

Linking local vulnerability assessments to climatic hazard losses for river basin management

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Abstract. To prepare for and confront the potential impact of climate change and related hazards, many countries have implemented programs of integrated river basin management. This has led to an imperative challenge for local authorities to improve the understanding of how the vulnerability factors link to climatic disaster losses. This article aims to examine whether highly vulnerable areas experience significantly serious damage caused by weather extreme events at the river basin levels, and explain what vulnerability and hazard impact factors determine the disaster losses. Using three river basins in southern Taiwan attacked by Typhoon Morakot in 2009 as case study areas, we proposed a novel methodology that combines a geographical information system (GIS) technique with a multicriteria decision analysis (MCDA) to evaluate and map composite vulnerability to climatic hazards across river basins. Then, the linkages between hazard impacts, vulnerability factors and disaster losses are tested by using a disaster damage model (DDM). In the case study, the results of the vulnerability assessments indicated that the vast majority of the most vulnerable areas is situated in the regions of the middle, and upper reaches and some coastlines of the three river basins. Using the DDM, it shows that the losses and casualties due to typhoon are significantly affected by local vulnerability contexts and hazard impact factors. Finally, we suggest the implications of adaptation policy lines for minimizing vulnerability and risk and for integrated river basin governance.

1 Introduction

Major portions of Asia have an increasing exposure and vulnerability to climate change and weather extremes due to rapid urbanization and overdevelopment in hazard-prone areas (IPCC, 2014). Particularly, Asia-Pacific region is the riskiest and the most seriously affected areas of the world. More than 1.2 billion people have been exposed to climate-related (climatic) hazards, and the number of people residing in cyclone-prone areas has grown from 71.8 million to 120.7 million (UNISDR,

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2012). Thus, it becomes increasingly important for water resource managers to implement integrated river basin management (RBM) that can cope with and reduce the potential impacts of climate change and climatic disaster risks (Hung et al., 2013).

Integrated water resource management is a process to promote the coordinated development and management of water, land uses and related resources (GWP 2000). This indicates that the integrated RBM program should adopt the river basin as a management unit, employing a comprehensive perspective to connect water resource management, agricultural irrigation with land use planning for building more resilient river basin contexts (Penning-Rowsell et al., 2006). Especially, vulnerability assessment plays a vital role for decision makers in scrutinizing the biophysical and socioeconomic conditions, as well as their distributions over river basins. This process of assessment also helps decision makers integrate various local connections into planning and policy lines for disaster damage and risk mitigation within the context of whole river basins (Hooijer et al., 2004; Hung and Chen, 2013; You and Zhang, 2015).

Climatic hazard losses and risk accumulation result from the interlinking between hazard and vulnerability factors, which has led to an emerging literature focus on characterizing these factors and their interaction (UNISDR, 2012; Hung et al., 2013). Within these studies, existing vulnerability analyses majorly focused on assessing, mapping and distinguishing the variability of the vulnerability distribution between regions (Adger, 2006; Hung and Chen, 2013; Ahumada-Cervantes et al., 2015). Most previous disaster loss and risk studies use computer-aided simulation, scenario analyses and multicriteria decision analysis (MCDA) (Tate et al., 2010; Ni et al., 2010; Hung et al., 2013; De Bruijn et al., 2014). Their findings are valuable in characterizing disaster risk, impacts and distributions that enable decision makers to create risk maps and communicate the high risk areas to stakeholders. Few studies have systematically examined how the vulnerability and hazard impact factors are linked to their potential effects on disaster losses (Hung and Chen, 2013; Visser et al., 2014). This would compromise the application of existing vulnerability and exposure studies to the disaster risk assessment and integrated RBM.

This article aims to examine whether localities characterized by high vulnerability experience significantly higher damage than other areas owing to onset weather extreme events at the river basin level, and explain what vulnerability, hazard and exposure factors influence these damages or losses. Using three river basins in southern Taiwan hit by Typhoon Morakot as case study areas, we propose a novel methodology based on existing disaster impact theory, which then combined an MCDA,

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GIS (geographical information system)-based statistics with multivariate analysis to assess climatic hazard vulnerability (especially typhoons and floods). Moreover, we examine the connection between vulnerability, hazard impact factors and disaster losses using a disaster damage model (DDM). This methodology may also be applicable to other river basins. Finally, we discuss the extension of our findings in providing policy directions for building adaptive capacity and for integrated RBM.

2 Vulnerability and disaster impacts

2.1 Vulnerability and its assessment

Vulnerability assessments have been broadly applied to various research communities with respect to climate change adaptation and disaster risk management, although not agreeing on a common view about the concept of vulnerability. In the traditions of disaster risk research, risk-hazard approach describes vulnerability as the degrees of susceptibility of these assets to suffer damage and loss (UNISDR, 2013). It denotes the relationships between the expected damages and the sensitivity and exposure attributes of the affected systems (Füssel, 2007). The disaster pressure-and-release (PAR) and pressure-state-response (PSR) models take this vulnerability concept as a starting point, defining risk as the product of hazard and vulnerability (Wisner et al., 2004).

Existing applications of the risk-hazard approach emphasized on mono-dimensional analyses, which were either focused on engineering, biophysical or socioeconomic vulnerability assessments (Adger, 2006; Mokrech et al., 2012). On the other hand, some studies had extended their applications in different integrated approaches, most notably the hazard-of-place model (Cutter et al., 2000). IPCC (2014) had conceptualized vulnerability as which encompasses a variety of concepts and elements, including sensitivity or susceptibility to harm and lack of capacity to cope and adapt. Such definition of vulnerability comprises adaptation capacity, which is referred to as the end point view of vulnerability (O'Brien et al., 2007). It, therefore, provides an integrated concept that links starting point and end point view of vulnerability (Adger, 2006; Scheuer et al., 2011).

