To the authors and editors:

This paper deals with the losses and damages of a typhoon and relates these to a composite vulnerability index. The underlying datasets and the statistical work is of relevance for the scientific community. However, there are significant lacks in

- The conceptual frame for the work
- A critical view of the approach followed and of the results achieved.

In addition, the text has to be significantly improved regarding the English language. I have given a number of proposed correctinos in the first half of the text (See below).

I would encourage the authors to review their paper thoroughly and particularly regarding the various concepts of vulnerability. I would also like to ask them to take the constraints of their methodologies into consideration when discussing their results.

General comments to the paper:

The concept of vulnerability and the implication that the conceptual approach has on the study is not clear:

- At the end of chapter 2.1 the authors state that it is necessary to integrate the vulnerability concepts of the disaster community and of the IPCC. The proposed formular (1) however does reflect only the IPCC concept. If the authors start to discuss these conceptual issues they need to be much more sharpened in their explanation of the differences of the various approaches and why and how they would like to integrate approaches
- The two approaches for investigating the relationships between vulnerability and disaster losses in chap 2.2 are not described clearly enough.
- The methodology for the selection of indicators is not transparent. There is a lack of clarity in the concept reflected in the description of the indicators in chapters. 3.1.X. For example, coping is mentioned as part of both sensitivity and adaptive capacity.
- A critical reflection on the selection of a limited number of indicators is missing
- A discussion of the problems when using statistical methods when only limited damage and loss data is available is entirely missing.
- A description of the typhoon event itself is missing
- It is not clear for which spatial extend the regression analysis has been carried out. For example, what was the spatial resolution of rainfall data? How did the authors deal with the fact that the data is available in different formats (point, raster etc).
- The MCDA has not been described in detail, what is it exactly and which role does it play?
- The discussion needs to consider the problem to look at hazard and vulnerability factors separately. The authors state that “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 3 impacts”. Unclear remains wht the difference is

between exposure and typhoon impacts (are impacts = damage?). Then they conclude, “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.” – these types of conclusions need to be explained further.

Specific comments in the text:

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

By
**Hung-Chih Hung[1](Corresponding author)**
[1] Professor, Department of Real Estate and Built Environment, National Taipei University, New Taipei City,23741,Taiwan
Address: 151, University Road, San-ShiaDistrict, New Taipei City, 23741, Taiwan
Phone: +886-2-8674-1111 ext.67433
Fax: +886-2-8671-5308
Email: hung@mail.ntpu.edu.tw
**Yi-Chung Liu[2]**
[2]National Science and Technology Center for Disaster Reduction, New Taipei City, 23143, Taiwan
Email: ycl@ncdr.nat.gov.tw
**Sung-Ying Chien[3]**
[3] National Science and Technology Center for Disaster Reduction, New Taipei City, 23143, Taiwan
Email:csy0904@ncdr.nat.gov.tw

**Abstract.** To prepare for and confront the potential impacts 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 high vulnerable areas experience significantly more 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 studies, we proposed a novel methodology that combined 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 were tested by using a disaster damage model (DDM). The results of the vulnerability assessments indicated that the vast majority of the most vulnerable areas is situated in the regions of middle, upper reaches and some coastlines of the river basins. Using the DDM, it shows that the typhoon losses and casualties are significantly influenced by local vulnerability contexts and hazard impact factors. Finally, we suggest the implications of adaptation policy lines for minimizing vulnerability and risk, as well as 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). For example, in August 2009, a devastating typhoon (Morakot) hit three major river basins in southern Taiwan. Meanwhile, approximately 700 people were killed and total economic losses were estimated to 2

**Comment [S1]:** More than what? Needs to be reformulated

**Comment [S2]:** Language check

**Comment [S3]:** propose ?

**Comment [S4]:** ??, please clarify

**Comment [S5]:** Language check

**Comment [S6]:** This is not an appropriate example for the statement in the first sentence since this is one event and does not tell as anything about recent trends have been US$ 0.6 billion (Liu et al., 2014). Thus, it becomes increasingly important for water resource managers to implement programs of integrated river basin management (RBM) that can cope with and reduce potential impacts of climate change and climate-related (climatic) disaster risk (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 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 in scrutinizing the biophysical, socioeconomic conditions and 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).

