential of managed aquifer recharge	Potential to enhance the recharge in area underlying aquifer	Direct proportionality	Higher awareness level and capacity of harvesting the rain, more will be adaptive capacity.	Wallace et al. (2012)
		Surface-groundwater interaction	Aquifer access to surface flow during wet seasons		Larger flow duration increase the recharge to aquifer and hence more capacity of aquifer to adapt to stresses.	
		Infrastructure	Availability of infrastructure in coastal areas		Higher the existing infrastructural facilities, more will be the current adaptive capacity.	

stream. Scenario-4 involved a human adjustment in terms of improved human water conservation (25% reduction in withdrawal) which shows a 12% reduction in average drawdown and a 20% increase in streamflow (Table 3). The reduction in streamflow in Scenarios-1 and 2 may be consequent to abstraction and drought, which alone reduces recharge and exacerbates pumping demand. These findings further strengthen the importance of the relative effect of indicators and emphasises the need to consider all possible indicators to enhance the reliability of assessments concerning the exposure of groundwater resources to climatic and non-climatic stressors.

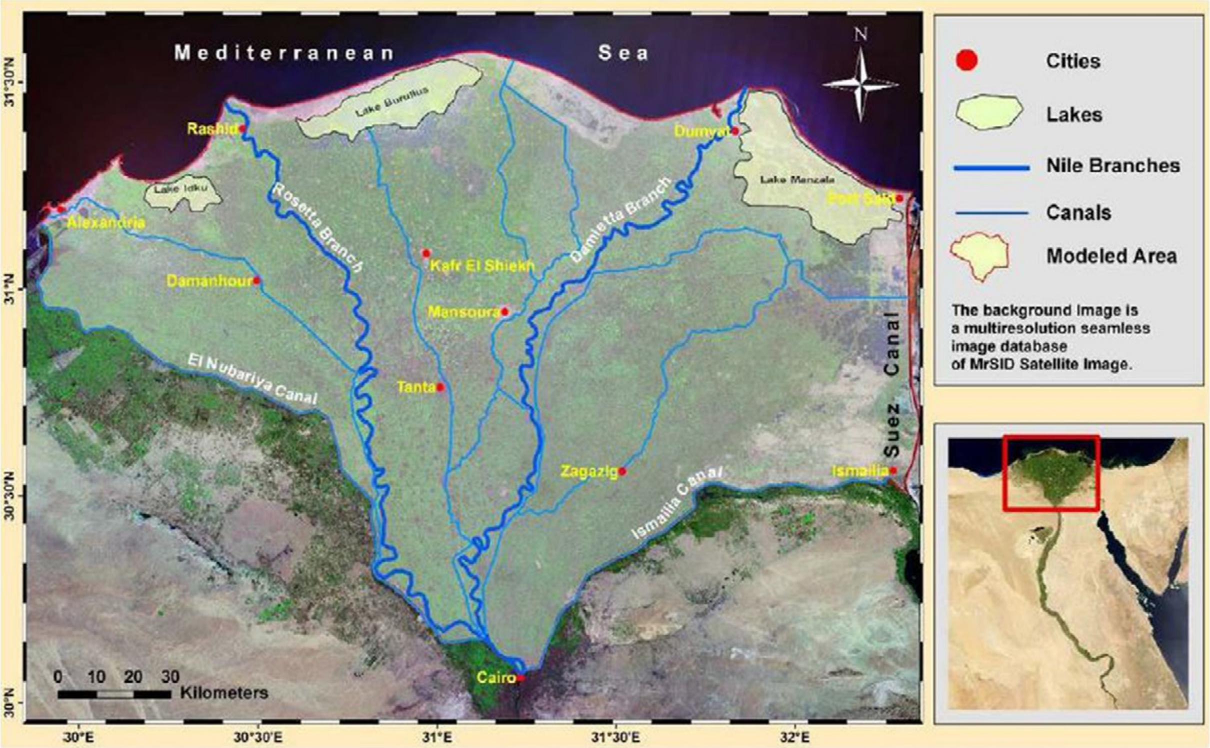


Fig. 4. Study area of the Nile Delta aquifer, Egypt (Sherif et al., 2012; Abd-Elhamid et al., 2016).

Table 3
Summary of results for exposure analysis in published literature.

References	Scenarios	Indicators	Status	Results	
Abd-Elhamid et al. (2016)	Saltwater intrusion (Horizontal) and GWL at equi-concentration				
	Baseline			0 km at shoreline	
	Scenario-1	Sea level rise	100 cm	77 km	
	Scenario-2	Groundwater water abstraction	Changing	79 km	
	Scenario-3	Sea level rise, abstraction	Changing	81.25 km	
	Scenario-4	Decreasing abstraction by 50%	Changing	(−3.5 km) to 77.75 km	
	Scenario-5	Increasing recharge by 50%	Changing	(−3.35 km) to 77.9 km	
	Saltwater intrusion (Horizontal) and GWL at equi-concentration 1				
	Baseline			0 km from shoreline	
	Scenario-1	Sea level rise	100 cm	90.75 km	
	Scenario-2	Groundwater water abstraction	Changing	91 km	
	Scenario-3	Sea level rise, abstraction	Changing	92.5 km	
	Scenario-4	Decreasing abstraction by 50%	Changing	(−0.25 km) to 90.25 km	
	Scenario-5	Increasing recharge by 50%	Changing	(−0.25 km) to 90.25 km	
Chang et al. (2016)	35Saltwater intrusion (Horizontal)				
	Baseline			1450 m from sea	
	Scenario-1	Wet/dry climate + Land use/cover + pumping	Constant	Very little/No	
	Scenario-2	Land use/cover	Changing	31.4 m	
	Scenario-3	Dry climate + Land use/cover	Changing	20 m	
	Scenario-4	Wet climate + Land use/cover	Changing	Back to baseline level	
	Scenario-5	Dry climate + Land use/cover + Pumping	Changing	26.8 m	
	Saltwater intrusion (Vertical)				
	Baseline			−10.9 m	
	Scenario-1	Wet/dry climate + Land use/cover + Pumping	Constant	−0.1 m	
	Scenario-2	Land use/cover	Changing	1.1 m	
	Scenario-3	Dry climate + Land use/cover	Changing	2.0 m	
	Scenario-4	Wet climate + Land use/cover	Changing	0.6 m	
	Scenario-5	Dry climate + Land use/cover + Pumping	Changing	2.0 m	
Zume and Tarhule (2011)	Groundwater drawdown and streamflow depletion				
	Baseline			0.73 m	
	Scenario-1	Projected pumping	Increasing	1.95	(−40%)
	Scenario-2	Severe drought	Changing	12.46	(−89%)
	Scenario-3	Prolonged wet period	Changing	(−5) 7.46	Zero
	Scenario-4	Human adjustment (25% reduced pumping)		(−1.5) 5.97	(+20%)
	Change in recharge to groundwater				
Leterme and Mallants (2011)	Dessel	Baseline		391 mm	
	(899 mm)	Crop (maize)	Changing	495 (+26%)	
		Meadow (grass)	Changing	307 (−21%)	
		Coniferous forest	Changing	239 (−39%)	
		Deciduous forest	Changing	375 (−04%)	
	Gijon	Rainfall (947 mm) warmer climate		361 mm	
		Crop (maize)	Changing	473 (+31%)	
		Meadow (grass)	Changing	276 (−24%)	
		Coniferous forest	Changing	211 (−42%)	
		Deciduous forest	Changing	315 (−13%)	
	Sisimiut	Rainfall (306 mm) colder climate		108 mm	
	(306 mm)	Crop (maize)	Changing	128 (+18%)	
		Meadow (grass)	Changing	96 (−11%)	
		Coniferous forest	Changing	73 (−33%)	
		Deciduous forest	Changing	104 (−04%)	
Roosmalen et al. (2009)	Change in groundwater recharge and level		Net recharge		Water level L-1 L-5
	Baseline		Changing	550 m	33.57 m 31.58
	A2	Precipitation + temperature	Changing	617	33.76 31.81
	B2	Precipitation + temperature	Changing	663	33.89 31.98
	Baseline		Changing	560 m	33.49 31.28
	A2	Precipitation + temperature + abstraction + irrigation		634	33.66 31.45
		Precipitation + temperature + abstraction + irrigation			33.79 31.67
	B2			678	

Note: Arrows show the increase/decrease in value.