From the perspective of integrated RBM, it needs transdisciplinary, multi-dimensional and more inclusive vulnerability approaches to involve various biophysical and socioeconomic properties of a specific river basin area in the risk management. Thus, vulnerability assessment should facilitate decision-makers to engage in the integrated analyses of the

interaction between the components of vulnerability and the properties of a specific river basin context (O'Brien et al., 2007; Engle and Lemos, 2010; Hung and Chen, 2013). To target support for integrated RBM, it needs to integrate IPCC (2014) with risk-hazard approaches to build more transdisciplinary and comprehensive vulnerability assessment framework. Therefore, the vulnerability can be generally described as a function of exposure, sensitivity and adaptive capacity:

Vulnerability = f (exposure, sensitivity, adaptive capacity) (1)

2.2 Vulnerability and disaster losses

Existing approaches to the relationships between vulnerability and disaster losses can be divided into two major types. The first type of approach frequently uses risk-hazard, PAR, PSR theory or MCDA with computer-aid simulation and GIS-based analysis to predict disaster losses (Ermoliev et al., 2000; Wisner et al., 2004; Tate et al., 2010; Scheuer et al., 2011; De Bruijn et al., 2014). PSR and PAR approaches show the linkage between hazard event and unsafe context that leads to disaster, as well as present how vulnerability influence hazard loss and risk (Wisner et al., 2004). They mostly take a risk-hazard approach to estimate expected damages caused by various kinds of hazards, which assumes that disaster risk is composed of two factors: hazard and vulnerability (Füssel, 2007). In a long-term scale, disaster risk requires the consideration of uncertainties in both hazard and vulnerability factors due to ambiguities in the possible changing of the future hazard and vulnerability factors over time (De Bruijn et al., 2014). However, in a short-term or single hazard event scale, the focus is on a single disaster damage that could vary with different hazard intensities, impacts and vulnerability factors (Cutter et al., 2003; Hung et al., 2013; Hung and Chen, 2013). This type of study majorly combines computer-aid approaches with MCDA in modelling or mapping vulnerability and risk (Scheuer et al., 2011; Hung and Chen, 2013). Moreover, most these studies use current vulnerability factors to project future risks or damages, which is a 'top-down' approach that can bring predicted distributions of disaster impacts and risks to the fore.

The second type of approach focuses on 'bottom-up' and data-based analysis, which often uses existing or surveyed databases to characterize the distributions of disaster damage (Zahran et al., 2008; Bhattarai et al., 2015). The findings not only can help decision makers identify disaster loss distributions, but also understand their determinants (Downton and Pielke, 2005). This approach concentrates more on mapping the disaster damage distribution at the national or regional levels than the local levels. It also majorly combines expert judgment with mono-dimensional evaluation to inspect the influential

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factors of disaster damage (Mokrech et al., 2012; Hung and Chen, 2013). However, little attention had been paid to linking of a multi-dimensional vulnerability assessment with an empirically-based disaster loss evaluation in the river basin contexts.

As above-mentioned, the first type approach seeks to systematically identify disaster losses and scrutinize their components, as well to project various disaster impacts resulting from different hypothetical events. By contrast, the second type approach enables decision makers a conjoint treatment of quantitative disaster loss data and qualitative human judgment. Nonetheless, these two types of approaches all considering disaster losses are inherent and dynamic due to ongoing interaction of climatic hazard impacts with the biophysical and socioeconomic components of vulnerability in a watershed system (O'Brien et al., 2007; Maru et al., 2014).

Increasing the understanding of the formation of climatic disaster risk highlights the importance of connecting aforementioned two types of approaches and their relative magnitudes in hazard risk analyses (Mokrech et al., 2012; Visser et al., 2014). Particularly, incorporating the first type into the second type approach allows us to create frameworks of disaster risk analysis that could assist in expanding the range of vulnerability assessments and in sequencing them to generate robust resilience and adaptation pathways (Hung et al., 2016).

3 Methods and data

An MCDA and GIS-based statistic analysis is integrated with a data-based multivariate analysis, in order to assess and map the vulnerability of three river basins in southern Taiwan and to examine the vulnerability factors that influence the disaster loss distributions. The procedure of analysis consists of three steps (Fig. 1). First, using the vulnerability defined by equation (1), we constructed a composite vulnerability indicator framework and combined with an MCDA to assess and map climatic hazard vulnerability at the river basin level. Second, based on the risk-hazard framework, the relationship between disaster loss distributions, impacts and vulnerability factors was tested and compared using numerous regression models. Finally, we discussed the findings and provided implications for better adaptation policy lines.

(Figure 1. Stepwise procedure for linking local vulnerability assessments to hazard loss analyses)

3.1 Linking vulnerability factors and climatic disaster losses

This study focuses on a single disaster event scenario for comparatively static modelling of hazard damages or losses at

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註解 [H25]: Replies to the Comment [S26]: The authors have added a Figure to explain their conceptual framework (including how we combine the risk-hazard approach with IPCC’s concept) and the stepwise procedure for conducting their empirical study.

