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# 1 Parametric and physically based modelling techniques for 2 flood risk and vulnerability assessment: a comparison

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## 15 Abstract

16  
17 Floods are one of the most common and widely distributed natural risks to life and property.  
18 There is a need to identify the risk in flood-prone areas to support decisions for risk  
19 management, from high-level planning proposals to detailed design. There are many methods  
20 available to undertake such studies. The most accepted, and therefore commonly used, of  
21 which is computer-based inundation mapping. By contrast the parametric approach of  
22 vulnerability assessment is increasingly accepted. Each of these approaches has advantages  
23 and disadvantages for decision makers and this paper focuses on how the two approaches  
24 compare in use. It is concluded that the parametric approach, here the FVI, is the only one  
25 which evaluates vulnerability to floods; whilst although the deterministic approach has  
26 limited evaluation of vulnerability, it has a better science base.  
27

28 **Keywords:** floods, vulnerability, risk, physically-based models, flood vulnerability index  
29  
30

## 31 1. Introduction

32  
33 Floods are one of the most common and widely distributed natural risks to life and property.  
34 Damage caused by floods on a global scale has been significant in recent decades (Jonkman  
35 and Vrijling, 2008). In 2011, floods were reported to be the third most common disaster, after  
36 earthquake and tsunami, with 5202 deaths, and affecting millions of people (CRED, 2012).  
37 River, coastal and flash floods can claim human lives, destroy properties, damage economies,  
38 make fertile land unusable and damage the environment. The development of techniques,  
39 measures and assessment methodologies to increase understanding of flood risk or  
40 vulnerability can assist decision makers greatly in reducing damage and fatalities. Different  
41 methods to assess risk and vulnerability of areas to flooding have been developed over the  
42 last few decades. This paper aims to investigate two of the more widely used methods:

43 traditional physically-based modelling approaches to risk assessment and parametric  
44 approaches for assessing flood vulnerability. The paper aims to present and discuss the  
45 benefits of each to decision makers.

46

#### 47 **Flood risk as a concept**

48 The term "risk" in relation to flood hazards was introduced by Knight in 1921, and is used in  
49 diverse different contexts and topics showing how adaptive any definition can be (Sayers et  
50 al., 2002). In the area of natural hazard studies, many definitions can be found. It is clear that  
51 the many definitions related to risk (Alexander, 1993; IPCC, 2001; Plate, E., 2002; Barredo  
52 et al., 2007) are interrelated and interchangeable and each of them has certain advantages in  
53 different applications (e.g. Sayers et al., 2002; Merz et al., 2007).

54

55 This study will consider risk as the product of two components, i.e. probability and  
56 consequence (Smith, 2004):

57

$$58 \text{ Risk} = \text{Probability} \times \text{Consequence} \quad (1)$$

59

60 This concept of flood risk is strictly related to the probability that a high flow event of a  
61 given magnitude occurs, which results in consequences which span environmental, economic  
62 and social losses caused by that event. The EU Flood Directive 2007/60/EC (EC, 2007) and  
63 UNEP, (2004) uses this definition of risk where "flood risk" means the combination of the  
64 probability of a flood event and of the potential adverse consequences for human health, the  
65 environment, cultural heritage and economic activity associated with a flood event

66

#### 67 **Hazard and Flood Hazard as a concept**

68 "The probability of the occurrence of potentially damaging flood events is called flood  
69 hazard" (Schanze, 2006). Potentially damaging means that there are elements exposed to  
70 floods which may be harmed. Flood hazards include events with diverse characteristics, e.g.  
71 a structure located in the floodplain can be endangered by a 20-year flood and a water level  
72 of 0.5m and by 50-year flood and a water level of 1.2m. Heavy rainfall, coastal or fluvial  
73 waves, or storm surges represent the source of flood hazard. Generally these elements are  
74 characterised by the probability of flood event with a certain magnitude and other  
75 characteristics.

76

#### 77 **Vulnerability and Flood vulnerability as a concept**

78 While the notion of vulnerability is frequently used within catastrophe research, researchers'  
79 notion of vulnerability has changed several times lately and consequently there have been  
80 several attempts to define and capture the meaning of the term. It is now commonly  
81 understood that "vulnerability is the root cause of disasters" (Lewis, 1999) and "vulnerability  
82 is the risk context" (Gabor and Griffith, 1980). Many authors discuss, define and add detail to  
83 this general definition. Some of them give a definition of vulnerability to certain hazards like  
84 climate change (IPCC, 2001), environmental hazards (Blaikie et al., 1994); (Klein and  
85 Nicholls, 1999), (ISDR, 2004), or the definition of vulnerability to floods (Veen &  
86 Logtmeijer 2005, Connor & Hiroki, 2005, UNDRO, 1982, McCarthy et al., 2001).

87

88 This study will use the following definition of vulnerability specifically related to flooding:

89            *The extent to which a system is susceptible to floods due to exposure, a perturbation,*  
90            *in conjunction with its ability (or inability) to cope, recover, or basically adapt.*

91

## 92    **2. The practice of flood risk and vulnerability assessment**

93

94    Different methods to assess or determine hazard, risk and vulnerability to flooding have  
95    evolved through ongoing research and practice in recent decades (Junqiang Xia et al., 2011;  
96    Hartanto et al., 2012; Gichamo et al., 2012). Two distinct method types can be distinguished  
97    and are considered in this paper:

98

- Deterministic modelling approaches which use physically based modelling approaches to estimate flood hazard/probability of particular event, coupled with damage assessment models which estimate economic consequence to provide an assessment of flood risk in an area.