Leterme and Mallants (2011), conducted a study in Nete catchment Germany (Fig. 7) using HYDRRS-1D model. They successfully evaluated the relative effect of rainfall and land use change indicators. To represent current climate conditions in the catchment, weather time series from Dessel station was chosen as analog station. However, future warmer and colder climate was represented by Gijon and Sisimiut analog stations respectively. Mean annual recharge under current climate and land use conditions was estimated to be 391 mm that was reduced to 361 mm (7.7%) for warmer climate scenario and further to 128 mm (67.3%) for colder climate scenario (Table 3). Under four other scenarios where current land use, which is a mixture of various types was considered to be completely changed for the entire catchment to maize, grass, coniferous forests and deciduous forests simultaneously. Under current climate conditions, only land use changed to maize increased the recharge to 26%.

However, under future warmer and colder climates, recharge increased by 31% and 18% respectively. Land use changes to all other types resulted a decrease in recharge in current as well as in warmer and colder climates. Reduction in recharge was more pronounced (79%) for warmer climate than current (64%) and colder (48%) climates. The decrease in recharge in warmer climate is due higher ET, however lesser decrease than colder climate is due to high water level (3 m).

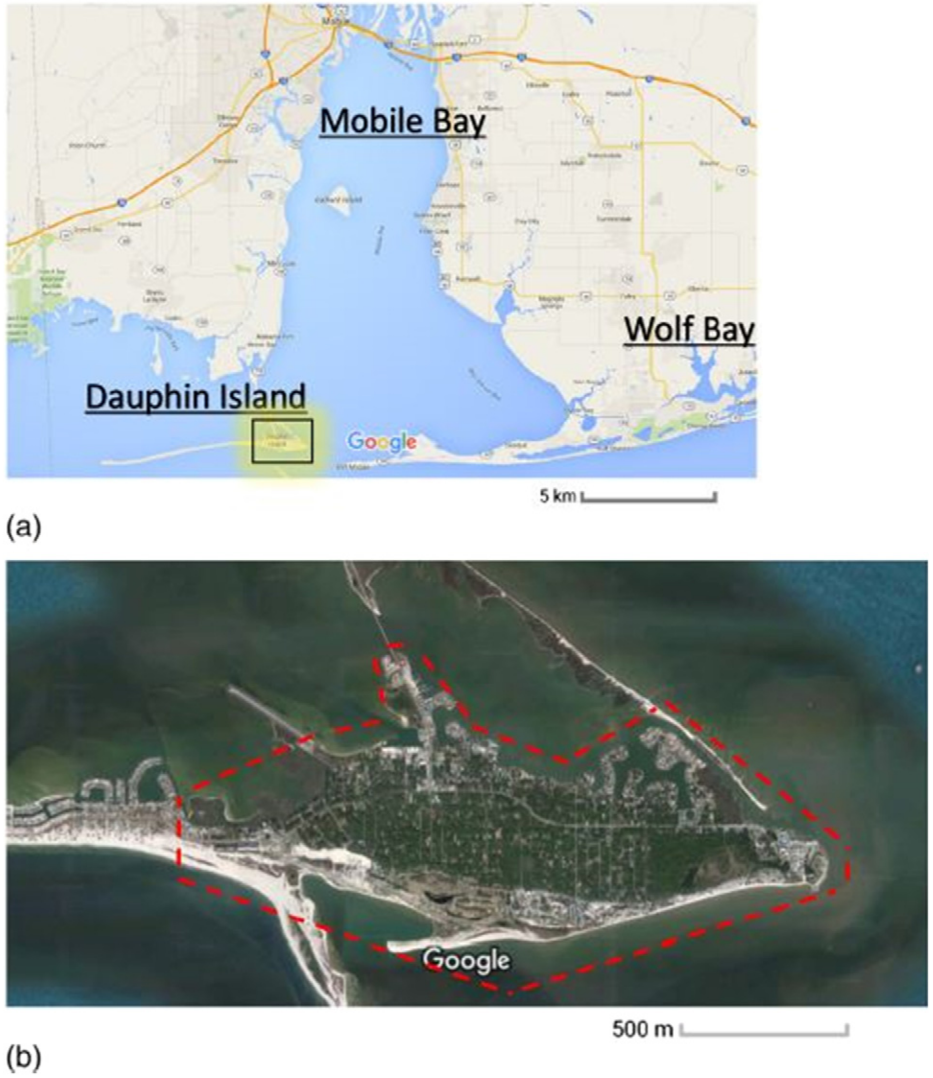


Fig. 5. Study area of Dauphin Island (Chang et al., 2016).

The high reduction in recharge for land use change scenario under colder climate is due to less rainfall (366 mm) which is much less than the warmer climate (947 mm). The authors admitted this fact that it is quite possible that the recharge is over estimated due to not including built areas into account. They further argued in favor of considering a combination of those factors/indicators (i.e. climate change and land use) in new studies which have dependency on each other.

In another study by Roosmalen et al. (2009), conducted in Jutland, Denmark (Fig. 8) which clearly highlights the significance of indicators. Under two SRES scenarios, A2 and B2 effect of precipitation, temperature, abstraction and irrigation on recharge and groundwater heads have successfully explained. Under baseline conditions net recharge was estimated to be 550 mm at which groundwater heads in layer 1 and 5 were 33.57 m and 31.58 m respectively (Table 3). The net recharge increased to 617 mm and 663 mm under scenarios A2 and B2 respectively. Mean groundwater heads changed to 33.76 and 33.89 m for layer 1 and 31.81, and 31.98 m for layer 5. However, under combined consideration for precipitation, temperature, abstraction and irrigation, net recharge increased to 634 and 678 mm (from a baseline of 560 mm) for scenarios A2 and B2. Groundwater heads under scenarios A2 and B2 changed from a baseline of 33.49 m to 33.66 and 33.79 m for layer 1. For layer 5 it changed from 31.28 m to 31.45 and 31.67 m under both scenarios. The larger increase in heads in layer 5 then layer 1 are associated to restricted water heads in layer due to a drain. Massive futuristic irrigation under A2 scenario caused more less increase in head. This study has included some of the important factors, however leaving their combined effect unattempted. They suggested to also considering combined effect of these factors in future.

Findings from the aforementioned studies clearly highlight the need to take all possible and closely linked indicators into account while assessing the exposure of groundwater resources to climate change. This is because the indicator itself and the interaction with others define its impact on the system under study.

In this regard, if a study misses any one of the indicators, reliability and scope of the results will be arguable. Furthermore, use of those results in any task shall be liable to conditions due to limitations in capturing the actual interaction among various stressors and their consequent impacts. Therefore, the more appropriate approach is to consider a diverse range of exposure indicators.