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different points over river basins. This approach allows us to concentrate on single disaster scenario, so that any variation in losses can be directly resulted from changes in hazard impacts and vulnerability factors (Hung et al., 2013). Therefore, the disaster loss model can be written as the following function:

$$\text{Disaster loss/risk} = f(\text{hazard, vulnerability}) \quad (2)$$

Equation (2) implies that disaster loss/risk is a function of hazard and vulnerability factors. In a short-term or a single disaster event scenario, the extent of disaster loss varies with hazard impacts (or intensities) and vulnerability factors. To more specifically identify the relationship between disaster losses and vulnerability factors, several regression models were used in the case studies.

3.2 Indicators of the vulnerability framework and hypotheses

An indicator-based assessment framework was developed with the aim to identify composite indicators that can serve as proxies for the components of vulnerability. Vulnerability assessments and mapping have widely used indicator-based approach combined with GIS to help stakeholders characterize distributions of vulnerable areas and understand factors leading to vulnerability (Cutter et al., 2003; Hung and Chen, 2013; Ahumada-Cervantes et al., 2015). The vulnerability assessment framework created here allows us to take advantage of the contributions of existing knowledge, as well as obtains the synergies and complexities of watershed contexts as discussed in detail in Hung and Chen (2013). According to our conceptual vulnerability, the indicators involved in the assessment framework consist of three dimensions: exposure, sensitivity and adaptive capacity. The indicators are selected stemmed from a summarizing review of the literature and the contextual characteristics of the river basins in southern Taiwan.

In terms of assessing the integrated vulnerability, we mainly adopted the framework of vulnerability indicators promulgated by Hung and Chen (2013), which was appropriate and widely applied to the river basin conditions in Taiwan. Hung and Chen (2013) also identified vulnerability based on the concept of IPCC. It had applied focus group meetings and in-depth interviews of experts, officers and community members to incorporate key stakeholders' participation and knowledge into an MCDA procedure. Then, an assessment of composite vulnerability was conducted across the case study areas at the village scale, which is the basic unit of local administration in Taiwan. Finally, those indicators considered to assess vulnerability are demonstrated in Table 1, along with their descriptions, data sources and the expected direction of the

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relationship to disaster losses.

(Table 1. Hazard impacts, vulnerability indicators (variables) and expected sign to disaster losses)

3.2.1 Exposure indicators

Exposure refers to the presence of areas, system or assets in places and settings that could be adversely affected (IPCC, 2014; Hung et al., 2016). To reflect the degrees of exposure, *averaged annual rainfall* and *potential debris flow torrents* were used. The expectation is that either higher rainfall or greater debris flow torrents enhance vulnerability and thus enhance the likely disaster losses¹ (Scheuer et al., 2011). Furthermore, the biophysical contexts also can be used to measure the extent of an area exposed to hazards. The hypothesized links between biophysical contexts and disaster losses are captured in examining the influence of *proximity to rivers* and *elevation* indicators on disaster losses. The areas where are more proximity to rivers and/or at higher elevations are more sensitive and vulnerable, which could increase disaster damages (Ni et al., 2010).

3.2.2 Sensitivity indicators

Sensitivity is a one of the most broadly used attributes to describe the vulnerability in climate change and disaster risk management (Cutter et al., 2003; O'Brien et al., 2014). The sensitivity indicators are mostly composed of inherent socioeconomic and land use sensitivity (Hung and Chen, 2013). The socioeconomic indicators include *populations*, *social dependence*, *income*, *employment* and *production values* of industries and services. These indicators are apt to reflect the extent of areas' contextual vulnerability in a watershed. Thus, increasing income, employment and/or production values by communities is expected to enhance coping strategies, thereby decreasing vulnerability and potential disaster losses (Zahran et al., 2008). Contrarily, populations and social dependence have expected a positive relation to disaster damage (Hung et al., 2016).

In the aspect of land-use, the indicators comprise *urban developments*, *agricultural uses*, *environmentally sensitive areas* and *road infrastructures*. Generally, while preserving more sensitive areas could decrease vulnerability and disaster losses,

¹ The *averaged annual rainfall* can be also considered as an indicator of climatic hazards. However, in the long-term scales, we deemed it as a measurement of the levels of an area exposure to climate hazard because the areas with higher averaged rainfall could have higher probability of exposure to hazards.

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the larger scales of either urban development, agricultural use or road infrastructure would encourage denser land use, agricultural developments and tourist activities, and that could lead to higher vulnerability and expected disaster losses (Cutter et al., 2003; Mehaffey et al., 2008).

3.2.3 Adaptive capacity indicators

Using adaptive capacity indicators to measure the ability of communities to adjust to potential damage, to take advantage of opportunities, or to respond to disaster consequences (IPCC, 2014), the indicators include *shelters, medical, fire and police* services. These indicators present an area's abilities of coping, evacuation and emergency responses. Therefore, improving these facilities could reduce vulnerability and likely disaster damage. We also involved behavior and heuristic factors that consisted of residents' *risk perceptions*, their ability to *access resources* and to successfully adapt to hazards (self-efficacy) are also considered. The hypothetical relationships between these factors and disaster damage are negative (Eakin et al., 2010).

3.3 Composite vulnerability index

To assess the integrated vulnerability for each village, the composite vulnerability index (CVI) was estimated using an MCDA procedure. This procedure comprises three steps. First, because the survey values of various indicators shown in Table 1 contain different scales and units, we applied a min-max scaling to directly normalize all of the data into a uniform [0, 1] scale with ratio properties. Second, the normalized values are then used to compute CVIs by:

$$CVI_i = \sum_{j=1}^m w_j x_{ij}. \quad (3)$$

where CVI_i represents the composite vulnerability index for village i ; x_{ij} denotes the normalized value for indicator j and w_j is the weight. With above hypotheses, if $x_{ij} > 0$, it indicates higher levels of overall vulnerability; if $x_{ij} < 0$, decreasing or lessening the overall vulnerability. Third, equal-weight was assigned to each indicator in order to build an equivalent basis for comparing the attributes of vulnerability and disaster losses among the river basins.