Existing vulnerability analyses have focused more on assessing, mapping and distinguishing the variability of the vulnerability distribution among regions (Adger, 2006; Hung and Chen, 2013; Ahumada-Cervantes et al., 2015). However, climatic disaster loss and risk accumulation result from the interlinking between hazard impacts, exposure and vulnerability components (UNISDR, 2012; Hung et al., 2013). The majority of extant studies inferred disaster losses and risks use computer-aided simulation, scenarioanalyses and multicriteriadecisionanalysis(MCDA) (Tate et al., 2010; Ni et al., 2010; Hung et al., 2013; De Bruijn et al., 2014). Theirfindings are valuablein characterizingdisaster risk,impactsand their distributions that enable decision makers to create risk mapsand communicate the highriskareas to



**Comment [S7]:** and ?

**Comment [S8]:** language – reformulate or give relation: more than?

**Comment [S9]:** Why 'however'?

**Comment [S10]:** Language, pls reformulate

**Comment [S11]:** Existant ?

**Comment [S12]:** Language check

stakeholders. Nonetheless, few studies have systematically examined how the vulnerability and hazard impactfactors link totheir potential influence on disaster losses. This would ~~compromis~~compromise ethe application of existing vulnerability and exposure studies tothedisaster risk assessmentand integrated RBM.

This article aims to examine whether ~~geographic~~ localities characterized by high vulnerability experience significantly more damage owing to onset weather extreme events at the river basin level, and to 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, GIS (geographical information system)-based statistics with multivariate analysis to assess climatic hazard vulnerability (especially typhoon and flood). Moreover, we examine the connection between vulnerability, hazard impact factors and disaster losses using a disaster damage model (DDM). The 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 assessment

Vulnerability assessments ha~~s~~ves 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 disaster impact research, vulnerability is widely described as the degreesof susceptibility of these assets to sufferdamage and loss (UNISDR, 2013). Furthermore, IPCC (2014) has conceptualized vulnerability as a variety of concepts and elements that encompass



**Comment [S13]:** Add references pls

**Comment [S14]:** Language check

sensitivity or susceptibility to harm and lack of capacity to cope and adapt. Watersheds' contexts consist of biophysical, socioeconomic, industrial and land use elements. Thus, from the perspective of integrated RBM, vulnerability assessment should facilitate decision-makers to engage in the integrated analyses of interaction between the components of vulnerability and the properties of a specific watershed context (O'Brien et al., 2007; Engle and Lemos, 2010; Hung and Chen, 2013). To target support integrated RBM, it should integrate IPCC's (2014) with UNISDR's (2013) concept 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 on the investigation of the relationships between vulnerability and disaster losses can be divided into two major types. Thefirst type of approach interpretsdisaster damageor risk as a function of vulnerability, and frequentlyusing the catastrophic, PSR (pressure-state-response), PAR (pressure-and-release) theories or MCDAcoupledwith computer-aid simulationand GIS-based analysesto predict disaster losses(Ermoliev et al., 2000; Wisner et al., 2004; Tate et al., 2010; Scheuer et al., 2011; De Bruijn et al., 2014). Therefore, disaster risk or potential losses can be directly projected by vulnerability assessment (Cutter et al., 2003; Hung and Chen, 2013). This type of researchuses a 'top-down'approach that can bringthe disaster information related to predicted distributions of disaster impacts and riskto the fore, although there areuncertainties and ambiguities in the processesof projection.