4. Sensitivity to climate change

The extent to which groundwater resources can be vulnerable, depends on the nature of climate change and degree of sensitivity of a particular aquifer (Australian Bureau of Meteorology (ABM) and CSIRO, 2011). Sensitivity is one of the three elements of vulnerability (Voice

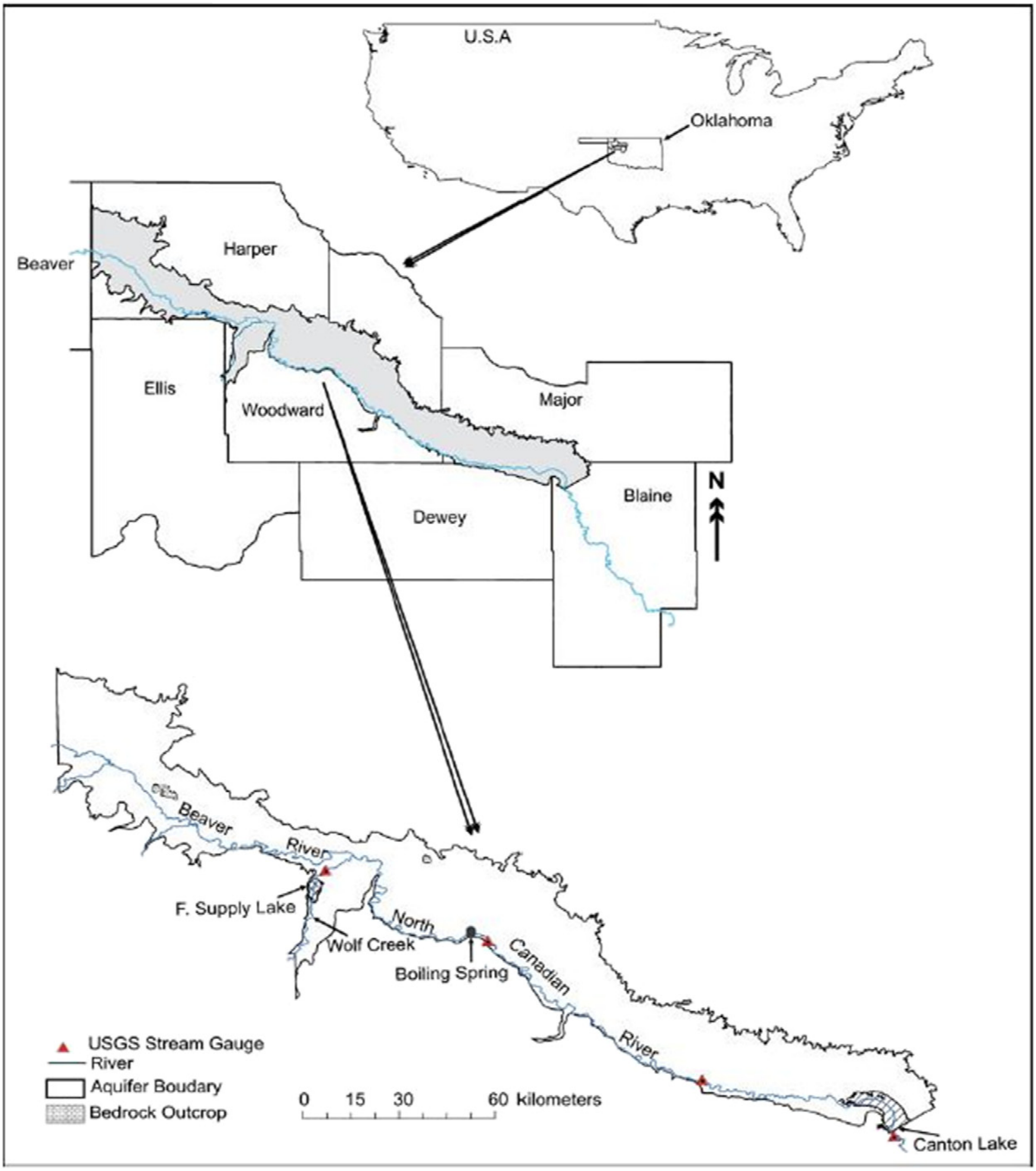


Fig. 6. Study area of the Southern Great Plain, USA (Zume and Tarhule, 2011).

et al., 2006) and links to the innate properties of the aquifer (Wallace et al., 2012).

The reviewed studies chose groundwater quality, groundwater level, and aquifer storage as indicators to assess the sensitivity of groundwater to rainfall, sea level rise, land use, soil surface slope, topographic highs, vadose zone impact, transmissivity, hydraulic conductivity, type of aquifer and population pressure (Luoma et al., 2016; Myers et al., 2011; Seeboonruang, 2016; Wallace et al., 2012).

On Dauphin Island, USA (Fig. 5), the effect of indicators was effectively highlighted by Chang et al. (2016), who undertook a sensitivity analysis on the quantity of groundwater resources by considering both types, individually and combined. Compared with the current salinity level of 1.2%, under Scenario-1 (with constant climate, land use/cover and pumping), land use/cover change (Scenario-2) caused a reduction in the volume of freshwater by 3.9%. Under dry climate plus land use/cover change (Scenario-3), the quantity of freshwater reduced by 3.3%. However, under the combined wet climate and land use/cover considerations (Scenario-4), the volume of freshwater returned to the baseline levels due to an increase in rainfall-triggered recharge. Under the combined consideration of dry climate, land use/cover change and increasing pumping (Scenario-5), freshwater quantity reduced by 8.6%. At 10 and 50% of initial salinity levels the magnitude of volume was different but the direction of impact was similar (Table 4). The results of Chang et al. (2016) highlight the relative sensitivity of groundwater quantity as a function of quality under the impact of climatic and non-climatic stressors and signifies the importance of indicator choice.

Myers et al. (2011) also explored groundwater sensitivity to population pressure and relative aquifer yield, and the average annual rainfall

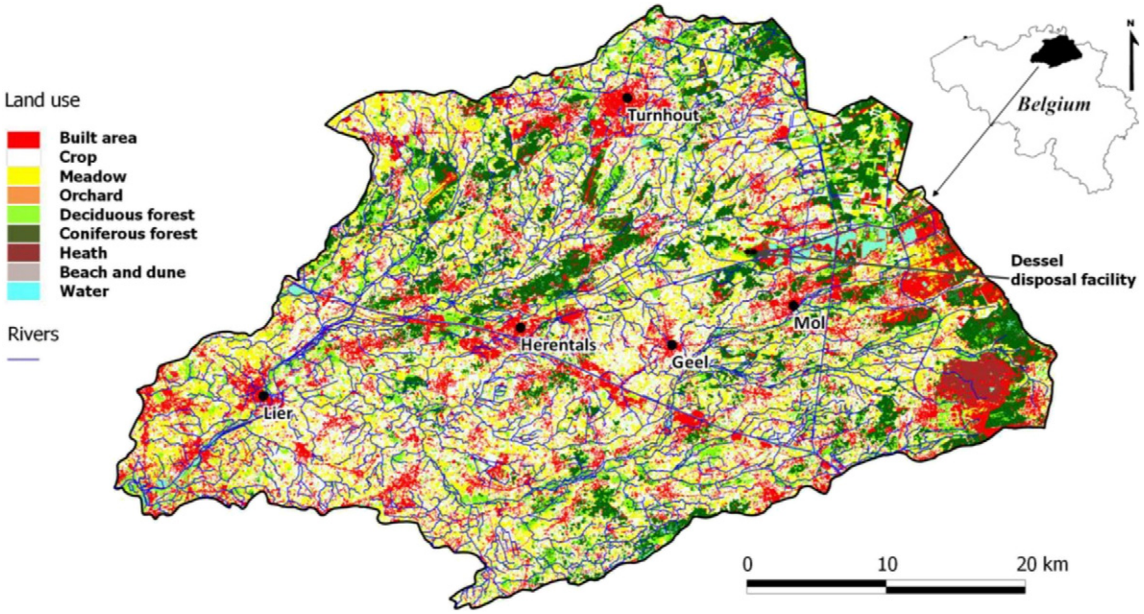


Fig. 7. Study area of the Nete catchment, Belgium (Leterme and Mallants, 2011).

in Timor Leste (Fig. 9). Sensitivity to mean annual rainfall and aquifer yield was quantified to be between low to medium for the aquifer beneath Baucau, and for Liquica it was between high to very high, whereas for Dili and Oecussi it was in the medium to high range. Aquifers located underneath areas other than these four were largely found to have low to medium sensitivity due to their geographical locations. The sensitivity of aquifers to population pressure at four locations (Baucau, Liquica, Dili and Oecussi) was in the medium to very high range, except for all other locations where it ranged largely from very low to medium (Table 4). The cumulative effect of both indicators reached a very high level, especially at four locations which were already medium to highly sensitive due to population pressure.