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3.4 Case study areas and data

This article explores three very different river basins, choosing for representing the areas with various degrees of development and different contexts in southern Taiwan (Fig. 2), but all having heavily struck by Typhoon Morakot in 2009. The case study areas include three major river basins: Gaoping, Tsengwen and Taimali River. According to the 2015 census, these three river basins encompass 598 villages, around 1.26 million inhabitants and cover an area of approximately 7,885km². Highly diversified topography distributes over the three watersheds. The altitude of this region ranges from coastal lowlands along the western shoreline to above 3,000 meters in the eastern high-mountain areas. Uncontrolled urban sprawl and environmental destruction are interwoven by growing threats from climate change and weather extremes mean that lead to the riskiest regions in Taiwan (Liu et al., 2013).

In modelling the linkages between vulnerability factors, disaster impacts and losses, the data were collected from multiple sources. The disaster loss database regarding Typhoon Morakot had been systematically built by the Department of Science and Technology, Taiwan. This database included the surveyed numbers of casualties, property and agricultural losses, the distributions of inundation and landslides, and damaged public facilities. The data on vulnerability factors were obtained through combining official censuses and random sampling face-to-face questionnaire surveys to residents (shown in Table 1 in detail).

(Figure 2. Distributions of the estimated composite vulnerability indices over three river basins)

4 Results and discussions

4.1 Composite vulnerability assessments

Using the estimated CVIs by equation (3), Fig. 1 shows the distributions of estimated index values superimposed on the administrative boundaries of villages throughout the three river basins. The CVI estimates were divided into five levels (at 20% intervals). The villages with the estimated index values within the 80-100th percentiles can be defined as the most vulnerable, and those within the 1st-20th percentiles as the least vulnerable.

In Fig. 1, it shows that there are highly heterogeneous in the spatial distributions of the estimated composite vulnerability

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across the study areas. In the Tsengwen River basin, the most vulnerable areas concentrated in the middle reaches and some coastlines. Moreover, most of the middle and upper reaches of the Gaoping and Taimali River basin (especially northern shore) were distributed by the most vulnerable villages, while most of the lower reaches spread with the least vulnerable ones. These spatial distribution patterns conform to historical experience with which numeral typhoons had hit these areas in past years, and resulted in serious casualties, property and crop losses.

The results corroborate similar findings from related studies (Hung and Chen, 2013; Liu et al., 2013), asserting that significantly show that **spatially-defined** clusters of highly vulnerable areas are mostly situated in midstream and upstream reaches. This leads to a challenge for watershed managers in understanding of why these areas are particularly vulnerable and how they link to disaster losses, as well as what the implications of this might be for land-use planners to reduce risk.

4.2 The distributions of losses due to Typhoon Morakot

Morakot, a Category 1 typhoon, hit southern Taiwan during 8–12 August 2009. It was the most severely damaged typhoon in Taiwan in the past 50 years. This typhoon caused torrential rainfall that results in widespread flooding and thousands of landslides. Typhoon Morakot killed nearly 700 people and left thousands of people either displaced or homeless. The estimated total amount of economic losses was approximately US\$ 0.6 billion (Liu et al., 2013).

The inundation areas due to Typhoon Morakot were concentrated in the convergent regions of Gaoping River with its tributaries, while the major landslide and debris flow torrents occurred in the middle and upper reaches. This would affect the distributions of property, public facility and agricultural damage (Fig. 3). Using *t* test for correlation analysis, it shows that the location of agricultural damage significantly corresponded to where the landslides (Spearman $\rho = 0.18$, $p < 0.01$; Pearson $r = 0.43$, $p < 0.01$) and damaged bridges occurred. The pattern of casualties also highly correlated with the numbers of landslides (Spearman $\rho = 0.22$, $p < 0.01$, Pearson $r = 0.23$, $p < 0.01$) and damaged bridges (Spearman $\rho = 0.40$, $p < 0.01$, Pearson $r = 0.42$, $p < 0.01$).

(Figure 3. Distributions of the losses due to Typhoon Morakot over three river basins)

In the Tsengwen river basin, the impacts of flooding and landslides caused more serious damage to the watersheds than debris flow torrents. If there are linear relationships between these typhoon losses, this would lead to that both casualty counts and agricultural losses significantly associated with patterns of landslides (casualties: Spearman $\rho = 0.17$, $p < 0.05$,

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Pearson $r = 0.53$, $p < 0.01$; agriculture: Pearson $r = 0.56$, $p < 0.01$) and damaged bridges (casualties: Spearman $\rho = 0.27$, $p < 0.01$, Pearson $r = 0.55$, $p < 0.01$; agriculture: Pearson $r = 0.40$, $p < 0.01$). Agricultural and property losses in the Taimali watershed were mostly agglomerated along the road systems. It indicates a noteworthy relationship between road infrastructure, land development and disaster loss that needs further investigation.