99

100

- Parametric approaches which aim to use readily available data of information to build a picture of the vulnerability of an area.

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Each method has developed from different schools of thought; the first approach mentioned is the traditional method which is routinely used in practice and academia alike. The second approach has evolved from several concerns such as: the internal characteristics of the system, global climate change and the political and institutional characteristics of the system. However, it takes a long time to develop the structural and non-structural measures required to prepare for flooding. In order to help guide such policy decisions, the development of a practical method for assessing flood vulnerability was needed. Among this need, this parametric approach points on vulnerability assessments to minimize the impacts of flooding and also to increase the resilience of the affected system.

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### **The physically based modelling approach**

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Floods are primarily the result of extreme weather events. The magnitude of such an extreme event has an inverse relationship with the frequency of its occurrence i.e. floods with high magnitude occur less frequently than more moderate events. The relationship between the frequencies of occurrence and the magnitude of the extreme event is traditionally established by performing a frequency analysis of historical hydrological data using different probability distributions.

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Once the frequency, magnitude and shape of the hydrograph are established, computer models which discretise the topographical river and land form are used to estimate flood depth, flood elevation and velocity (Hansson et al., 2008). Calculation of flood inundation depth and inundation extent is done using computational models based on solutions of the full or approximate forms of the shallow water equations. These types of models are one (1D) or two-dimensional (2D). 1D modelling is the common approach for simulating flow in a river channel, where water flow in the river is assumed to flow in one dominant direction which is aligned with the centre line of the main river channel. A 1D model can solve flood flows in open channels, if the shallow water assumptions that vertical acceleration is not significant and that water level in the channel cross-section is approximately horizontal are valid. However problems arise when the channel is embanked and water levels are different in the floodplain than in the channel and 2D models are needed in this situation. The hydraulic results from a computer model, such as inundation depth, velocity and extent can be used for loss estimation due to a particular design flood event. These parameters can then

135 be linked to estimates of economic damage and loss in the affected area. Different models of  
136 damage and loss are available and are based on established economic relationships (ref).

137

138 This method relies on a significant amount of detailed topographic, hydrographic and  
139 economic information in the area studied. If the information is available, fairly accurate  
140 estimates of the potential risk to an area, as a result of economic losses, can be calculated.  
141 This type of flood hazard and associated economic loss information is reasonably easily  
142 communicated to the public. With the case of economic loss the public is used to hearing  
143 information provided in this manner. However, if the information for the model construction  
144 is not available, the method is likely to incur significant anomalies, which can call into  
145 question the validity of the assessment. These types of knowledge gaps and uncertainties are  
146 difficult to communicate effectively and can confuse decision makers and the public alike.

147

148 The scientific community therefore has researched methods that will overcome these  
149 problems. In this context it becomes important to evaluate the hazard, risk and vulnerability  
150 to flooding also from a different perspective: the parametric approach.

### 151 **The parametric approach**

152 The parametric approach, introduced in 80's by Little and Robin, (1983), starts from the  
153 perspective of limited data, and has developed further since. The parametric approach aims to  
154 estimate the complete vulnerability value of a system by using only a few readily available  
155 parameters relating to that system, though the implementation of the approach is not simple.

156

157 Four types of parametric approaches have been developed by the scientific communities: i)  
158 estimating the complete vulnerability value of a system by using only few parameters  
159 relating to that system, ii) estimation of "the imputation of non-observable values" (Glynn et  
160 al., 1993), in which the observed parameters are used to model the non-observed ones. (This  
161 assumption can be wrong), iii) the "parametric modelisation via maximum likelihood" (Little  
162 and Rubin, 1987), which is not a direct approach and is based on large number of  
163 assumptions; and iv) the "semi-parametric approach" (Newey, 1990) which allows modelling  
164 only of what is strictly necessary.

165

166 This study considers the first type of parametric approach, where the indicators and results  
167 rely on assumptions that cannot be validated from the observed data. This parametric  
168 approach tries to design a methodology that would allow the experts to assess the  
169 vulnerability results depend on the system characteristics and also to show the drawbacks, the  
170 practical and the philosophical in the specifications of the likelihood function (Serrat and  
171 Gomez, 2001).

172

173 In a general context, vulnerability is constructed like an instrumental value or taxonomy,  
174 measuring and classifying social, economic and environmental systems, from low  
175 vulnerability to high vulnerability. The vulnerability notion has come from different  
176 disciplines, from economics and anthropology to psychology and engineering (Adger, 2006);  
177 the notion has been evolving giving strong justifications for differences in the extent of  
178 damage occurred from natural hazards.

179

180 Whatever the exact measure of vulnerability one chooses to work with, the starting point is to  
181 estimate the right parameters of the process under the specification of the datasets.  
182 Vulnerability assessments have to be explicitly forward-looking. No matter how rich the  
183 data, the vulnerability of various systems is never directly obvious.