The second type of approach focuseson the 'bottom-up'and data-basedanalysis,

**Comment [S15]:** Language check, unclear

**Comment [S16]:** Needs clarification and more sharpened explanation. Fore example ok that Wisner et al. interprete losses as a function of vulnerability. But first, this vulnerability is differently understood then the vulnerability of the authors' formular (1) and second, Wisner would for sure not predict disaster losses with computer / GIS techniques…
Also lang issues – why is it 'catastrophic?'.

**Comment [S17]:** If the authors' have found this strong statement in the cited references, please give the page number (or best a word-for-word citation. If this statement is supported by the authors' finding it needs more explanation

**Comment [S18]:** Unclear, lang check needed, what are the main reasons for uncertainty and ambiguity ?

which often uses historical or surveyed data to characterize the disaster damage (Zahranet al., 2008; Bhattaraiet al., 2015). The findings not only can help decision makers identify disaster loss distributions, but also examine their determinants (Downton and Pielke, 2005). Thisapproachconcentrates more on mapping the disaster damage distribution at the national or regional levels. It also majorly combines expert judgment with mono-dimensionalevaluation to inspect the influentialfactors of disaster damage(Mokrech et al., 2012; Hung and Chen, 2013). However, little attention had been paid to linking multi-dimensional vulnerability assessment with empirically-based disaster loss evaluation inthe river basin contexts.

Using theoretical-based simulation and MCDA, thefirst type approach seeks to systematically identify disaster loss and scrutinizeits components,as well as to project various disasterimpactsresulting from different hypotheticalevents. By contrast, thesecond type approach enablesdecisionmakers a conjoint treatmentof quantitativedisaster loss dataand qualitativehuman judgment. Nonetheless, these two types of approachesall consideringdisaster lossesareinherent and dynamic due to ongoing interaction of climatic hazard impactswith the biophysical and socioeconomic dimensions of vulnerability in awatershedsystem (O'Brien et al., 2007; Maru et al., 2014).

Increasingthe understanding of the formationof climaticdisaster risk highlights the importance of connectingaforementioned two types of approaches and their relative magnitudes(Mokrechet al., 2012; Visseret al., 2014). Particularly, incorporatingthe first typeinto the second typeapproach allowsus to create frameworks of disaster risk analysisthat could assist in expanding the range of vulnerability assessments and in sequencing them to generate robust resilience and adaptation pathways (Hung et al., 2016).



**Comment [S19]:** How? By looking at loss and damage data? Or by using expert opinion as described below? Than the sentence below should come up. Please clarify

**Comment [S20]:** More than?? See comments above

**Comment [S21]:** What is this? It has not been discussed in the chapter where the authors debate the vulnerability concept

**Comment [S22]:** What is this? Pls explain

**Comment [S23]:** You mean *those* two types?

## 3 Methods and data

To characterize the disaster loss distributions and their linkages with various vulnerability components, we incorporated an MCDA and GIS-based statistic analysis into a data-based multivariate analysis. First, the composite vulnerability framework was constructed to summarize a review of the literature and combined with an MCDA to assess climatic hazard vulnerability at the river basin level. Second, based on PSR 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.

### 3.1 Indicators of vulnerability framework and hypotheses

The assessment framework created here was based on the IPCC’s (2014), UNISDR’s (2013) concepts of vulnerability and literature review. This framework allows us to take advantage of the contributions of existing knowledge, as well as obtain synergies and complexities of watershed contexts as discussed in detail in Hung and Chen (2013). We identified the indicators involved in the framework consisting of three dimensions: exposure, sensitivity and adaptive capacity. 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. 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.

#### 3.1.1 Exposure indicators

Exposure refers to the biophysical factors and the extent to which properties of



**Comment [S24]:** Check language, please reformulate

**Comment [S25]:** What does this mean? That you selected your indicators based on literature review? Please be clearer

**Comment [S26]:** If the PSR plays such a crucial role it needs to be shown in a figure. Based on this figure you should then clarify between which components you try to describe relations by regression models

**Comment [S27]:** This is the first time you mention indicators, what are they indicating? Why did you select this method?