5 **4.3 The determinants of disaster losses**

The regression analyses for examining the determinants of typhoon losses include casualties, property and agricultural losses. The choice of regression models was based on the distribution types of disaster loss data. The distribution of disaster casualties is non-normal. Zero counts significantly skew the distribution leftward—93% of villages Typhoon Morakot caused no recorded injuries or fatalities. The total casualties were 684, the arithmetic mean is 1.01 and the standard deviation is 18.76—dispersion is 18.6 times greater than the average. The casualties were a non-negative integer exhibiting significant over-dispersion with a disproportionate number of zero counts. We thus investigated the data using a ZINB (zero-inflated negative binomial) or ZIP (zero-inflated Poisson) regression model, which allows us to estimate the net effects of independent vulnerability factors on casualties (Cameron and Trivedi, 1998; Zahran et al., 2008). To more comprehensively scrutinize the effect of disaster losses, the integrated typhoon loss index (ITLI) was estimated to acts as proxies for combined losses of typhoon:

15
$$ITLI_i = Agriculture_i + Property_i + Casualty_i. \tag{4}$$

where $Agriculture_i$ and $Property_i$ are agricultural and property losses for village i , respectively, and $Casualty_i$ is casualty counts. A Lagrange multiplier (LM) test points to evidence of which the ITLI is a non-negative rational number significantly spreading in a certain range. Thus, we applied a Tobit (Censored) regression model to examine the affecting factors of ITLI.

20 (Table 2. Regression analyses of the determinants of climatic disaster losses)

Table 2 reports the results of the ZINB and ZIP regression analyses for typhoon casualties, as well as Tobit models for

ITLIs. Six separate models are estimated, with predictors for each watershed (excluding Taimali River due to little sample size) and for all three river basins. To screen variables for multicollinearity, we used zero-order correlation and Variance Inflation Factor tests in an Ordinary Least Squares regression. It showed that the *risk perceptions* and *access to resources* have significantly high multicollinearity with other variables. These two variables were thus eliminated in some regression analyses.

In all regression models, results indicate that most hazard impact factors play an important role in determining typhoon casualties and losses. As expected, landslides, damaged bridges, agricultural losses, property losses and flooding were positively associated with typhoon losses, although agricultural losses were negatively related to casualties in Gaoping watershed. These findings correspond with the PSR framework that could consider the hazards as pressures and their impact would change the quality of the environment. The higher the hazard impact, the higher the odds of casualty and disaster loss were distributed (OECD, 1993; Wisner et al., 2014).

Regarding the biophysical exposure indicators, average rainfall was a major positive contributor to the casualty counts in both Gaoping and Tsengwen watersheds, while it was a negative predictor of disaster losses. In Gaoping River basin, the high casualties occurred in the areas with higher levels of rainfall and elevations rather than in debris flow torrents distributed areas. These areas within 0-200m to rivers significantly increased the numbers of casualty over three river basins, and enhanced typhoon losses in both Gaoping and the Tsengwen watersheds. Most of these results are consistent with our expectation and earlier studies on the linkage between biophysical factors and disaster losses (OECD, 2012; Hung et al., 2016). It implies that the areas with higher risk are mostly located in the regions with higher elevations and more proximity to the rivers over the watersheds.

In the compilation of socioeconomic factors, population density was a strong predictor of casualty counts and disaster losses, and was negatively related to casualty counts, while its relationship to disaster losses was positive (except for

Gaoping River basin). Findings reflected that the patterns of disaster damage would depend on the types of hazard impacts. The upstream areas were frequently distributed with the low population density, but more landslides occurred, and that would cause higher casualties. Generally, the inundation was mostly assembled in downstream areas, which would lead to more overall losses than casualties.

5 The lower income areas were likely generating more casualties. Furthermore, as one enhances the production values of industries and services in an area, the increase of the capacity of pre-disaster preparedness and emergency responses that can decreased disaster loss and risk. Except for a significantly positive relationship between employment rates and casualty numbers, and between social dependence counts and disaster losses in Gaoping watershed, the other socioeconomic factors had a weak relation to casualty and loss distributions. These results do not fully conform to existing studies that highlight the
10 relationship between social vulnerability factors and disaster losses (or risk) is functional (Zahran et al., 2008; Hung and Chen 2013). Rather, their relations have remained complex and difficult to model, depending on multiple influences of local contexts and disaster impacts involved in each watershed (UNISDR, 2012).

In all regression models, urban or agricultural development significantly increased casualty counts and typhoon losses, although increasing agricultural uses strongly decreased casualty distributions in Gaoping watershed. These results also
15 reflected in that more sensitive areas reserved could reduce the occurrence of casualties and losses (excluding for the Tsengwen watershed). In addition, provision of road or transportation infrastructures would be helpful in the evacuation and disaster relief, and led to fewer casualty counts after typhoon hitting. As most extant studies emphasized (Mehaffey et al., 2008; Hung et al., 2016), our case study shows the evidence that higher levels of urbanization and farming reclamation would increase hazard vulnerability and further result in higher damage.

20 Concerning the adaptive capacity variables, they also played a critical role in predicting disaster damage. Especially, increasing medical services, access to resources and self-efficacy significantly attenuated the disaster losses, as well as

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strongly decreased casualty counts in both Gaoping and Tsengwen river basins. These results confirm the earlier findings that emphasizing the improvement of adaptive capacity could effectively reduce disaster damage and risk (Eakin et al., 2010; Hung and Chen, 2013). However, one noteworthy exception was that the areas with higher ability to access to resources had been distributed with more typhoon casualties across the three river basins. One possible explanation is that most these areas are particularly vulnerable and frequently received large amounts of external aids in the aftermath of a disaster hitting. However, these exterior aids might be valuable in temporary disaster relief rather than improving long-term vulnerability.