184

185 At spatial and temporal scales, several methodologies such as parametric-based approaches  
186 are applied to a vast diversity of systems: Environmental Vulnerability Index (EVI), Pratt et  
187 al, 2004; The Composite Vulnerability Index for Small Island States (CVISIS), Briguglio,  
188 2003; Global Risk and Vulnerability Index (GRVI), Peduzzi et al., 2001; Climate  
189 Vulnerability Index (CVI), Sullivan and Meigh, 2003, etc..

190

191 This study uses a parametric approach proposed by Balica et al., (2009) to determine and  
192 index flood vulnerability for four system components (social, economic environmental and  
193 physical).

194 The parametric approach has some drawbacks, such as: an inevitable level of assumptions,  
195 the need for a sensitivity analyses, reliable sources and the subjective manner of interpreting  
196 the results.

### 197 **Comparison of approaches**

198 Physically based modelling and parametric approaches offer two different techniques for  
199 assessing flood risk and vulnerability. In light of these two distinct approaches, a clear  
200 question arises: what are the different advantages and disadvantages for decision makers  
201 using these techniques and “how do the two approaches compare in use?”

202

203 In order to answer this research question it is important to assess what decision makers  
204 require from these techniques in order to reach decisions. For the purposes of this study the  
205 following key components are identified:

- 206 • Information on the mechanism and cause of flooding (flood hazard) in the area  
207 studied.
- 208 • Information on the health and safety implications for the affected population of the  
209 flood hazard posed in the area, and the relative areas or population who are  
210 particularly vulnerable (and why).
- 211 • Information on the economic damage and losses expected in the area given a  
212 particular event.

213 In addition to these key components a fourth criteria was identified:

- 214 • How easily is this information communicated, both
  - 215 ○ From the expert undertaking the study to the decision-maker and
  - 216 ○ From the decision-maker to the public

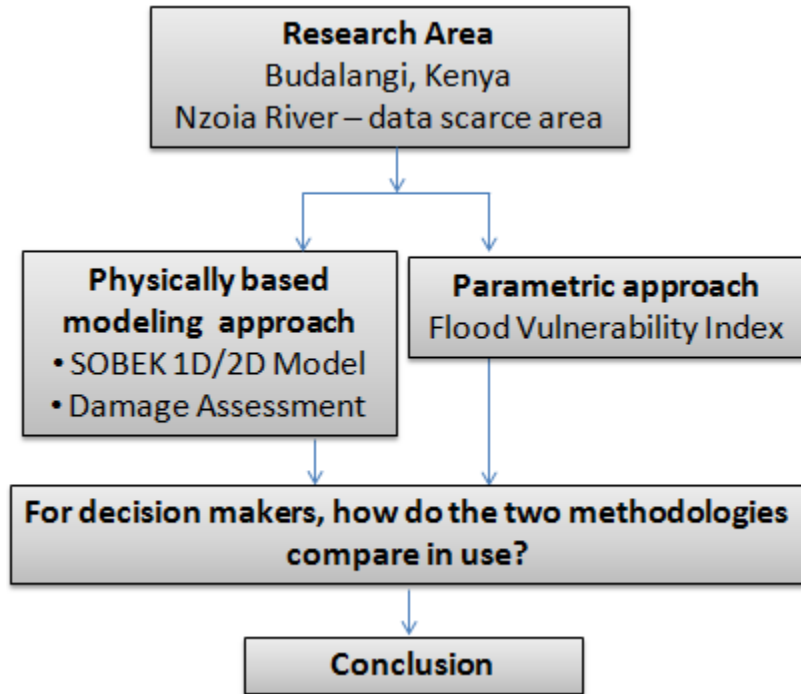
217

218 This study will use the above identified criteria to compare the application of the two  
219 techniques (physically based modelling and the parametric approach) to a case study area in  
220 Budalangi, on the Nzioa River in Western Kenya. The paper aims to investigate the benefits  
221 and drawbacks of each approach, with the purpose of informing decision makers of the use.

222

223 **3. Methodology**

224 The scope of the present paper is to compare a parametric approach (Flood Vulnerability  
225 Index (FVI)) with traditional physically-based hydraulic modelling for flood risk analysis in  
226 order to determine what are the advantages of using one or the other in design and decision-  
227 making when flood hazard is involved. The general framework for the methodology is set  
228 out in Figure 1.  
229



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231  
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Figure 1. Proposed methodology

233 **3.1 Case Study Area**

234 The Nzoia river originates in the South Eastern part of Mt. Elgon and the Western slopes of  
235 Cherangani Hills at an elevation of about 2300 m.a.s.l and it is one of the major rivers  
236 flowing into Lake Victoria. Nzoia river basin covers an area of 12709 km<sup>2</sup> in Western Kenya  
237 (Figure 2). The Nzoia River discharges into Lake Victoria in Budalangi, Busia district. The  
238 river is of international importance, as it is one of the major rivers in Nile basin contributing  
239 to the shared water of Lake Victoria (NRBMI, (nd)).