The sensitivity of aquifers in the remaining areas ranged between very low to low or medium. Since these four locations were sensitive to both climatic and non-climatic indicators, it was further exacerbated under the combined effect of both indicator categories. Aquifers in other areas with little or no population, and negligible or zero groundwater pumping were only sensitive to mean annual rainfall. Therefore, sensitivity remained unchanged even after combining the effect of both indicators. The findings from Myers et al. (2011) solidify the fact that

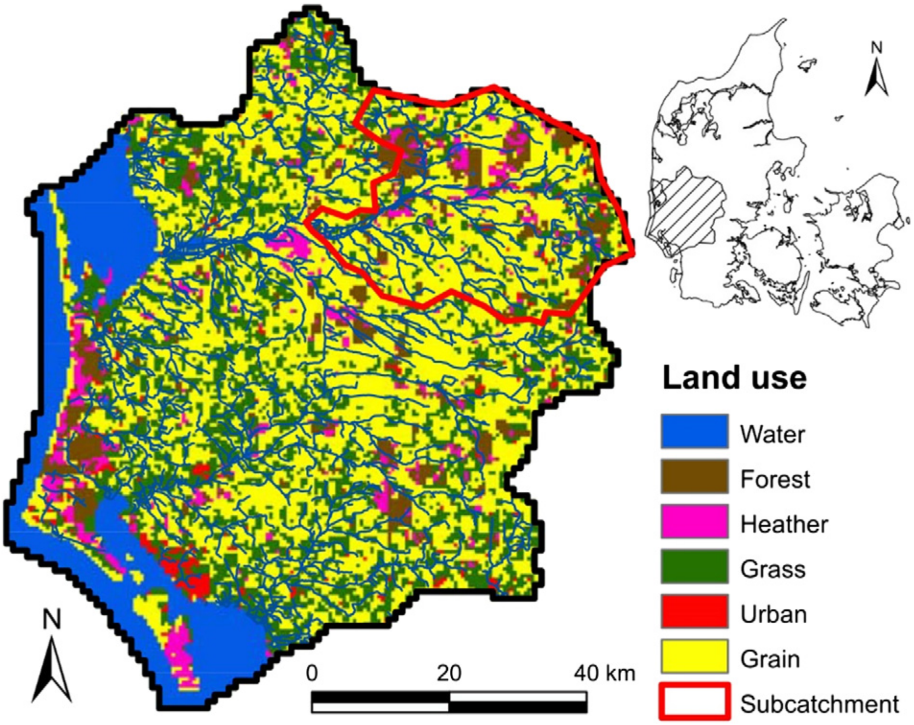


Fig. 8. Study area located in the western part of Jutland, Denmark (Roosmalen et al., 2009).

Table 4
Summary of results for sensitivity analysis in published literature.

References	Scenarios	Indicators	Status	Results	
Chang et al. (2016)	Volume of groundwater resources (salinity level < 1.2%)				
	Baseline				
	Scenario-1	Wet/dry climate + land use/cover + pumping	Constant	2.69×10^7 m^3	
	Scenario-2	Land use/cover	Changing	(−3.9%) 2.58×10^7	
	Scenario-3	Dry climate + land use/cover	Changing	(−3.3%) 2.50×10^7	
	Scenario-4	Wet climate + land use/cover	Changing	Returned to B.L	
	Scenario-5	Dry climate + land use/cover + pumping	Changing	(−8.6%) 2.46×10^7	
	Volume of groundwater resources (salinity level < 10%)				
	Baseline				
	Scenario-1	Wet/dry climate + land use/cover + pumping	Constant	2.79×10^7 m^3	
	Scenario-2	Land use/cover	Changing	(−3.1%) 2.7×10^7	
	Scenario-3	Dry climate + land use/cover	Changing	(−5.7%) 2.63×10^7	
	Scenario-4	Wet climate + land use/cover	Changing	Returned to B.L	
	Scenario-5	Dry climate + land use/cover + pumping	Changing	(−7%) 2.59×10^7	
	Volume of groundwater resources (salinity level < 50%)				
	Baseline				
	Scenario-1	Wet/dry climate + land use/cover + pumping	Constant	2.97×10^7 m^3	
	Scenario-2	Land use/cover	Changing	(−2.5%) 2.9×10^7	
	Scenario-3	Dry climate + land use/cover	Changing	(−5.1%) 2.82×10^7	
	Scenario-4	Wet climate + land use/cover	Changing	Returned to B.L	
	Scenario-5	Dry climate + land use/cover + pumping	Changing	(−6%) 2.79×10^7	
Myers et al. (2011)	Sensitivity of aquifers at various locations			Province	Sensitivity
	n/a	Sensitivity of aquifer to rainfall and aquifer yield	–	Baucau Liquica	Medium to high
		Population pressure		Dili	
				Oecussi	
				All other areas	Medium to low
Zume and Tarhule (2011)	Groundwater drawdown and streamflow depletion				
	Baseline				
	Scenario-1	Projected pumping	Increasing	–	40%↓
	Scenario-2				
	Scenario-3	Severe drought	Changing	26%	89%↓
	Scenario-4				
		Prolonged wet period	Changing	−94%	Zero
		Human adjustment (25% reduced pumping)	–	−12%	20%↑

Note: Arrows show increase/decrease in value; H-High; M-Medium; L-Low and B.L- Baseline. Values in parenthesis show percentage change (sensitivity) of groundwater reserves as a function of various influencing indicators.

