A synthesized biophysical and social vulnerability assessment for Taiwan

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Abstract. Taiwan, located in the Western Pacific, is a country that is one of the most vulnerable to disasters that are associated with the changing climate; it is located within the Ring of Fire, which is the most geologically active region in the world. The environmental and geological conditions in Taiwan are sensitive and vulnerable to such disasters. Owing to increasing urbanization in Taiwan, floods and climate-related disasters have taken an increasing toll on human lives. As global warming accelerates the rising of sea levels and increasing of the frequency of extreme weather events, disasters will continue to affect socio-economic development and human conditions. Under such circumstances, researchers and policymakers alike must recognize the importance of providing useful knowledge concerning vulnerability, disaster recovery and resilience. Strategies for reducing vulnerability and climate-related disaster risks and for increasing resilience involve preparedness, mitigation and adaptation. In the last two decades, extreme climate events have caused severe flash floods, debris flows, landslides, and other disasters and have had negative effects of many sectors, including agriculture, infrastructure and health. Since climate change is expected to have a continued impact on socio-economic development, this work develops a vulnerability assessment framework that integrates both biophysical and social vulnerability and supports synthesized vulnerability analyses to identify vulnerable areas in Taiwan. Owing to its geographical, geological and climatic features, Taiwan is susceptible to earthquakes, typhoons, droughts and various induced disasters. Therefore, Taiwan has the urgent task of establishing a framework for assessing vulnerability as a planning and policy tool that can be used to identify not only the regions that require special attention but also hotspots in which efforts should be made to reduce vulnerability and the risk of climate-related disaster. To analyze the biophysical vulnerability of Taiwan, hazards on eight maps from Taiwan’s National Science and Technology Center for Disaster Reduction (NCDR) are analyzed. Statistical data from the NCDR on social vulnerability are also adopted. Finally, a GIS overlaying method was used to perform the synthesized vulnerability analysis of biophysical and social vulnerability for municipalities and counties in Taiwan.

1. Introduction
Owing to climate change, the incidence and frequency of extreme weather events have greatly increased. Not only does climate change create uncertainties in natural disasters, it also affects our daily lives differently across different regions [1-4], and will increase the vulnerability of most countries in the Asia-Pacific region to extreme weather events [5]. Natural disasters are serious threats to the country of Taiwan, for example [2, 4, 6-8]. The socio-economic development of Taiwan has...
been substantially affected by climate changes, whose effects have cost Taiwan a significant percentage of its GNP and have reduced the quality of life of its residents [4,6].

The United Nations suggested two key methods, mitigation and adaptation, to deal with the above effects [3]. The mitigation strategy involves various approaches to reduce the amount of greenhouse gases that are emitted into the atmosphere. The adaptation strategy includes various means of adapting to climate change, including changing lifestyle and industrial activities, taking advantage of climate change-related opportunities, and adapting to environmental changes [7].

Recognizing and elucidating issues of vulnerability and resilience are important in urban planning and management [1-2, 4, 9-14]. The construction of resilient cities has recently been examined [2,4,15]. More active and progressive perspectives and methods have been used to increase the carrying capacity of urban areas in the face of disasters and to improve vulnerability [2, 7, 16-17].

Major challenges in disaster risk management in urban areas include reducing vulnerability, improving adaptability, increasing resilience, considering different characteristics of, and relationships among, cities and improving stakeholder participation [18]. However, current studies focus on one-dimensional static evaluations and correlation analyses of vulnerability, adaptability and resilience [19-20].

Taiwan is an island state in the Western Pacific Region, which is frequently hit by typhoons and under many meteorological influences. The island is mostly mountainous in the east, with gently sloping plains in the west. Accordingly, the presence of short rivers with narrow mouths and the continuous reduction of green open spaces in the west contribute to low water drainage rates and reduced capacities of the land to contain and store water, favoring disasters such as floods, falling rocks, debris flows and rock slides [4].

Taiwan has a dynamic, capitalist and export-driven economy. Economic growth has led to the overdevelopment of much of the land in Taiwan. Since Taiwan is an island state that is sensitive to biophysical and geographical changes, its overdevelopment has led to development reaching on mountains, slope lands and rivers. For example, over 73% of the land and population in Taiwan are exposed to at least three hazards. In particular, typhoons bring extreme precipitation every summer [21]. Vulnerable to climate change, Taiwan has undergone urbanization in recent years. Accordingly, suitable responses to the effects of climate change, given limited resources, and maintenance of a stable balance among natural ecosystems will help Taiwan move toward sustainability [7].