4.4 Policy implications

This research presents a systematic starting point to investigate a novel topic on the relationship between vulnerability attributes, hazard impacts and disaster losses. Through composite vulnerability assessments and regression analyses, it shows that the villages with higher elevations, in upper streams and more proximity to rivers tended to suffer more disaster casualties and losses due to their higher exposure to typhoon impacts. However, constraints associated with local government adaptation efforts in the river basins reflect a range of challenges in relation to how the integrated RBM adaptation efforts have structured. The efforts to facilitate adaptation should largely target the mitigation of vulnerability and risk. Especially, combining resilient types of infrastructure, warning system with risk communication to improve the emergency system is essential for pre-disaster hazard-mitigation planning that helps reduce risk and save the lives (Hung and Chen, 2013; Hung et al., 2013).

In the long-term policy lines for integrated RBM that the land use planning coupled with regulation, relocation and building codes can help restrain urban and agricultural developments encroaching onto hazard-prone areas (Neuvel and van den Brink, 2009). As the vulnerability distributions and their linkages to disaster losses as presented in this study, it enables the policy makers to generate hazard risk maps that provide a useful initial step to identify and communicate the riskiest areas to stakeholders. In the upper streams, land use management can be further integrated into river basin governance in order to keep the environmental sensitive areas from excessive urban sprawl, agriculture and tourism activities, as well as to appraise adaptation options for the most vulnerable areas. Besides structural engineering projects, the downstream areas need to incorporate wetland preservation, flood insurance, warning systems and related risk-sharing arrangements into the existing

RBM framework [for minimizing risk](#).

5 Conclusions

[Growing climate change and weather extreme impacts pose impending](#) challenges and high uncertainties for the RBM. Therefore, an understanding of the interlinks between disaster impact, vulnerability factors and disaster losses is critical for hazard risk and river basin governance [within the options of which the adaptation strategies take place](#).

This article proposes a novel approach that [stems from the combination of previous studies](#) on vulnerability assessments and disaster impacts to [unpack and characterize](#) the vulnerability over river basins, and to examine its influence on typhoon losses. A composite vulnerability assessment framework was constructed [in hybrid with](#) an MCDA to create vulnerability maps that [can be valuable to inform policy-making and communicate](#) the core areas in which adaptive measures are most needed to reduce vulnerability and risk. [Applying various regression models](#) to examine the key vulnerability and hazard impact factors that determined the casualties and losses caused by Typhoon Morakot, [as well as](#) compare the typhoon losses [between river basins due to the variability in local contexts](#).

The findings indicate that both the hazard impacts and the vulnerability factors [can strongly vary spatial distribution](#) patterns of disaster losses. Especially, local biophysical, socioeconomic and land use attributes are key predictors to disaster losses. Local agencies should make some tradeoffs between building adaptive capacity and reducing vulnerability. However, the disaster event considered in this study is limited. Further case studies across other river basins provide more insights into [how crucial the tradeoffs may be to reduce risk](#). Moreover, the robustness and application of our modelling need to be [examined by comparing the operationalized loss surveys of additional cases](#) in the aftermaths of other disaster events. This is [able to offer the integrated RBM with some useful policy and land use planning indications in building more resilient river](#) basins.

Acknowledgements

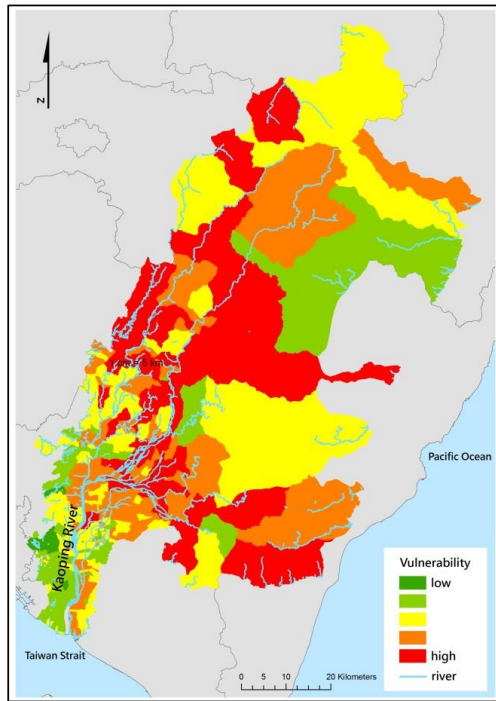
The authors would like to acknowledge the assistance from the Ministry of Science and Technology, Taiwan under Grants: MOST 103-2625-M-305-001. None of the conclusions expressed here necessarily reflect views other than those of the authors.

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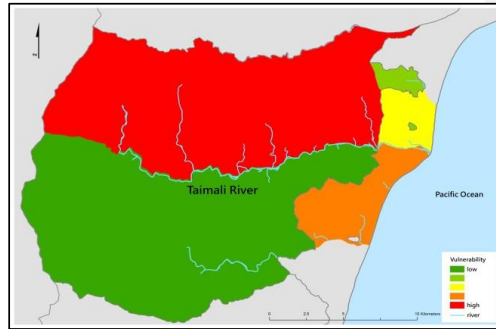
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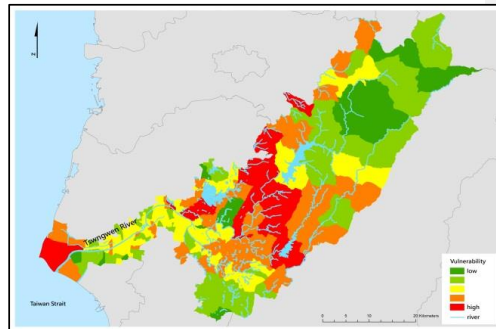
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(1) Kaoping River basin