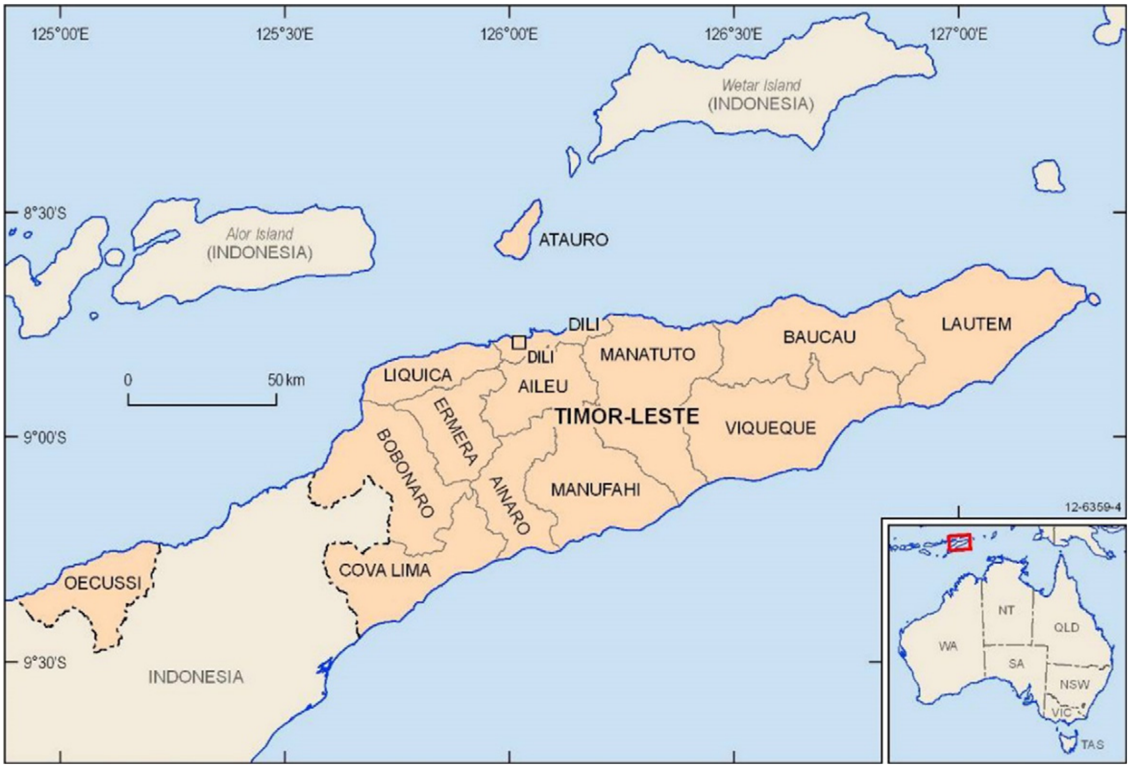


Fig. 9. Study area of Timor Leste (after Asian Development Bank, 2003).

consideration of both climatic and non-climatic indicators gives more practical and reliable estimates for the sensitivity of groundwater to climate change.

(Zume and Tarhule, 2011) also highlighted the sensitivity of groundwater levels (drawdown) to climatic and non-climatic stressors in the Southern Great Plains, USA (Fig. 6). Under a projected pumping scenario, they found a 40% increase in streamflow depletion. While a 26% increase in drawdown and depletion of 89% in streamflow were found under the severe drought scenario compared with that of projected pumping. Overall, 13% more of the aquifer area was affected by drawdown under the severe drought scenario. Drawdown was reduced by 94% relative to baseline drawdown under the very wet scenario. The human adjustment scenario showed a 12% decrease in drawdown relative to baseline and a 20% increase in streamflow (Table 4). The dominant effect of climate stressors is apparent in these results but the effect of non-climate stressors cannot be ignored. Therefore, this evidence also strengthens the need for the inclusion of composite indicators in assessing the vulnerability of groundwater to climate change.

From the study results discussed in the sensitivity section, it is apparent that under normal climate conditions, the effect of non-climatic stressors such as population pressure, pumping and land use/cover change, dominates that of climatic stressors. Alternatively, it can be inferred that the system is more responsive to non-climatic stressors. Exceptions exist for extreme climate conditions (drought, dry climate) where a fair dominance of climatic stressors is also clear. This fact, based on the relative impacts of stressors and resultant response of the system signifies the importance of each indicator towards the fate of the system under study. The sensitivity of groundwater resources was further highlighted when indicators were considered in combination. It can be assumed that the response of the groundwater system to combined stressors is more realistic because consideration of multiple indicators takes into account the interaction among various stressors, which naturally exist in terms of their interdependence. Thus, they increase the proximity of modelled results to naturally occurring impacts as well as the response (sensitivity) of the groundwater system.

5. Adaptive capacity of the social and physical system

Adaptive capacity plays a role in limiting the vulnerability of a system to climate change. It can be assessed independently or inferred from the indicators of exposure and sensitivity. There are broadly three classes of adaptive capacity indicators (i.e., assets of actors in a system, available resources and governing institutions) which should be included, especially if adaptive capacity is assessed as an independent part of vulnerability. Inclusion of a variety of indicators selected on the basis of their functional relationships with each other and magnitude of influence on the system will ultimately enhance the reliability of assessed results (Adger et al., 2009; Luers and Moser, 2006; Whitely Binder et al., 2009).

Myers et al. (2011) assessed the adaptive capacity of communities to vulnerable groundwater systems in Timor Leste (Fig. 9) using 18 indicators from three groups namely, health, wealth and education (Table 5a). The poverty indicator (i.e., population in the lowest wealth percentile) was found to be negatively correlated to wealth proxies (motorbike ownership, tiled or concrete floors in the house, a corrugated iron roof, etc.). A direct relationship was found between indicators and proxies of health (use of mosquito nets by pregnant women and children, etc.). Since values of indicators were very high for Dili, they exaggerated the overall correlation between indicators for other cities. Therefore, they considered the values of these indicators for Dili as outliers and again calculated the correlation, which was very weak but the trend remained the same. Among 13 cities, Dili was found to be highly adaptive due to its high capacity in opting for adaptive measures, whereas Oecussi possessed minimum capacity for adapting to vulnerable groundwater resources. Social capital indicators (i.e., community level management of water resources and access to them) also showed the highest capacity in Dili compared to other cities. This was a national level study which was supposed to consider possible indicators of health, education and governance, which are internal to a system or operated within it. In turn, these are also linked to social capital (Brooks and Adger, 2003).

Myers et al. (2011) successfully incorporated many of the aforementioned indicators, but did not consider those appertaining to governance, and institutional capacity in particular, which also have a functional correlation (relationship) with those included in this investigation. This fact may seriously limit the scope of their findings. A functional relationship has a dominant effect on defining the adaptive capacity of a system, as evidenced in this study. Therefore, ignoring any one of the most relevant indicators is likely to give sub-optimal results. Myers et al. (2011) have acknowledged this limitation and suggested the possible inclusion of a variety of indicators, with a few from each group in future studies.

Seeboonruang (2016) undertook a study in Eastern Thailand (Fig. 10) by considering only persistence (one to three occurrences) of drought in an area as an indicator of adaptive capacity. He found that

Table 5a
Results for the adaptive capacity of a population to vulnerable aquifers in Timor Leste (Source: Myers et al., 2011).

Indicators		Proxy	Results		
			High	Medium	Low
Wealth	Poverty	Percentage of population in the two lowest wealth quintiles	Dili	Lautem	Oecussi
	Radio	Percentage of households owning a radio	Dili	Bobonaro	Viqueque
	Mbike	Percentage of households owning a motorcycle	Dili	Lautem	Ermera
	Floor	Percentage of houses having a tiled or concrete floor	Dili	Manatuto	Viqueque
	Roof	Percentage of houses having a corrugated metal roof	Dili	Covalima	Oecussi
	Light	Percentage of houses with electric light	Dili	Viqueque	Ermera
	Wood	Percentage of households using wood as a fuel for cooking	Dili	Ainaro	Ermera
	Water	Percentage of households with access to drinking water supplies (indoors or outdoors)	Liquica	Manufahi	Baucau
Education	NoEd	Percentage of individuals five years or older who have never attended school	Dili	Viqueque	Ermera
	Vacc	Percentage of anaemia-affected children who have received the four main vaccinations: DPT, polio, hepatitis B and measles	Aileu	Manatuto	Manufahi
	NoVacc	Percentage of children who have not received any of the four vaccinations	Dili	Manatuto	Oecussi
Health	Mal	Percentage of children with a height for age of more than three standard deviations below average	Dili	Covalima	Ermera
	Wt4Ht	Percentage of children with a weight for height of more than three standard deviations below average	Lautem	Ainaro	Aileu
	Wt4age	Percentage of children with a weight for age of more than three standard deviations below average	Lautem	Manufahi	Oecussi
	Anaem	Percentage of children with anaemia	Ermera	Liquica	Manatuto
	NetK	Percentage of children who slept under any kind of mosquito net the night before the survey	Covalima	Bobonaro	Ainaro
	NetW	Percentage of pregnant women who slept under any kind of mosquito net the night before the survey	Manatuto	Lautem	Ainaro
	W4Dec	Percentage of women who participate in decisions relating to four areas: own healthcare, major household purchases, daily needs and visits to friends and family	Bobonaro	Viqueque	Lautem