Generally, the goals of assessing vulnerability are related to risk identification, understanding of the context of vulnerability and factors that govern vulnerability [2, 22]. Presently, information required to assess the risk facing Taiwan is lacking, and a complete assessment requires long-term observations, exploration and research [7]. However, studies of the effects of climate change and short-term variations of climate impacts focus only on such disasters as debris flows, landslides and floods. The effects of such disasters can be investigated in relation to the dimensions of prevention, adaptation and relief management. Therefore, quantitative data concerning biophysical and social vulnerability, collected from Taiwan’s National Science and Technology Center for Disaster Reduction (NCDR), are used to evaluate vulnerability to climate change as a foundation for adaptation, mitigation and resilience planning.

This study assesses the potential effects of climate change in Taiwan. Vulnerability data from Taiwan’s NCDR were obtained to elucidate cities/townships that are vulnerable to climate change and to identify highly vulnerable areas as adaptation hotspots using the Geographic Information System (GIS).

2. Vulnerability
Since the beginning of this century, global warming, rising sea levels and rapid urbanization have had negative effects. The frequency and intensity of heavy rain, storm surges and other dangerous incidents have increased drastically [3-4].

The sustainable development of a country or region vis-à-vis a changing environment requires a strong adaptive capacity, which involves overcoming unexpected disasters or risks. Adaptive capacity
has two dimensions, which are adaptation and the time required for the country or region to respond to the effects of disasters. Adaptation can be measured in terms of sustainability, vulnerability, and/or resilience [23-24]. Moreover, resilience assessment is important to the integration of landscape, society and land use with adaptive capacities [2, 11, 25-26].

Vulnerability, resilience and adaptation are the three key concepts that are related to climate change, and have an important role in dealing with climate change and disaster-related issues [10-11, 20, 27]. Vulnerability is a basic element in turning a hazard into a disaster, and inabilities and delays in the reduction of hazard exposures will increase the number of natural disasters and losses [28].

IPCC indicated that vulnerability does not depend entirely upon sensitivity [3]. Vulnerability incorporates various concepts and includes various elements, including sensitivity; the adaptive capacity of a system under climate change should also be considered. Generally, vulnerability is the susceptibility of a system to losses that are caused by climate change [20] and the capacity of a system to recover [17]. More specifically, vulnerability is “a function of exposure to a stressor, effect (also called sensitivity or potential impact) and recovery potential (also called resilience or adaptive capacity)” [14]. Vulnerability is context-specific, and varies greatly among regions of a country [6-7, 10-11, 14].

Essentially, vulnerability is “a function of the character, magnitude and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity” [29]. Therefore, Eq. (1) defines vulnerability and Eq. (2) specifies it empirically.

\[ V = f(E, S, A) \]  
\[ V = E \times S - A \]  

Many of the vulnerability-related investigations involve spatial analyses that are supported by GIS to elucidate vulnerability and include various indicators [2, 6-8, 14, 20, 31-33].

Vulnerability assessment and mapping, climate monitoring, the prediction and timely warning of extreme climate events are some of the best methods for mitigating negative effects of climate-related factors on humanity, property and the environment, and of exploiting possible positive effects. Therefore, accurate and updated information regarding climate change, including associated vulnerabilities, are critical inputs in sustainability planning [2, 14, 20, 23-24].

Vulnerability research can provide useful information on the people and places that are at risk, and can elucidate conditions that weaken the adaptive capacity of people to respond to climate-related risks [14, 34]. This information can then be used to create strategies that facilitate adaptation governance. Therefore, identifying and distinguishing vulnerable areas and degrees of disaster management are crucial [8, 14, 31]. Although various studies have used various definitions of vulnerability, the two main types of vulnerability are “biophysical (or physical) vulnerability” to natural disasters and “social vulnerability” due to socio-economic factors [2, 7, 14, 27, 35-36].

This study addresses the context of vulnerability and maps vulnerable regions using the GIS technique. Synthesized vulnerability, including biophysical and social vulnerability, is therefore conducted. The goal of vulnerability mapping is to generate useful knowledge that is required to identify and assess the allocation of resources and to develop adaptation plans and strategies for vulnerable areas, sectors, groups, and so on, to help mitigate the risks of climate change in the country.

3. Method
To evaluate the vulnerability to help Taiwan identify and distinguish hot spots for planning adaptation to climate change and related actions, biophysical vulnerability and social vulnerability were mapped
using the GIS technique. Data from Taiwan’s NCDR were used to evaluate biophysical vulnerability and social vulnerability, and further to calculate synthesized vulnerability.