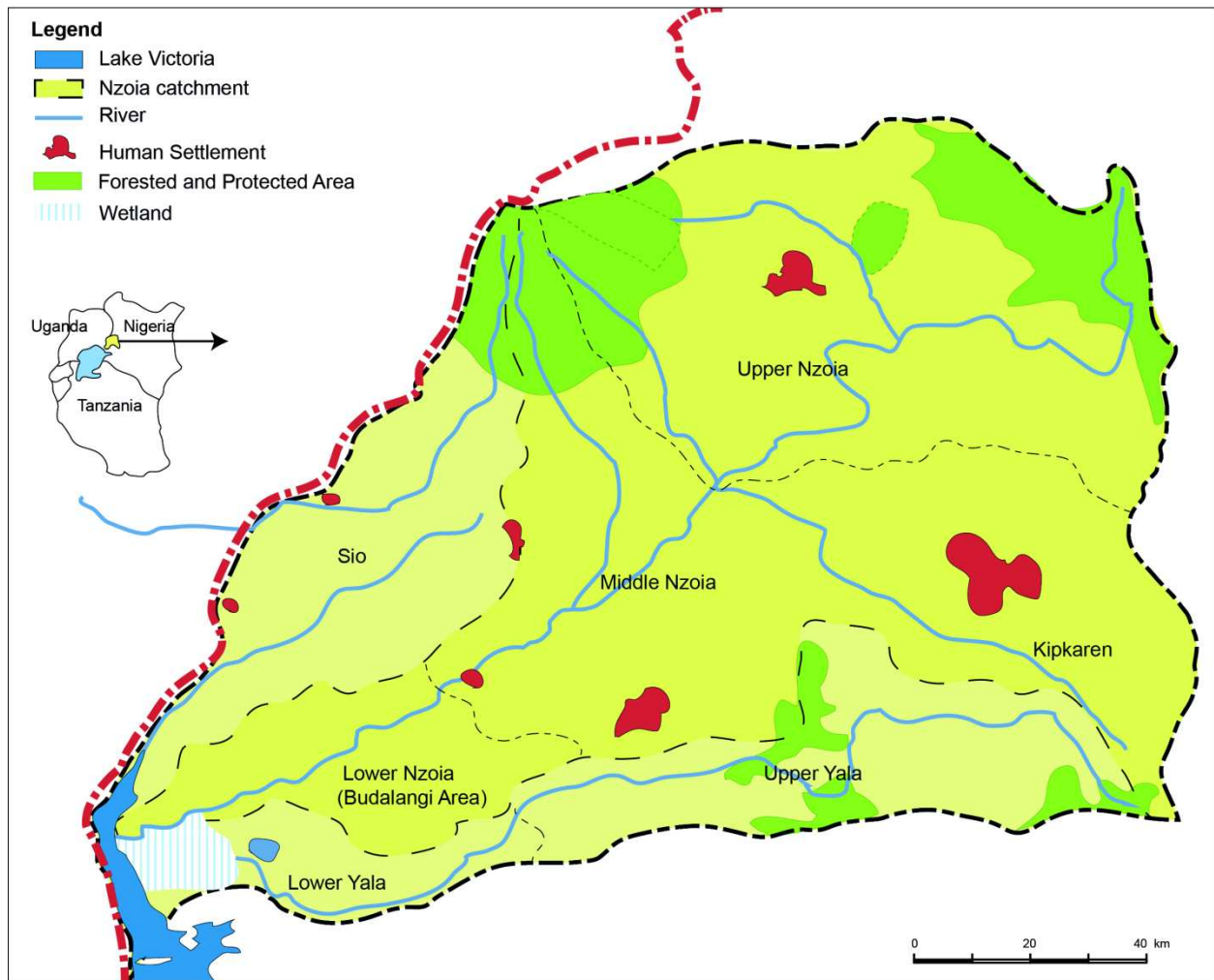


Figure 2. Nzoia River Basin

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The Nzoia river basin is divided into three sub-catchments: the Lower Nzoia, characterised as flat and swampy; the Middle Nzoia and the Upper Nzoia, characterised with hills and steep slopes. The major tributaries of the Nzoia River are: Koitogos (Sabwani), Moiben, Little Nzoia, Ewaso Rongai, Kibisi, Kipkaren and Kuywa. The climate is tropical-humid and the area experiences four distinct seasons. Nzoia catchment has two rainy periods per year, one from March to May, with long rains and a second one from October to December, with short rains associated with ITCZ (the Inter Tropical Convergence Zone). The mean annual rainfall varies from a minimum of 1076 mm in the lowland to a maximum of 2235mm in the highlands. Average annual volume of precipitation of the catchment is about  $1740 \times 10^6 \text{ m}^3$ . The average temperature of the area varies from 16°C in the upper catchment (highlands) to 28° C in the lower catchment (lower semi-arid areas).

The dominant land use in the river basin is agriculture and the main agriculture production of the area are corn, sorghum, millet, bananas, groundnuts, beans, potatoes, and cassava and cash crops are coffee, sugar cane, tea, wheat, rice, sunflower and horticultural crops (Githui et al, 2008). The river basin plays a large role in economic development at local and also at national level. Major problems and challenges in the basin are soil erosion and



260 sedimentation, deforestation, flooding, and wetland degradation. The area located at the most  
261 downstream end of the catchment is, as previously mentioned the Budalangi area, which is  
262 the focus of the present study. Floods are frequent in the Budalangi area  
263 (WMO/MWRMD/APFM, 2004) and their impact is felt through loss of life, damage to  
264 property and agricultural/crop destruction.