**Comment [S28]:** Ok but needs a bit more explanation, you must be able to understand this paper without having read Hung and Chen (2013), vulnerable system are in contact with hazards(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 debris flow torrents would increase vulnerability and thus enhance the likely disaster losses (Wisner et al., 2004).

### 3.1.2 Sensitivity indicators

Sensitivity is 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 biophysical and societal contexts, and the societal context can be further classified into socioeconomic and land use sensitivity (Hung and Chen, 2013).

The hypothesized links between biophysical context 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 both the more vulnerable and sensitive to disaster damage (Ni et al., 2010). 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 and fragility 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*, *envornmental sensitive areas* and *road infrastructures*. Generally, while preserving more sensitive areas could decrease vulnerability and disaster losses, the larger scales of either urban developments, agricultural uses or road infrastructures



**Comment [S29]:** But Wisner would not say that rainfall is part of vulnerability since he is following a different concept. Ok if you include in your V concept the parameter rainfall (or other bio-physical paramters) but you cannot really give Wisner as a reference. It all goes back to the point that the description of vulnerability in 2.1 needs to be improved.

**Comment [S30]:** Language check

**Comment [S31]:** In your concept you say that sensitivity is part ov vulnerability. Therefore this does not make sense here

**Comment [S32]:** Fragility has not mentioned before – wehre dos this fit in your picture of vulnerability?

would encourage denser land, agricultural developments and more tourist activities, and that could lead to higher vulnerability and expected disaster losses (Cutter et al., 2003; Mehaffey et al., 2008).

### 3.1.3 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 to resources* and to successfully adapt to hazards (self-efficacy). The hypothetical relationships between these factors and disaster damage are negative (Eakin et al., 2010). Finally, those indicators considered to assess vulnerability are demonstrated in Table 1, along with their descriptions, data sources, and expected directions of relations to disaster losses.

**Comment [S33]:** This should not come under one component only

## 3.2 Composite vulnerability index

To assess the vulnerability for each village, the composite vulnerability index (CVI) was estimated. However, the surveyed values of various indicators contain different scales and units. We applied a min-max scaling to directlynormalize all the data into a uniform [0, 1] scale with ratio properties. Then, the normalized values were used to computeCVIsby:

**Comment [S34]:** This needs an introduction, or just formulated differently since the explanation follows below

$$CVI_i = \sum_{j=1}^{m} w_j x_{ij} \quad (2)$$

Where $CVI_i$represents thecomposite 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. Furthermore, 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.

### 3.3 Linking vulnerability factors and climatic disaster losses

This study focuses on single-scenario disaster eventfor comparativelystatic modelling ofdamages and losses at differentpointsover river basins. This approach allows us to controlthe disaster scenario, so thatany variationin lossescan be directly resulted from changesin hazard impactsand vulnerability factors(Hung et al., 2013).Therefore,the disaster damage model can bewritten asthe following function:

$$\text{Disaster loss} = f(\text{hazard, vulnerability}) \qquad (3)$$

Equation (3) implies that the interaction of hazard impacts and vulnerability generates disaster losses. Therefore, the extent of disaster damage and/or losses will vary with vulnerability contexts, while climatic hazard (i.e., typhoon event) impacts are deemed as outerdependant factors. To more specifically identify the relationship between disaster losses and vulnerability factors, several regression models were used in the case studies.

### 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 contexts in southern Taiwan (Fig. 2), but all having heavily struck by the Typhoon Morakot in 2009. The case study areas include three major river basins: Gaoping, Tsengwen, and Taimali Rivers. According to the 2015 census, these three river basins encompass598 villages,around 1.26



**Comment [S35]:** Ok, now we have the disaster community concept of risk where hazard and vulnerability are considered separately. But in the concept used for V earlier the rainfall has been included. This does not fit to the formula 3 here

**Comment [S36]:** Lang check

million populations and cover an area of approximately 7,885$km^2$. Highly diversified topography distributes over thethreewatersheds. The altitudeof thisregionranges from the coastal lowlands along the western shoreline to over 3,000 meters in the eastern high-mountain areas.Uncontrolled urban sprawl and environmental destructionare interwoven by growing threats from climate change and weather extremes that lead tothe riskiestregions in Taiwan(Liu et al., 2013).