3.1. Biophysical Vulnerability Index
The NCDR data included figures and maps of cities/townships that are affected by several indicators. In this investigation, seven phenomena that are related to climate change were considered to assess biophysical vulnerability; they are landslides, falling rocks, daily rainfall and flooding, debris flows, rock slides, tsunamis, and the dip slope distribution. Seismic faults are also considered to indicate the non-climate-related indicator. The GIS mapping method was used to calculate the ratio of each biophysically vulnerable area to the total area of the city/township. Since a city/township can suffer from more than one potential disaster, summing all potential disaster areas and multiplying each number by 1/8 (for 8 indices) yields the severity of vulnerability. The biophysical vulnerability formula is as follows.

- $N_2$: Total area of biophysical vulnerability
- $n'_i = n_i \times \frac{1}{8} \times \%$

3.2. Social Vulnerability Index
Social vulnerability, evaluated from 2016 NCDR data, has four dimensions, which are degree of exposure, mitigation and preparedness, response capacity and recovery capacity. The degree of exposure dimension concerns (1) industry, (2) household assets, and (3) population. The mitigation and preparedness dimension includes (1) prevention engineering, (2) regulations and enforcement, and (3) disaster prevention education. The response capacity dimension includes (1) refuge shelter, (2) disaster disadvantaged, (3) rescue, and (4) health care. The recovery capacity dimension includes (1) economy and (2) social network (Fig 1). The four dimensions are associated with different variables (Table 1).

Figure 1. Four main dimensions of social vulnerability.
Table 1. Definition and factor of social vulnerability.

| Layer 1 (Dimension) | Layer 2 (Factor) | Layer 3 (Variable) |
|---------------------|------------------|--------------------|
| Degree of exposure  | Industry         | Total value of products from the primary industry (agriculture, forestry and fishing industries) |
|                     | Household asset  | Household and building value |
|                     | Population       | Households protected from mudslides by the Water Conservation Bureau (actual number of occupants) |
| Mitigation and preparedness | Prevention engineering | Degree of shock-proofing, obtained from Taiwan Earthquake Loss Estimation System (TELES) construction data |
|                     | Regulations and enforcement | Degree of hillside overuse |
|                     | Disaster prevention education | Number of mudslide prevention drills |
|                     | Refuge shelter   | Number of country roads connected to main roads |
|                     | Disaster disadvantaged | Number of elderly people living alone |
| Response capacity   | Rescue           | Number of fire fighters (including volunteer fire fighters) |
|                     | Health Care      | Number of disaster relief vehicles, ambulances and lifeboats |
|                     | Economics        | Number of low-income households |
| Recovery capacity   | Social network   | Ratio of social welfare budget to number of people |

4. Results

4.1. Biophysical Vulnerability
Taiwan has 22 cities and counties in four regions. The largest threats to Taiwan’s biophysical system include flooding, debris flows, rock slides and the dip slope distribution. Table 2 presents the biophysical vulnerability of cities/counties with the largest areas in Taiwan. The cities and counties with the greatest biophysical vulnerability are Taichung City (five districts), Kaohsiung City (five districts), Pingtung County (five townships), Nantou County (three townships), Taoyuan City (two districts), Tainan City (two districts), New Taipei City (one district), Keelung City (one district), Yunlin County (one township), Changhua County (one township), Hualien County (one township),
Chiayi County (one township), Miaoli County (one township) and Yilan County (one township). In this study, three degrees of vulnerability are identified, which are V1 (least vulnerable) to V3 (most vulnerable). The GIS technique for overlaying maps was used to create a map of biophysical vulnerability in Taiwan (Fig. 2).

Table 2. Biophysical vulnerability in Taiwan.