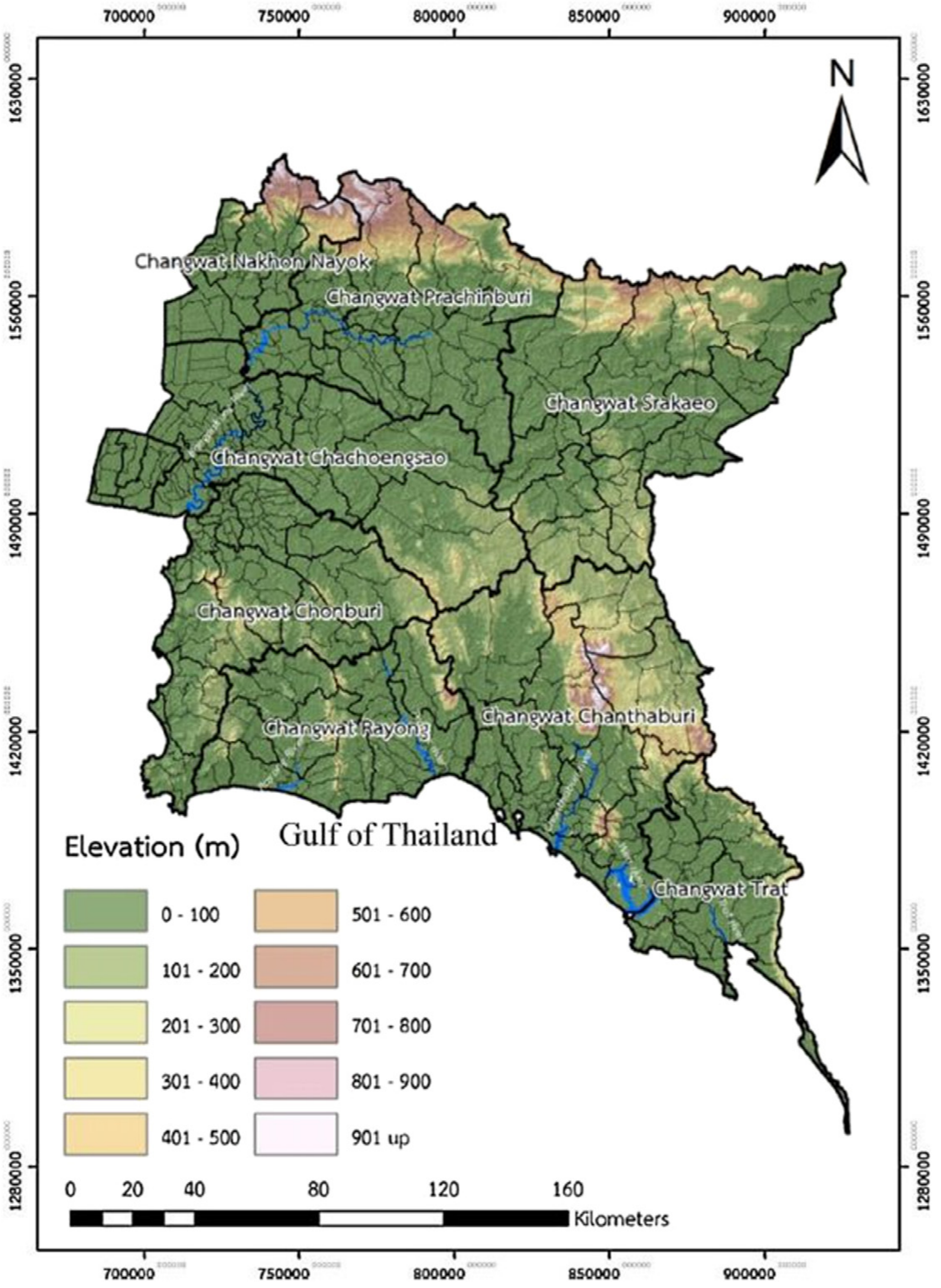


Fig. 10. Study area of Eastern Thailand (Seeboonruang, 2016).

20 to 25% of sub-districts in four provinces (Chanthabur, Chachoengsao, Prachinburi and Trat) were free from drought and 10% of sub-districts in three provinces (Chonburi, Rayong and Srakaeo) also lie in the same category. The remaining sub-districts from these provinces face issues such as limited access to water resources. Whereas >20% of the sub-districts face medium drought persistence or can say they have medium adaptive capacity.

Nearly 50% of sub-districts in Chonburi were found to be highly impacted by drought, and 30% in Prachinburi, 24% in Srakaeo, 19% in Chachoengsao and 11% in Rayong were also in the same category. Alternatively, it can be inferred from the results that drought-free sub-districts have a high capacity for adapting to vulnerable groundwater resources, whereas those areas where drought persistence and impacts are very pronounced have less adaptive capacity (Table 5b).

The scale of this study is subnational, and according to Brooks and Adger (2003), such a study has to consider both types of indicator, namely those internal and external to a system. Otherwise, the study may not be able to successfully address the adaptive capacity. Therefore, the inclusion of other closely linked indicators of adaptive capacity is necessary to further improve the findings of this research.

Table 5b
Results for the adaptive capacity of a social system to vulnerable groundwater resources in Eastern Thailand (Source: Seeboonruang, 2016).

Indicator	Proxy	Results		
		Province	% Sub-districts	Adaptive capacity
Drought persistence	Percentage of drought-free area (less groundwater reserves/increased dependence on groundwater resources)	CTBR	20–25	High
		CHG		
		PCB		
		TRT		
		CBR	10	
		RYG		
		SKE		
		CTBR	20	Medium
		CHG		
		PCB		
		TRT		
		CBR		
		RYG		
		SKE		
		CTBR	–	Low
		CHG	19	
		PCB	30	
		TRT	50	
		CBR	11	
		RYG	24	
		SKE		

Note: CTBR: Chanthabur; CHG: Chachoengsao; PCB: Prachinburi; TRT: Trat; CBR: Chonburi; RYG: Rayong, SKE: Srakaeo.

In Timor Leste (Fig. 11), Wallace et al. (2012) found that intergranular aquifers had low (small catchments) to high (large catchments) adaptivity to rainfall change and sea level rise based on the indicators of water management options (i.e., infrastructure, surface and groundwater interaction, potential for managed aquifer recharge, etc.). The adaptive capacity of karst and localised fractured aquifers was in the range of low (topographically high) to medium (topographically low) due to the limited scope of management options (Table 5c). Wallace et al. (2012) omitted the indicators of institutional performance which play a key role in ongoing and proposed water resources management plans. Instead, they only pointed out certain challenges (lack of technical and institutional capacity) being faced by the institutions of Timor Leste. The study findings would have been more practical if those indicators had been considered.

A review of previous studies shows that there are numerous factors which need to be considered when assessing the adaptive capacity of a system. These may include a system under stress, its dependent systems and the systems responsible for control. The scale of the study also has a key role in adaptive capacity assessment. Therefore, indicators appertaining to all systems should be considered in order to have an authentic picture of the capacity of the groundwater system for adapting to climate change impacts.