In modelling the linkagesbetween vulnerability factors, disasterimpacts and losses, the data were collectedfrom multiple sources. The disaster loss database regarding Typhoon Morakot had been systematically built by the Department of Science and Technology, Taiwan. Thisdatabase includedthe surveyednumbers of casualties, property and agricultural losses, the distributions of inundation and landslide, and damaged public facilities. The data on vulnerability factors were obtained through combing official statistic censuses and random sampling face-to-face questionnaire survey to residents (shown in Table 1 in detail).

# 4 Results and discussions

## 4.1 Composite vulnerability assessments

Using the CVIs estimated by equation (2), Fig. 1 shows the distributions of estimated index values superimposed on the geopolitical 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 $80-100^{th}$ percentiles can be defined as the most vulnerable, and within the $1^{st}-20^{th}$ percentiles as the least vulnerable.

**Comment [S37]:** Rather administrative

In Fig. 1, it shows that there are highly heterogeneous in the spatial distributions of estimated compositevulnerability across the study areas. In the Tsengwen River basin,

**Comment [S38]:** Language check

the most vulnerable areas concentrated in the middle reaches and some coastlines. Moreover, most 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 were spread with the least vulnerable ones. These spatial distribution patterns highly 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 a significantly specially-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.

**Comment [S39]:** Spatially?

## 4.2 The distributions of disaster losses due to Typhoon Morakot

The inundation areas due to Typhoon Morakot concentrated in the convergent regions of Kaoping River and 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 showed 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 $r = 0.42$, $p < 0.01$).

**Comment [S40]:** A short description of the typhoon would be helful

In the Tsengwen river basin, the impacts of flooding and landslides caused more serious damage to the watersheds than debris flow torrents. This would lead to that both casualty counts and agricultural losses significantly associated with patterns of landslides (casualties: Spearman $\rho = 0.17$, $p < 0.05$, 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 infrastructures, land developments and disaster losses that needs further investigation.

### 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 Typhoon Morakot caused no recorded injuries or fatalities. The total casualties are 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 are 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 Posisson) 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 influence of disaster losses, the integrated typhoon loss index (ITLI) was estimated to serve as proxies for combined losses of typhoon:

$$\mathrm{ITLI}_i = Agiculture_i + Property_i + Casualty_i. \quad (4)$$

Where $Agiculture_i$ and $Property_i$ are agricultural and property losses for village $i$, respectively; $Casualty_i$ 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.

Table 2 reports the results of ZINB and ZIP regression analyses for typhoon casualties, as well as Tobit models for ITLIs. Six separate models are estimated, with predictors both 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 Ordinary Least Squares regression. It showed that the *risk perceptions*and *access to resources*have significantly higher 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, the landslides, damaged bridges, agricultural losses, property losses and flooding areas are positively associated with typhoon losses, although agricultural losses are negatively related to casualties in Gaoping watershed. These findings correspond with the PSR framework that could consider the hazards as pressures and their impacts would change the quality of the environment. The higher the hazard impacts, the higher the odds of casualty and disaster loss (OECD, 1993; Wisner et al., 2014).

Regarding the biophysical exposure indicators, averaged 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, the high casualties occurred in the areas with higher levels of rainfall and elevations rather than in debris flow torrents distributed areas. The areas within 0-200m to rivers significantly increased the numbers of casualty over three river basins, and enhanced typhoon losses in both Gaoping and 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 relation to disaster losses was positive (excluding Gaoping River). 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 density population, 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.