265

266 This case study is data scarce area. The lower the accuracy in the data, the lesser the accuracy  
267 in the predictions, therefore in data scarce areas this can result in bad or poor vulnerability  
268 predictions. Consequently, the results of the two approaches chosen may prove which one is  
269 a more appropriate approach to be used by the decision makers in such cases.

270

### 271 **3.2. Assessing the flood risk of Budalangi region using physically based modelling**

272 There are many simulation models available for solving problems of unsteady or steady flow.  
273 In this present study, an unsteady flow analysis was carried out using the SOBEK 1D/2D  
274 tool, developed by Deltares. SOBEK 1D/2D couples one-dimensional (1D) hydraulic  
275 modelling of the river channel to a two-dimensional (2D) representation of the floodplains.  
276 The hydrodynamic 1D/2D simulation engine is based upon the optimum combination of a  
277 minimum connection search direct solver and the conjugate gradient method. It also uses a  
278 selector for the time step, which limits the computational time wherever this is feasible.  
279 Detailed numerical implementation of the solution of the Saint Venant flow equations in  
280 SOBEK 1D/2D is given in the technical user manual of Verwey, (2006).

281

282 Generally the damages by flooding are classified as damages which can be quantified as  
283 monetary losses (tangible) and the damages which cannot be evaluated quantitatively in  
284 economic terms (intangible). These damages may be direct or indirect depending upon the  
285 contact to the flooding.

286

287 Flood damage estimation methodologies are applied worldwide (Dutta et al., 2003). For  
288 example, in the United Kingdom a standard approach to flood damage assessment is used  
289 (developed in the mid 1970s). Since then continually refined, this approach is mandatory for  
290 local authorities and agencies wanting central government assistance with flood mitigation  
291 measures. In United States, U.S. Army Corps of Engineers (USACE) has developed its own  
292 guidelines for urban flood damage measurement, (USACE, 1988). The method is based on  
293 the US Water Resources Council's 1983 publication on 'Principles and Guidelines for Water  
294 and Related Land Resources Implementation Studies'. The approach adopted in the method is  
295 very comprehensive for estimation of damage to urban buildings and to agriculture. In  
296 Australia, authorities considered that is no standard approach and it is a little attempt to  
297 achieve standard approach. Flood damage estimation methodologies are applied as well in  
298 many countries in Europe (Forster et al., 2008). These approaches are useful in conducting  
299 cost-benefit analyses of the economic feasibility of flood control measures.

300

301 This paper uses the Forster et al., 2008, approach where the expected damage (ED) on  
302 agriculture was calculated using the following equation, which is modified from Forster et  
303 al., (2008).

304

305 ED = MV \* Y \* A \* DI, where ED – estimation damage; MV – market value; Y – yield per  
306 unit area; A- area of cultivation; DI – damage impact factor.

307

308 The number of houses in the inundated area was calculated using the information on  
309 population density and average number of family member per household.

310

311  $NH = \frac{IA * PD}{FM}$ ; where NH – number of houses in inundated area; IA – inundated area; PD –  
312 population density; FM – average number of family per household.

313

314 In order to estimate the flood damage, the estimation of some flood parameters are needed:  
315 flow velocity, depth and duration at any given point, proper classification of damage  
316 categories considering nature of damage, establishment of relationship between flood  
317 parameters and damage for different damage categories.

318

### 319 **Flood Inundation Modelling**

320 In order to build the 1D/2D hydrodynamic model of the Budalangi river, in SOBEK,  
321 available topographical information from the Shuttle Radar Topography Mission (SRTM) at  
322 a resolution of 90m by 90m and sparse cross-section data were used. Hydrograph variations  
323 at the upstream boundaries of the model were provided by a calibrated hydrological SWAT  
324 model of the Nzoia catchment. Recorded water levels for Lake Victoria were used as  
325 downstream boundary conditions. The SWAT model used to provide the upstream boundary  
326 condition was the one originally built and described by Githui et al. (2008) and recalibrated  
327 by van Hoey (2008). The 1:200 years design flood determined by SWAT was routed  
328 downstream by the hydrodynamic SOBEK model and inundation extents were drawn. A 1 in  
329 200 year return flood was recorded on Nzoia river on November 2008, and therefore the  
330 inundation extent produced by the model was compared with available aerial information  
331 captured by the Advanced Land Imager (ALI) on NASA's earth observing-1 satellite on  
332 the 13th November 2008.

333 The results of the model, at the moment of the largest flood extent, for the 1:200 return flood  
334 period are represented in Figure 3.

335

### 336 **Flood Damage Evaluation**

337 Many flood damage assessment methods have been developed since 1945 (White, 1945).  
338 However, quantifying the expected flood damage is very difficult because the impact of a  
339 flood is a function of many physical and behavioural factors. For the purposes of this paper,  
340 flood damage was assumed to be related only to the flood depth.