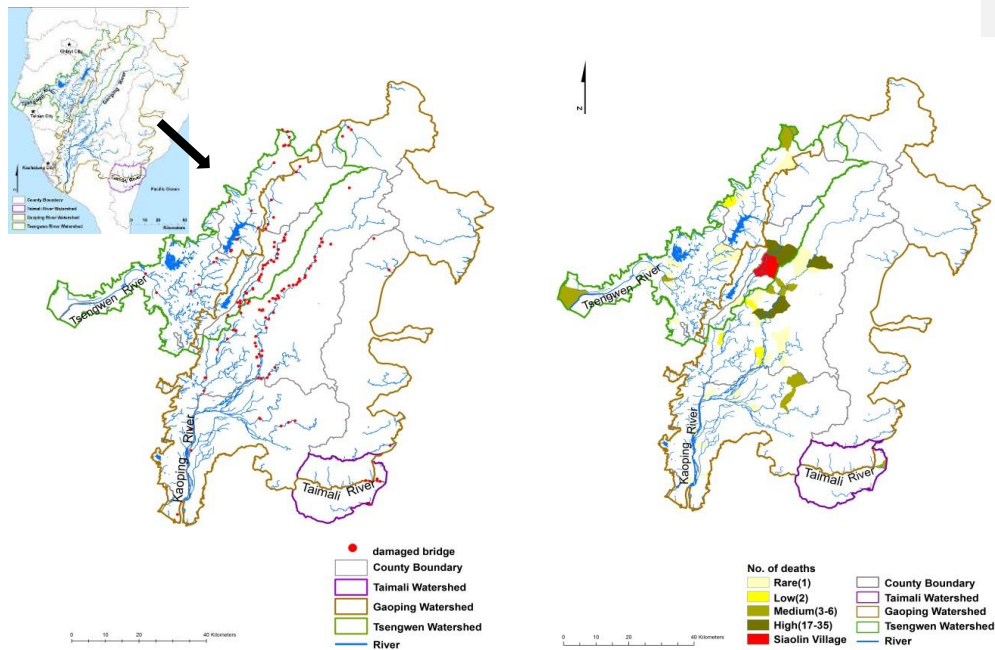


(2) Taimali River basin



(3) Tsengwen River basin

Figure 1. Distributions of the estimated composite vulnerability indices over three river basins



(1) Distributions of damaged bridges

(2) Distributions of casualties

Figure 2. Distributions of the losses due to Typhoon Morakot over three river basins

Table 1. Hazard impacts, vulnerability indicators (variables) and expected sign to disaster losses

Category	Indicator	Description	Data source	Mean (S.D.) ^a	Sign
Hazard impacts	Casualties	Number of casualties (people)	NCDR ^b , Taiwan	1.01 (18.76)	+
	Landslides	Areas of landslides (km ²)	NCDR, Taiwan	0.48 (2.22)	+
	Damaged bridges	Number of damaged bridges	NCDR, Taiwan	0.24 (0.90)	+
	Agricultural losses	Amount of agricultural losses (1000 NT\$)	NCDR, Taiwan	14.01 (39.34)	+
	Property losses	Number of damaged dwelling	NCDR, Taiwan	48.68 (126.8)	+
	Flooding areas	Areas of inundation (km ²)	NCDR, Taiwan	0.32 (0.94)	+
Exposure	Rainfall	Average annual rainfall (mm)	Central Weather Bureau, Taiwan	1932 (364)	+
	Debris flow torrents	Number of potential debris flow torrents and landslides	Council of Agriculture, Taiwan	0.41 (1.07)	+
	Proximity to rivers	Areas within 0m-200m to rivers (km ²)	Measured by GIS	0.18 (0.21)	+
	Elevation	Average elevation (m)	Ministry of the Interior, Taiwan	169.7 (355.3)	+
Sensitivity	Populations	Population density (thousand people/km ²)	Ministry of the Interior, Taiwan	2.74 (5.60)	+
	Social dependence	Ratio of people over age 65 and under age 6, and females (%)	Ministry of the Interior, Taiwan	58 (5)	+
	Income	Annual disposable household incomes (1000 NT\$)	DGBAST ^c , Taiwan	660.1 (23.7)	—
	Employment	Employed population (employed population/ population)	DGBAST, Taiwan	0.15 (0.26)	—
	Production values	Annual production values of industries and services (million NT\$)	DGBAST, Taiwan	27.9 (81.4)	—
	Urban developments	Area of residential, commercial, industrial, educational and public land uses (km ²)	Land Use Investigation of Taiwan	0.35 (0.48)	+
	Agricultural uses	Areas of agricultural land uses (km ²)	Land Use Investigation of Taiwan	2.17 (2.91)	+
	Sensitive areas	Environmentally sensitive areas (km ²), e.g., flood plain, mountain slope reserve areas	Land Use Investigation of Taiwan	10.4 (40.4)	—
	Road infrastructure	Areas of road infrastructure (km ²)	Ministry of the Interior, Taiwan	0.16 (0.14)	+
	Shelters	Number of shelters	Measured by GIS	1.16 (1.43)	—
Adaptive capacity	Fire and police services	Number of fire and police manpower	County and city government	2.05 (2.02)	—
	Medical services	Hospital beds	County and city government	10.5 (16.0)	—
	Risk perceptions	Average levels of perceived residential risk to climate hazards (5-point Likert scale)	Questionnaire interviews ^d	2.97 (0.17)	—
	Access to resources	Average levels of ability to access to resources (including financial and material aid) (5-point Likert scale)	Questionnaire interviews	2.03 (0.18)	—
	Adaptation appraisal	Average levels of residents evaluate their ability to perform adaptations successfully (5-point Likert scale)	Questionnaire interviews	2.43 (0.50)	—