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 decrease 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 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, mounting urban or agricultural developments significantly increased casualties and typhoon losses, although increasing agricultural uses strongly decrease casualty distributions in Gaoping watershed. These results also reflected in that more sensitive areas reserved could reduce the occurrence of casualties and losses (excluding Tsengwen watershed). In addition, provision of road or transportation infrastructures would be helpful in the evacuation and disaster relief, and lead 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.

Comment [S41]: ??

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 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 is 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 losses. Through the 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 predisaster 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 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 system and related risk-sharing arrangements into the existing RBM framework forminimizingrisk.

# 5 Conclusions

Growing climate change and weather extreme impacts pose impending challenges and high uncertainties for the RBM. Therefore, the understanding of the interlinks between disaster impacts, vulnerability factors and losses is critical for disaster risk and river basin governance within the options of which adaptive 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 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 can 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 aftermath 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.

## References

Adger, W. N.: Vulnerability, Glob Environ Chang, 16, 268–281, doi:

10.1016/j.gloenvcha.2006.02.006, 2006.
Ahumada-Cervantes, R., Velázquez-Angulo G., Rodríguez-Gallegos, H., Flores-Tavizón, E., Félix-Gastélum, R., Romero-González, J., and Granados-Olivas, A.: An indicator tool for assessing local vulnerability to climate change in the Mexican agricultural sector, Mitig. Adapt. Glob. Change, 1-16, doi:10.1007/s11027-015-9670-z, 2015.
Bhattarai, R., Yoshimura, K., Seto, S., Nakamura, S., and Oki, T.: Statistical model for economic damage from pluvial flood in Japan using rainfall data and socio-economic parameters, Nat. Hazards Earth Syst. Sci. Discuss., 3, 6075-6116, doi:10.5194/nhessd-3-6075-2015, 2015.
Cutter, S., Boruff, B. J.,and Shirley,W. L.:Social vulnerability to environmental hazards,Soc.Sci.Q.,84,242-61, doi:10.1111/1540-6237.8402002, 2003.
De Bruijn, K. M., Diermanse, F. L., and Beckers, J. V.: An advanced method for flood risk analysis in river deltas, applied to societal flood fatality risk in the Netherlands, Nat. Hazards Earth Syst. Sci.,14, 2767-2781, doi:10.5194/nhess-14-2767-2014, 2014.
Downton, M. W. and Pielke. R. A.:How accurate are disaster loss data? The case of U.S. flood damage. Nat.Hazards,35,211-228,doi:10.1007/s11069-004-4808-4, 2005.
Eakin, H., Lerner, A.,and Murtinho, F.:Adaptive capacity in evolving peri-urban spaces: Responses to flood risk in the Upper Lerma River Valley, Mexico,Glob. Environ. Chang, 20,14-22, doi:10.1016/j.gloenvcha.2009.08.005, 2010.
Engle, N. L. and Lemos, M. C.: Unpacking governance: Building adaptive capacity to climate change of river basins in Brazil, Glob Environ Chang, 20, 4–13, doi: 10.1016/j.gloenvcha.2009.07.001, 2010.
Ermoliev, Y. M., Ermolieva, T. Y., MacDonald, G. J., Norkin, V. L. and Amendola, A.: A system approach to management of catastrophic risks, Eur. J. Oper. Res., 122, 452-460, doi:10.1016/S0377-2217(99)00246-5, 2000.
GWP (Global Water Partnership): Integrated water resource management. Technical Advisory Committee Background Paper, No 4, Stockholm, Sweden, 2000.
Hooijer, A., Klijn, F., Pedroli, B., and Van Os, A.: Towards sustainable flood risk management in the Rhine and Meuse River Basins: Synopsis on the finding of IRMA-SPONGE, River. Res. Appl., 20, 343–357, doi:10.1002/rra.781, 2004.
Hung, H.-C. and Chen, L.-Y.: Incorporating stakeholders' knowledge into assessing vulnerability to climatic hazards: application to the river basin management in Taiwan, Clim. Change, 120, 491–507,doi:10.1007/s10584-013-0819-z,2013.
Hung, H.-C., Ho, M.-C., Chen, Y.-J., Chien, C.-Y., and Chen, S.-Y.: Integrating long-term seismic risk changes into improving emergency response and land-use planning: a case study for the Hsinchu City, Taiwan, Nat. Hazards, 69, 491–508, doi:10.1007/s11069-013-0714-y, 2013.