6. Research gaps and proposed approach

This section presents the research gaps observed in the reviewed studies followed by a description of a new integrated Approach proposed for assessment of the vulnerability of groundwater resources to climate change (Fig. 12). There are very few studies dedicated to addressing the vulnerability of groundwater to climate change. All the reviewed studies have assessed the components and thus the overall vulnerability of a few indicators without considering many others which might more or less be equally contributing to groundwater vulnerability. Exploring the possibility of integrating all the indicators within a system depending upon local conditions, scale of the study, data availability, and identifying their functional relationship and dependency on other indicators can be an active area of research. This will help in the exploration of new insights into their combined effects.

The IPCC (2007) framework identifies and considers adaptive capacity as an integral part of the vulnerability assessment process. Other studies (e.g., Schröter et al., 2004; Voice et al., 2006) further highlight

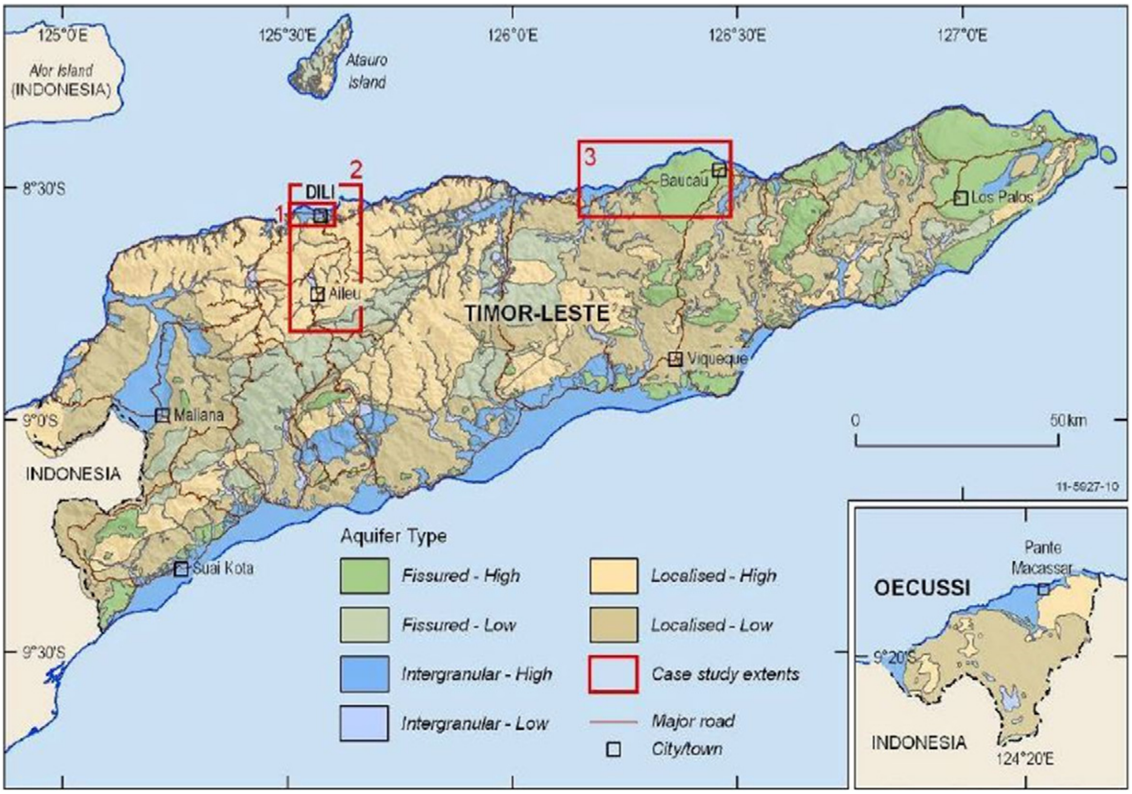


Fig. 11. Study area of Timor Leste (Wallace et al., 2012).

Table 5c
Results for the adaptive capacity of a population to vulnerable aquifers in Timor Leste
(Source: Wallace et al., 2012).

Indicator	Proxy	Results		
		Aquifer type	A/C to rainfall changes	A/C to SLR
Potential of managed aquifer recharge	Potential to enhance the recharge in area underlying aquifer	Intergranular (large catchments)	High	High
		Intergranular (small catchments)	Low	Low
Surface-groundwater interaction	Aquifer access to surface flow during wet seasons	Fissured (topographically high)	Low	Medium
	Availability of infrastructure in coastal areas	Fissured (topographically low)	Medium	Low
Infrastructure		Localised (topographically high)	Low	Medium
		Localised (topographically low)	Medium	Low

the importance of adaptive capacity. On the one hand, modelling techniques for vulnerability assessment have a unique way of quantifying vulnerability. Similarly, index-based assessment has a predefined method that necessitates the inclusion of adaptive capacity (IPCC, 2007; Schröter et al., 2004; Voice et al., 2006). Only three previous studies consider adaptive capacity in their assessments. The integrated use of impact modelling and index-based methodologies, which also consider adaptive capacity, could provide better results in future research, thereby taking advantage of both methodologies as well as minimising some of their limitations. Further details are discussed in the following sections.

Climatic phenomena, both in variability and change, influence the groundwater system. Some researchers even consider variability more influential than change. However, the variability factor is completely ignored in the reviewed studies. This also provides another wide area for further research. Studies focusing on sea level rise and recharge estimation as part of their assessment, considered simplifications for many important influential factors (Section 2.2). There is a need for further research on scenarios of gradual sea level rise, consideration of real slopes, the heterogeneity of aquifer geology and hydraulic conductivity.

Addressing the aforementioned research gaps demands a new approach towards vulnerability assessment, which can compensate for weaknesses in index-based methods (e.g., subjectivity involved in assigning weights and trade-off between indicators), incorporate adaptive capacity into impact modelling, and bring advantages to modelling techniques. Fig. 12 presents the proposed integrated approach in this regard, which has the capability to quantify the exposure and sensitivity components of vulnerability by a model-based approach. The use of climate and impact models to estimate two of the three components of vulnerability should address any limitations (e.g., instantaneous sea level rise, lumped slope/hydraulic conductivity and homogeneous geology) associated with index-based methods, making the results more convincing. Although model-driven (climate and hydro(geo)logical) results are likely to contain uncertainty, they can easily be quantified and assigned to enhance the reliability of the assessment.

The limitations identified in the reviewed studies are classified into two types: assumption-based limitations and methodology-based limitations. The way the proposed approach addresses those limitations are tabulated in Table 6 and elaboration is given in the following subsections.

6.1. Assumption-based limitations

6.1.1. Instantaneous sea level rise

The new approach overcomes this limitation by considering gradual sea level rise assumption, it takes yearly rises in sea level into account as projected by IPCC (0.2 to 4 m/year), instead of considering a single high value for a longer duration.

6.1.2. Uniform soil slope (topography)

Assuming a single lumped slope value can simplify the process, the departure from actual towards calculated results is obvious. Therefore, the proposed approach overcomes this limitation by changing the parameter from lumped to its nearly accurate value, taking spatial variability into account by using the Digital Elevation Model (DEM).