| Disaster types                        | Vulnerability of cities/counties with the largest areas                                                                 |
|---------------------------------------|-----------------------------------------------------------------------------------------------------------------------|
| Falling rocks                         | Nanhua District, Tainan City: 9.74%                                                                                   |
|                                       | Zuozhen District, Tainan City: 9.65%                                                                                  |
|                                       | Tianliao District, Kaohsiung City: 9.46%                                                                               |
| Rock slides                           | Jiaxian District, Kaohsiung City: 1.89%                                                                               |
|                                       | Gushan District, Kaohsiung City: 1.66%                                                                                |
|                                       | Gukeng Township, Yunlin County: 1.15%                                                                                 |
| Debris flows                          | Shuili Township, Nantou County: 2.45%                                                                                |
|                                       | Puli Township, Nantou County: 1.63%                                                                                  |
|                                       | Tianzhong Township, Changhua County: 1.13%                                                                             |
| Falling rocks                         | Xiulin Township, Hualien County: 2.18%                                                                              |
|                                       | Alishan Township, Chiayi County: 1.98%                                                                               |
|                                       | Heping District, Taichung City: 1.92%                                                                               |
| Dip slope                             | Qidu District, Keelung City: 19.44%                                                                               |
|                                       | Zhuolan Township, Miaoli County: 19.39%                                                                              |
|                                       | Pingxi District, New Taipei City: 17.51%                                                                             |
| Daily rainfall and flooding (600mm)   | 100% of potential flooding area (600mm):                                                                         |
|                                       | Zhongli District, Taoyuan City                                                                                       |
|                                       | Pingzhen District, Taoyuan City                                                                                      |
|                                       | Shengang District, Taichung City                                                                                     |
|                                       | Yuchi Township, Nantou County                                                                                        |
|                                       | Lingya District, Xinxing District, Kaohsiung City                                                                  |
|                                       | Linluo Township, Zhutian Township, Kanding Township, Nanzhou Township, Pingtung County                           |
| Tsunamis                              | Qijin District, Kaohsiung City: 51.91%                                                                              |
|                                       | Linbian Township, Pingtung County: 51.77%                                                                             |
|                                       | Wujie Township, Yilan County: 46.43%                                                                               |
| Seismic faults (150m)                 | Shigang District, Taichung City: 12.53%                                                                             |
|                                       | Fengyuan District, Taichung City: 10.18%                                                                            |
|                                       | Houli District, Taichung City: 8.80%                                                                               |
4.2. Social Vulnerability

The district/township with the highest total score for “degree of exposure” was Zhongzheng District, Taipei City (3.09), and that with the lowest total score was Maolin District, Kaohsiung City (-0.54). The district/township with the highest total score for “mitigation and preparedness” was West District, Chiayi City (2.33), and that with the lowest total score was Ren’ai Township, Nantou County (-4.25). The district/township with the highest total score for “response capacity” was Datong Township, Yilan County (0.97), and that with the lowest total score was Taiwu Township, Pingtung County (-1.17). The district/township with the highest total score for “recovery capacity” was Xinyi Township, Nantou County (0.22), and that with the lowest total score was Banqiao District, New Taipei City (-3.06).

Similarly, social vulnerability was rated using three scores, which are V1 (least vulnerable) to V3 (most vulnerable). The GIS technique and V1-V3 vulnerability data were used to obtain the social vulnerability distribution on the map (Fig. 3) by spatial analysis. The cities/counties with the highest levels of social vulnerability are concentrated on the west of Taiwan. The V3s (most vulnerable) were concentrated in the coastal areas of Yunlin and Chiayi counties.
4.3. Synthesized Analysis of Biophysical and Social Vulnerability

Nine categories of vulnerability were defined by cross-comparisons of biophysical and social vulnerabilities. They are Low-Low, Low-Medium, Low-High, Medium-Low, Medium-Medium, Medium-High, High-Low, High-Medium, High-High (Table 3). V1 was the lowest synthesized vulnerability and V5 was the highest synthesized vulnerability.

Table 3. Cross-comparisons of biophysical and social vulnerabilities

| Biophysical vulnerability | Social vulnerability |
|---------------------------|----------------------|
| Low                       | V1, V2               |
| Medium                    | V2, V3               |
| High                      | V3, V4, V5           |

Figure 4 presents a map of classified synthesized vulnerability. The cities/counties with the highest synthesized vulnerability to environmental change are concentrated in the coastal districts/townships of the western region. These districts/townships have high potential for being negatively affected by
climate change, and have low mitigation, response and recovery capacities; they require attention first. In contrast, Yuli and Fuli in Hualien County are townships with relatively low biophysical and social vulnerabilities. These townships have low potential for being negatively affected by climate change, and have high mitigation, response and recovery capacities.

In the northern region, the districts/townships with the highest synthesized vulnerability (V5) are Zhongli District, Taoyuan City; Taoyuan District, Taoyuan City; and East District, Hsinchu City. The major reason for a V5 score is potential flooding. Most secondary industrial production and household assets with a high degree of exposure are found in the metropolitan areas, which are thus hot spots for adaptation.