Hung, H.-C., Yang, C.-Y., Chien, C.-Y., and Liu, Y.-C.: Building resilience: mainstreaming community participation into integrated assessment of resilience to climatic hazards in metropolitan land use management, Land Use Pol., 50, 48-58, doi:10.1016/j.landusepol.2015.08.029, 2016.

IPCC (Intergovernmental Panel on Climate Change): Climate Change 2014: Impacts, Adaptation, and Vulnerability. Working Group II Contribution to the AR5 of IPCC, 2014.

Liu, Y.-C., Chien, S.-Y., Hung, H.-C., and Chen, L.-C.: Exploring the spatial patterns of disaster impacts caused by Typhoon Morakot, J. Chin. Inst. Eng., 37, 582-594, doi:10.1080/02533839.2012.727594,2014.

Mehaffey, M., Wainger, L., Wade, T., Yankee, D., Smith, E., Bott, V., and Yarbourgh, R.: Assessing vulnerability from alternative development patterns, Landsc. Urban Plan., 87, 84–95, doi:10.1016/j.landurbplan.2008.04.010, 2008.

Mokrech, M., Nicholls, R. J., and Dawson, R. J.: Scenarios of future built environment for coastal risk assessment of climate change using a GIS-based multicriteria analysis, Environ. Plan. B, 39: 120-136, doi:10.1068/b36077, 2012.

Neuvel, J. and van den Brink, A.: Flood risk management in Dutch local spatial planning practices, J. Environ. Plan. Manag., 52: 865-880, doi:10.1080/09640560903180909, 2009.

Ni, J., Sun, L., Li, T., Huang, Z., and Borthwick, A. G.: Assessment of flooding impacts in terms of sustainability in mainland China, J. Environ. Manage., 91, 1930-1942, doi:10.1016/j.jenvman.2010.02.010, 2010.

O'Brien, K., Eriksen, S., Nygaard, L. P., Schjolden, A.: Why different interpretations of vulnerability matter in climate change discourses,Clim.Policy,7, 73–88, doi: 10.3763/cpol.2007.0706, 2007.

O'Brien, K., Eriksen, S., Schjolden, A., and Nygaard, L.: What's in a word? Conflicting interpretations of vulnerability in climate change research, CICERO Working Paper, 2014.

OECD: OECD core set of environmental performance reviews. Environmental monograph no. 93, Organization for Economic Cooperation and Development, Paris, France, 1993.

OECD: Global Modelling of Natural Hazard Risks: Enhancing Existing Capabilities to Address New Challenge, Paris, France, 2012.

Penning-Rowsell, E., Johnson, C., and Tunstall, S.: 'Signals' from pre-crisis discourse: lessons from UK flooding for global environmental policy change? Glob. Environ. Chang, 16(4), 323-339,doi:10.1016/j.gloenvcha.2006.01.006,2006.

Scheuer, S., Haase, D., and Meyer, V.: Exploring multicriteria flood vulnerability by integrating economic, social and ecological dimensions of flood risk and coping capacity: From a starting point view towards an end point view of vulnerability, Nat. Hazards, 58, 731-51, doi:10.1007/s11069-010-9666-7, 2011.

Tate, E., Cutter, S. L., and Berry, M.: Integrated multihazard mapping, Environ. Plan. B, 37, 646-663,doi:10.1068/b35157,2010.

UNISDR (United Nations International Strategy for DisasterReduction):Reducing Vulnerability and Exposure to Disasters: The Asia-PacificDisaster Report 2012, Bangkok, Thailand,doi: 10.4135/9781452275956.n185, 2012.