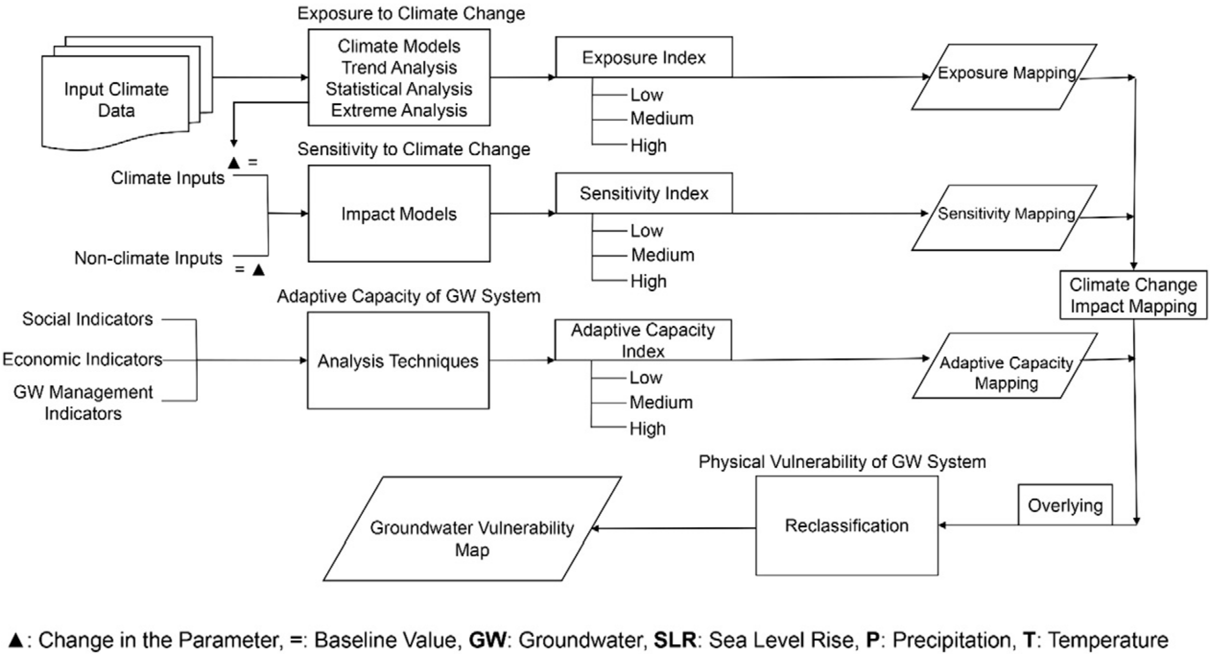


Fig. 12. Proposed approach for a groundwater vulnerability assessment to climate change.

Table 6
Summary of the limitations identified in previous studies and solutions for addressing such limitations through the proposed approach.

S.N.	Limitations	Ways the proposed approach addresses the limitations
1	Assumption-based limitations	
a	Instantaneous sea level rise	Considering the yearly rise in sea level (0.2 to 4 m/year), projected by IPCC
b	Uniform soil slope (topography)	Using the Digital Elevation Model (DEM) to calculate the actual slope
c	Homogeneous aquifer properties	Using a fully-distributed 3D groundwater model such as MODFLOW
d	Linearity of groundwater contamination	
e	Simplifying the rainfall recharge process (omission of land use, aquifer media, depth to groundwater, topography of area, soil characteristics and hydraulic conductivity)	Using semi-distributed models which consider the complexity and heterogeneity of processes and parameters (SWAT, WetSpass etc.)
2	Methodology-based limitations	
a	Climate variability is missing	Incorporating a monthly and seasonal analysis of climatic extremes, and inter-annual variability
b	Downscaling	BCSD downscaling technique; incorporates both climate change and variability in the plain area
	• Delta change does not account for climate variability • SOMD underestimates rainy days	Use of dynamically downscaled RCMs can overcome the limitation of the missing terrain effect for mountainous areas
c	• Subjectivity in assigning weights • Trade-off between indicators	• Use of modelling technique for exposure and sensitivity analysis • Indexing of model results based on their range (which does not require judgment) • Mapping of indexed results
d	Lack of adaptive capacity in impact modelling	Measurement of adaptive capacity as an independent component using Modified-DRASTIC-AHP Incorporating adaptive capacity results to climate change impacts quantified from impact modelling

6.1.3. Homogeneous aquifer properties

Using the proposed integrated approach, homogeneity assumptions for the aquifer and its properties can be addressed using semi or fully-distributed hydrological models. Fully-distributed, 3D groundwater flow models such as MODFLOW can provide a facility to incorporate heterogeneity in the aquifer and its properties.

6.1.4. Linearity of groundwater contamination and simplification in the rainfall recharge process

Previous studies have quantified the contamination from surface resources and recharge using simplified methods and tools. This approach suggests the use of semi-distributed models such as SWAT and WetSpass, and several other models are also available. These models do not require as much data as the fully-distributed model and also introduce heterogeneity in various processes (contrary to lumped models) at Hydrological Response Unit (HRU) or sub-basin levels, thereby providing an optimum solution to the limitations involved in previous methodologies.

6.2. Methodology-based limitations

6.2.1. Missed climate variability component

While quantifying the exposure or change in climate, previous studies have missed the variability aspect completely. Variability is as important as change. Therefore, the new approach also considers variability while quantifying the exposure to changes in climate by incorporating monthly and seasonal analysis of climatic extremes as well as inter-annual variability.

6.2.2. Downscaling

Robust analysis of the exposure and sensitivity to climate considers both variability and change. Downscaling techniques (i.e., delta change and SOMD) do not take variability into account or underestimate rainy days or otherwise, and the use of hypothetical scenarios as in previous studies, affects the quantified results. The proposed approach suggests the use of the BCSD technique to downscale GCMs in plain areas because it does not account for the terrain effect. Whereas dynamically downscaled RCMs can successfully take account of variability in climate as well as terrain effects (Andréasson et al., 2003).

6.2.3. Subjectivity in assigning weights and trade-off between indicators

Assigning weights to indicators and normalising them are challengeable, due to the subjectivity and under and/or overestimation of their actual weights. Previous studies have employed these techniques to quantify the components of vulnerability and some have directly quantified vulnerability. The proposed new approach quantifies the exposure and sensitivity of groundwater systems using impact models. An index is then developed by dividing the complete range of changes in the calculated results into different categories such as low, medium and high (Seeboonruang, 2016), thereby, overcoming both limitations of the previous methodologies.

6.2.4. Lack of adaptive capacity in impact modelling

The proposed approach cannot quantify the adaptive capacity of the system. This is because the quantification of adaptive capacity of groundwater dependent systems and groundwater itself is bound to indicator-based methodologies (Brooks and Adger, 2003). Therefore, the proposed approach assesses this component in the same way which could be a limitation. However, the quantification of exposure and sensitivity can compensate for any resulting uncertainty. Furthermore, this approach quantifies the vulnerability of groundwater resources both at spatial and temporal scales.

7. Conclusions

The need for scientific knowledge based on the climate change impacts on groundwater systems for better preparedness is generally understood. Assessing the vulnerability of groundwater to possible stressors helps to translate such impacts into actions. In this regard, several attempts have recently been made across the globe at different scales. A comprehensive review was undertaken in order to develop a better understanding of previous research work and critically analyse and identify knowledge gaps based on the assumptions involved at various stages of the methodologies used. In addition, the review also highlighted the significance of indicator choice in assessing the components and overall vulnerability of groundwater to climate change as well as the limitations and gaps in the methodologies. Part of the review is presented in tables to further highlight the most significant attributes of those studies. To successfully address the limitations and gaps, a new integrated approach is proposed with a detailed explanation of key points to provide a solution to each limitation found in previous methodologies. The proposed approach integrates impact modelling and an index-based approach to assess the vulnerability of groundwater resources to climate change. It can overcome the limitations in both approaches, and may thereby be the best alternative for further research.

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