341

342 The Budalangi region is a poorly developed rural area whose main industry is agriculture.  
343 Consequently the main expected damages were anticipated to be on the agricultural sector  
344 and were calculated based on a formula developed by Forster et al., (2008). The main cash  
345 crops in the area are known to be sugarcane, maize and rice. These crops were used, with  
346 readily available yield and expected local market values, to calculate the potential losses due  
347 to floods as a result of the 200 year return period event. In addition, loss of property and the  
348 affected population were included in the damage estimation, however it is recognised that in

349 excluding the calculation of damage in relation to velocity this estimation is significantly  
350 simplified.

351

### 352 **3.3. Assessing flood vulnerability of Budalangi using a parametric method**

353 As mentioned above the parametric method used in this study is the one developed by Balica  
354 et al, 2009, which consists in determining a flood vulnerability index (FVI), based on four  
355 components of flood vulnerability: social, economic, environmental and physical and their  
356 interactions, which can affect the possible short term and long term damages.

357

358 The four components of the flood vulnerability have been linked with the factors of  
359 vulnerability: exposure, susceptibility and resilience (Bosher et al., 2007, Penning-Rowsell  
360 and Chatterton, 1977).

361

362 The conceptual FVI equation is:

$$363 \quad \text{FVI} = (E * S) / R, \quad (2)$$

364 where E-exposure, S-susceptibility and R-resilience.

365

366 The indicators belonging to exposure and susceptibility increase the flood vulnerability index  
367 therefore they are placed in the nominator; however the indicators belonging to resilience  
368 decrease the FVI, this is why they are placed in the denominator (Quang et al, 2012).

369

370 The application of this formula for each component leads to four distinct FVI indices;

371  $FVI_{\text{Social}}$ ,  $FVI_{\text{Economic}}$ ,  $FVI_{\text{Environmental}}$  and  $FVI_{\text{physical}}$ , which aggregates into:

$$372 \quad \text{Total FVI} = \frac{\left(\frac{E * S}{R}\right)_{\text{Social}} + \left(\frac{E * S}{R}\right)_{\text{Economic}} + \left(\frac{E * S}{R}\right)_{\text{Environmental}} + \left(\frac{E * S}{R}\right)_{\text{Physical}}}{4} \quad (3)$$

373

374 The exposure can be understood as the intangible and material goods that are present at the  
375 location where floods can occur, such as: loss of photographs and negatives, loss of life,  
376 delays in formal education (Penning-Rowsell et al., 2005). The susceptibility relates to  
377 system characteristics, including the social context of flood damage formation (Begum et al.,  
378 2007) and can be i.e. poverty, people with special needs, education, level of trust.  
379 Susceptibility is defined as the extent to which elements at risk (Messner & Meyer, 2006)  
380 within the system are exposed, which influences the chance of being harmed at times of  
381 hazardous floods. Resilience to flood damages can be considered only in places with past  
382 events, since the main focus is on the experiences encountered during and after floods  
383 (Cutter, 1996, Cutter et al., 2003, Pelling, 2003, Walker et al., 2004, Turner II et al., 2003).  
384 Resilience describes the ability of a system to preserve its basic roles and structures in a time  
385 of distress and disturbance. Indicators showing resilience are flood insurance, amount of  
386 investment, dikes and levees, storage capacities, etc.

387

388 There are in total 29 indicators identified to contribute to Eq (3), each with their own unit of  
389 measure. Some indicators are not always used while evaluating the FVI of a region. They are  
390 evaluated in each case and the most representative are used for the FVI. A comprehensive  
391 description of such indicators in case of floods in the Mekong delta can be found in Quang et  
392 al (2012).

393 After identifying the indicators, in order to use them in Eq (3) they need to be normalised  
394 using a predefined minimum and maximum. In general classical proportional normalization  
395 is used, which keeps the relative ratios in the normalized values of the indicators as they were  
396 before normalization. The indicators become dimensionless, but still keep their proportion.

397  
398 The FVI of each of the social, economic, environmental and physical component is computed  
399 using Eq. 1. The results of each FVI component (social, economic, environmental and  
400 physical) are summed up in Eq. 3.

401  
402 The FVI methodology does not require researchers to judge the relative importance of  
403 different components, i.e. they do not need to develop arbitrary weights for the indicators.

404 The Equation 1 links the values of all indicators to flood vulnerability components and  
405 factors (exposure, susceptibility and resilience), without weighting, as suggested by Cendrero  
406 and Fisher in 1997. This is done because of different number of rating judgments which “lie  
407 behind combined weights”, or interpolating. The same approach of assigning no weights was  
408 used by Peduzzi et al., 2001, the Global Risk and Vulnerability Index –Trends per Year,  
409 GRAVITY, by Briguglio, 2003 in the Economic Vulnerability Index and Rygel et al., 2006.

410  
411 The main issue while computing the FVI is actually to determine these indicators. There are  
412 different sources for determining the values of the indicators, and these are in general  
413 statistical data stored by environmental agencies, water boards, UN overviews and annual  
414 data from city halls.

415

#### 416 **4. Results obtained when applying the two approaches**

##### 417 **4.1. Physically based modelling approach**

418 The SOBEK simulation of the 1:200 year event results were water depths and inundation  
419 extents, as can be seen in figure 3. The model is able to produce velocities of flow during an  
420 inundation event as well; however these velocities were not considered in the estimation of  
421 the damages and therefore not reported herein.