UNISDR: From Shared Risk to Shared Value–The Business Case for Disaster Risk Reduction. Global Assessment Report on Disaster Risk Reduction,Geneva, Switzerland, 2013.

Visser, H., Petersen, A. C., and Ligtvoet, W.: On the relation between weather-related disaster impacts, vulnerability and climate change, Clim. Change, 125, 461-477, doi:10.1007/s10584-014-1179-z, 2014.

Wisner, B., Blaikie, P., Cannon, T., and Davis, I.: At risk: Natural Hazards, People's Vulnerability and Disasters, Routledge, London, 2004.

You, W. J. and Zhang, Y. L.: Evaluation of social vulnerability to floods in Huaihe River basin: a methodology based on catastrophe theory, Nat. Hazards Earth Syst. Sci. Discuss., 3, 4937-4965,doi:10.5194/nhessd-3-4937-2015, 2015.

Zahran, S., Brody, S. D., Peacock, W. G., Vedlitz, A., and Grover, H.: Social vulnerability and the natural and built environment: A model of flood casualties in Texas, Disasters, 32, 537-60, doi:10.1111/j.1467-7717.2008.01054.x, 2008.

**Fig 1.** Distributions of the estimated composite vulnerability indices over three river basins
(1) Kaoping River basin

(2) Taimali River basin
(3) Tsengwen River basin 22

(1) Distributions of damaged bridges (2) Distributions of casualties Fig. 2 Distributions of the losses due to Typhoon Morakot over three river basins 23

Table 1Hazard impacts, vulnerability indicators (variables) andexpected sign toclimaticdisaster losses

| Category | | Indicator | Description | Data source | Mean (S.D.) | Sign |
|---|---|---|---|---|---|---|
| **Hazard impacts** | | Casualties | Number of casualties(people) | NCDR[a], 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$) | NCDR, Taiwan | 0.32 (0.94) | + |
| **Exposure** | | Rainfall | Averagedannual rainfall (mm) | Central Weather Bureau, Taiwan | 1932(364) | + |
| | | Debris flow torrents | Number of potential debris flow torrents and landslides | Council of Agriculture, Taiwan | 0.41(1.07) | + |
| **Sensitivity** | Biophysical context | Proximity to rivers | Areas within 0m-200m torivers ($km^2$) | Measured by GIS | 0.18 (0.21) | + |
| | | Elevation | Averagedelevation (m) | Ministry of the Interior, Taiwan | 169.7(355.3) | + |
| | Socioeconomic sensitivity | Populations | Population density (populations/$km^2$) | Ministry of the Interior, Taiwan | 2.74 (5.60) | + |
| | | Social dependence | Ratioof people over age 65 and under age 6, and females (%) | Ministry of the Interior, Taiwan | 58 (5) | + |
| | | Income | Annual disposable household incomes (1000 NT$) | DGBAST[b], 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 | DGBAST, Taiwan | 27.9 (81.4) | – |

| | | | | | |
|---|---|---|---|---|---|
| | | NT$) | | | |
| Land uses | Urban developments | Area of residential, commercial, industrial, educational and public land uses ($km^2$) | Land Use Investigation of Taiwan | 0.35(0.48) | + |
| | Agricultural uses | Areasof agricultural land uses ($km^2$) | Land Use Investigation of Taiwan | 2.17(2.91) | + |
| | Sensitive areas | Environmentalsensitive areas ($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) | + |
| **Adaptive capacity** | Shelters | Number of shelters | Measured by GIS | 1.16(1.43) | — |
| | Fire and police services | Number of fire and police manpower | Countyand city government | 2.05(2.02) | — |
| | Medical services | Hospital beds | Countyand city government | 10.5(16.0) | — |
| | Risk perceptions | Average levels of perceived residential risk to climate hazards (5-point Likert scale) | Questionnaire interviews | 2.97(0.17) | — |
| | Access to resources | Average levels of ability to access to resources (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) | — |