In the central region, the districts/townships with the highest synthesized vulnerability (V5) are Changhua City, Changhua County; Hemei Township, Changhua County; and Yuanlin City, Changhua County. The major reasons for a V5 score are potential flooding and seismic faults (within 150 m) with respect to biophysical vulnerability and a high degree of mitigation and preparedness with respect to social vulnerability.

In the southern region, the districts/townships with the highest synthesized vulnerability (V5) are West District, Chiayi City, and Sanmin District, Kaohsiung City. Although biophysical vulnerability is low in West District, Chiayi City and East District, Chiayi City, the social vulnerabilities in those districts are high, so synthesized vulnerability is high. Sanmin District, Kaohsiung City has a high degree of social vulnerability and a large area subject to potential flooding, causing this district to exhibit a high degree of synthesized vulnerability.

In the eastern region, districts/townships with the highest synthesized vulnerability (V5) are Chenggong Township, Taitung County; Chishang Township, Taitung County; and Guanshan
Township, Taitung County. The eastern region has lower degrees of both social and biophysical vulnerability than the other three regions.

5. Conclusions

Natural disasters are a part of our daily life; as their frequency and diversity increase, they represent a critical challenge to achieving sustainability [38]. Taiwan is no exception. Properly addressing the vulnerabilities in a certain area can improve its sustainability, resilience and adaptive capacity [24] and further reduce the potential negative impacts of climate change.

Although the call for sustainability is undoubtedly global, Taiwan is fast emerging as one of the countries where the challenges are most serious: its economic growth, coupled with industrialization and urbanization, clearly favors many potential and actual environmental degradations and variations (such as land subsidence, scarcity of water, forest reserves’ facing exhaustion, and others).

The above analyses reveal that the biophysical vulnerabilities of the regions of Taiwan follow the order, from high to low, southern region > central region > northern region > eastern region. According to Taiwan’s NCDR data, Taiwan is affected more by rainfall and coastal erosion than by other biophysical disasters. Although certain areas exhibit high degrees of biophysical vulnerability, as long as they can increase their socio-economic adaptation and disaster prevention capacities, they can exhibit low degrees of synthesized vulnerability. Biophysical vulnerabilities differently affect urban and rural areas. In urban areas with high degrees of biophysical vulnerability, disaster prevention and reduction should be emphasized, whereas in rural areas, the focus should be on the provision of necessary infrastructure.

This study is based on Taiwan’s NCDR. According to the prediction by IPCC AR5 [3], climate change will become worse. Current technology cannot exactly predict future biophysical vulnerability. Therefore, appropriate and thorough analyses of biophysical vulnerability must be performed to provide more solid information in support of the development of climate-related policies and strategies.

Factors that affect social vulnerability include the secondary industry and household assets. Highly developed districts and townships, owing to a concentration of incomes and population, have high degrees of social vulnerability vis-à-vis climate change. The above results reveal that districts and townships with high degrees of social vulnerability are scattered around Taiwan. In particular, owing to weak disaster responses and recovery response, both Changhua and Yunlin counties exhibit a high degree of social vulnerability. Disaster prevention techniques, law enforcement and disaster prevention education should be promoted before disasters occur, and the elderly who live alone and the handicapped should be taken care of when they do occur.

Taiwan passed the “National Land Use Planning Act” in 2016. According to Article 6 of the Act, national land use planning must comply with international conventions and regulations and promote sustainable development. Natural conditions, water resources and climate change shall be considered in national land use planning to establish the capacity to prevent disasters on national land and facilitate emergency responses. Furthermore, national land conservation zones shall be used for conservation purposes and other uses may be prohibited or restricted accordingly. Environmental conservation shall be considered in land use and fair and efficient regulatory mechanisms shall be established.

Therefore, in areas with a synthesized vulnerability score of V5, the non-conservation-related developments should be avoided, except for necessary public facilities or basic infrastructure. Regulations should be set by the competent authority of relevant industries to achieve the goal of resource conservation and environmental protection. In areas with a synthesized vulnerability score of V4, flexible spatial planning for conditional developments should be conducted to achieve efficient national land uses and to protect vulnerable groups. However, the conditions of land use control should be improved to regulate types and intensity of land use.

Future investigations can focus on developing principles and guidelines for sustainable land use planning and control in Taiwan, such as the maximum conservation principle to preserve precious resources, departmental spatial development strategies, functional land use zoning, growth
management policies and measures, extensive public participation and informational transparency, fair and efficient regulatory mechanisms, adaptation strategies for areas with potential natural disasters, and adaptation strategies for areas with biophysical vulnerability and social vulnerability.

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