422

423 The maximum inundation extent was checked with an available satellite image on 13  
424 November 2008. The obtained maximum inundation extent from the model was of 12.61km<sup>2</sup>,  
425 which represents 97% of the inundation extent of the satellite image. Due to lack of data in  
426 the area, it is considered that this is good for the calibration of the model.

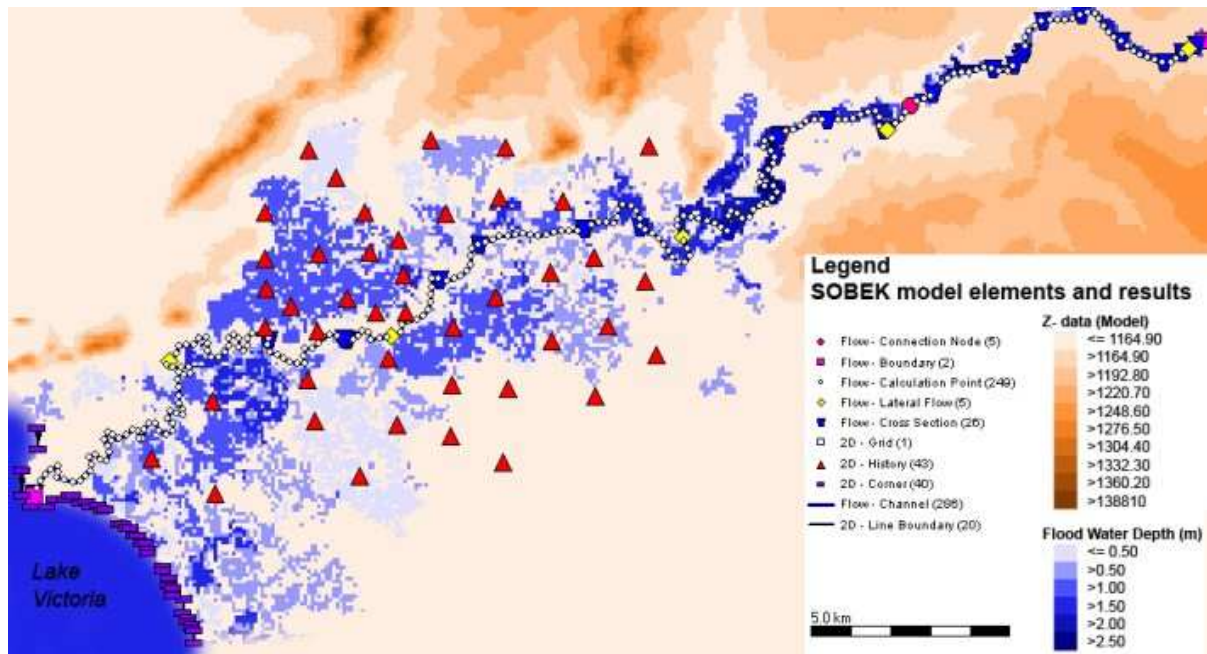
427

428 In order to determine the impact of flood and to evaluate the damages water depths obtained  
429 from the model were analysed. The obtained water depths were overall less than 2m (95% of  
430 the inundated area), and only 5% bigger than 2m in the upstream of the river. The main water  
431 depth is less than 0.5 m for 30% of the inundated area; 0.5m for 20% of the inundated area,

432 between 1m and 1.5m for 35% of the inundated area; and 1.5 -2m for 10% of the inundated  
433 area.

434

435



436

437

438

Figure 3. Lower Nzioa Flood Inundation Extent 1:200 year prediction

439 Based on the results from the hydrodynamic model, damage in the Budalangi area was  
440 computed using Forster et al, (2008) method and damage functions (Duggal & Soni, 2005).

441

442 In the Budalangi area the expected potential damages of 1.54M Euros (+/-80000 Euros was  
443 calculated for the event of 1:200 year return.

444

#### 445 4.2. Parametric approach

446 The FVI methodology was applied to Budalangi Settlement, the results can be seen in Table  
447 2. Budalangi vulnerability in the social and economic components is higher than the  
448 environmental and physical component, (1.00 means the highest vulnerability, see Table 1  
449 for flood vulnerability index designations).

450

451 The incorporation of flood vulnerability designations is probably the most difficult of all  
452 variables to include in the vulnerability index. There are problems involved in deciding how  
453 to rank vulnerability zones; but since the purpose of the FVI is to assess vulnerability in  
454 relation to flood vulnerability components and indicators, it was decided to rank the  
455 designation zones on the basis of standardised vulnerability indices results, between 0 and 1.