^a: Mean and S.D. are average and standard deviation values of the villages; ^b: National Science and Technology Center for Disaster Reduction; ^c: Directorate-General of Budget, Accounting Statistics; ^d:

Table 2. Regression analyses of the determinants of climatic disaster losses

Variable	All river basins		Gaoping River basin		Tsengwen River basin	
	ZINB	Tobit	ZIP	Tobit	ZIP	Tobit
Constant	31.26*** (2.98) ^a	-15.46 (-0.82) ^a	1.98 (0.34)	72.42** (2.40)	20.97 (1.63)	-15.04 (-0.62)
Landslides	0.93*** (3.08)	0.23*** (4.11)	0.50*** (6.27)	0.28*** (3.83)	-0.53 (-0.47)	0.12*** (7.95)
Damaged bridges	0.61*** (4.18)	6.04*** (7.37)	1.30*** (16.37)	6.57*** (6.12)	0.89*** (2.62)	1.40* (1.65)
Agricultural losses	-0.52 (-1.14)	—	-0.80*** (-4.62)	—	0.18* (1.67)	—
Property losses	0.004*** (2.57)	—	0.005*** (8.94)	—	0.009*** (2.58)	—
Flooding areas	0.54*** (2.70)	3.36*** (4.66)	1.01*** (4.79)	5.29*** (3.81)	3.28*** (2.64)	6.68*** (3.73)
Rainfall	-0.001(-0.13)	-0.005** (-2.28)	0.001*** (3.49)	-0.01*** (-3.40)	0.003* (1.74)	-0.003 (— 1.07)
Debris flow torrents	-0.03 (-0.17)	0.67 (0.88)	-0.30*** (-4.90)	-0.009 (-0.01)	-0.13 (-0.43)	-0.80 (-1.04)
Elevation	0.03*** (3.21)	0.01*** (2.86)	0.003*** (9.51)	0.01** (2.41)	0.001 (0.62)	-0.003 (-0.79)
Proximity to rivers	0.32* (1.66)	0.28 (0.70)	-0.69 (-0.58)	0.12** (2.19)	-0.15 (— 0.61)	0.97** (2.05)
Population density	-1.10*** (-3.45)	2.65*** (3.36)	0.86 (1.29)	-0.001** (-1.97)	-1.81** (-2.28)	6.75*** (4.59)
Social dependence	-5.80 (-0.80)	-5.04 (-0.37)	-2.67 (-0.35)	30.10* (1.58)	-7.70 (-1.02)	-1.22 (-0.10)
Income	-2.59* (-1.74)	0.0004 (0.15)	-0.007*** (-5.17)	0.002 (0.21)	-0.002 (-0.57)	-0.001 (-0.35)
Employment	-0.40 (-0.12)	-1.52 (-0.38)	4.84** (2.71)	-3.50 (-0.41)	-3.52 (-0.58)	1.38 (0.45)
Urban developments	0.30*** (4.31)	0.70*** (3.82)	0.24*** (10.22)	0.69*** (3.03)	0.32*** (2.52)	0.40* (1.65)
Agricultural uses	0.12*** (2.54)	3.28*** (5.61)	-0.32*** (-4.51)	3.00*** (3.28)	0.12 (1.07)	0.14*** (3.76)
Sensitive areas	-0.15*** (-3.23)	-0.11*** (-3.05)	0.34*** (3.02)	-0.13*** (-2.93)	-0.17** (-1.96)	1.58* (1.73)
Road infrastructure	-1.52*** (-2.99)	0.17 (0.78)	-1.11*** (-4.09)	-1.85 (-1.06)	-1.10* (-1.66)	-0.71 (-0.89)
Production values	-0.12 (-0.55)	-0.18* (-1.66)	-0.49*** (-3.53)	-0.35 (-0.18)	0.76 (0.21)	-0.95 (-0.29)
Shelters	0.06 (0.28)	-0.32 (-0.57)	0.38*** (9.80)	0.25 (0.31)	-0.50 (-1.17)	-0.47 (-0.75)
Fire and police services	-0.11* (-1.67)	0.51 (0.97)	-0.004 (-0.08)	0.15 (0.23)	0.16 (0.54)	0.79 (1.23)
Medical services	-0.02 (-0.79)	-0.38*** (-5.64)	-0.04* (-1.85)	-0.50*** (-5.60)	-0.32* (-1.65)	0.01 (0.05)
Access to resources	2.79*** (2.88)	-11.91*** (-2.72)	—	-30.97*** (-3.90)	—	-16.57*** (-3.16)
Adaptation appraisal	0.82 (1.20)	-4.29*** (-2.71)	1.25*** (3.12)	-7.76*** (-3.32)	-1.41* (-1.66)	-1.58 (-0.74)
Alpha	1.16*** (2.57)	—	—	—	—	—
χ^2	36.30***	—	5571.26***	—	359.82***	—
Log-likelihood function	-219.62	-1692.15	-196.38	-1093.23	-44.10	-566.21
LM test	—	325.37***	—	223.43***	—	174.69***
Sample size (N)	598		436		179	

^a: Z-test value in parentheses; *: significant at $p < 0.1$; **: significant at $p < 0.05$; ***: significant at $p < 0.01$