456

457 Flood vulnerability designations are assigned based on vulnerability potential in the event of  
458 flooding. A very high vulnerability designation is assigned if there is very high potential for  
459 loss of life and/or extreme economic loss based on vulnerability indicators, i.e. low amount  
460 of investment in counter measures or very slow recovery. A high vulnerability designation is

461 assigned if there is a high potential for loss of life but still high economic loss. A medium  
 462 vulnerability designation is assigned if there is a medium potential for loss of life but an  
 463 appreciable economic loss, the area can recover in months and the amount of investment in  
 464 counter measures is enough to maintain the existing structural measures. A low flood  
 465 vulnerability designation is assigned if there is a small but still existing potential for loss of  
 466 life and the economic loss is minor. Lastly, a very low flood vulnerability designation is  
 467 assigned if there is a vanishingly small potential for loss of life and the economic loss can be  
 468 minor or even if flood insurances apply.

469 The data for the Budalangi area consulted to gather the indicators are: UNDP: United Nations  
 470 Development Programme (HDI, child mortality, inequality); INTUTE: a web-site which  
 471 provides social data for education and science research, (population density, unemployment,  
 472 disabled people); the World Fact-Book, a database developed by the CIA with basic  
 473 information on all the countries in the world (communication penetration rate, past  
 474 experience); UNEDRA: University Network for Disaster Risk Reduction in Africa; Nzoia  
 475 River Basin Management Initiative a public private partnership between Water Management  
 476 Resource Authority and Mumia Sugar, Pan Paper and Nzoia Sugar Company (land use, flood  
 477 insurance, shelters, closeness to river); DEFRA - Department for Environment, Food and  
 478 Rural Affairs economic and statistical database at no cost charge (urban growth, population  
 479 growth, amount of investment, dikes-levees, storage capacity); WKCDD & FMP, Western  
 480 Kenya Community Driven Development & Flood Mitigation Project (river discharge,  
 481 rainfall, evaporation); Western Water Board, Kenya (drainage, topography, industries,  
 482 evacuation roads).

483 *Table 1. Flood Vulnerability Designations*

<b>Designation</b>	<b>Index Value</b>	<b>Description</b>
Very small vulnerability to floods	<0.01	Very small Vulnerability to floods, the area recover fast, flood insurances exist, Amount of investment in the area is high
Small vulnerability to floods	0.01 to 0.25	Social, economic, environmental and physical the area can once in a while experience floods, the area is vulnerable to floods and the recovery process is fast due to the high resilience measures, high budget, on the other hand if the area is less developed economic, even if a flood occurs the damages are not high, so small vulnerability to floods
Vulnerable to floods	0.25 to 0.50	Social, economic, environmental and physical the area is vulnerable to floods, the area can recover in months average resilience process, amount of investments is enough
High Vulnerability to floods	0.50 to 0.75	Social, economic, environmental and physical the area is vulnerable to floods, recovery process is very slow, low resilience, no institutional organizations
Very high vulnerability to floods	0.75 to 1	Social, economic, environmental and physical the area is very vulnerable to floods, the recovery process very slow. The area would recover in years. Budget is scarce.

484

485  
486  
487

Table 2. Budalangi FVI results

<b>Budalangi Flood Vulnerability Index</b>		
<b>FVI Components</b>	<b>FVI Values</b>	<b>FVI designation</b>
FVI Social	0.768	Very high vulnerability to floods
FVI Economic	0.521	High vulnerability to floods
FVI Environmental	0.314	Vulnerable to floods
FVI Physical	0.341	Vulnerable to floods
FVI Total	0.490	Vulnerable to High vulnerability to floods

488

489 Socially, the Budalangi area has very high vulnerability to floods, since has high population  
490 density, high child mortality rate, and a large affected population due to floods. The study  
491 also shows that the region has few shelters (0.6/km<sup>2</sup>), no warning systems, no evacuation  
492 roads (no asphalted road), and only limited emergency services.

493

494 Economically the region is high vulnerable to floods since the area has low exposure to  
495 floods as the main economic activity is agriculture. The Human Development Index is low,  
496 and the area is not covered by flood insurance. Budalangi has few industries, the investment  
497 levels and a recovery process take long to recover after a flood event.

498

499 Environmentally, the Budalangi settlement is vulnerable to floods. The environmental  
500 component includes indicators which refer to damage to the environment caused by flood  
501 events or manmade interferences which could increase the vulnerability of certain areas. But  
502 activities like industrialisation, agriculture, urbanisation, deforestation, can increase the flood  
503 vulnerability, which may also create even more environmental damages.

504

505 When examining the physical vulnerability, the Budalangi area has very low slope and the  
506 settlement area is in contact with the river all along the length of the river so the exposure of  
507 Budalangi is high and has low resilience with little or no installed storage capacity.

508

509 Overall, the area following the designations of FVI is high vulnerable to floods, the recovery  
510 process is slow, the area has low resilience and no institutional organizations.

511

## 512 **5. Discussion (Comparison – analysis and discussion of the approaches)**

513

### 514 **5.1 The physically based modelling approach**

515 Physically based models have the advantage that they calculate the solution of a complicated  
516 and coupled set of equations that describe the phenomena of river flow and flooding. These  
517 models are dependent on physical knowledge that they incorporate into the equations and  
518 associated parameters. A key element for a good physically based model is the minimum of  
519 historical data that they need to determine the values for the parameters included in the

520 physically based equations. Often, historical data is not available, in particular in areas of  
521 weak infrastructure, and this would make physically based models unusable in certain areas.

522

523 The advantage in using physically based models is their high capability for prognosis and  
524 forecasting, and their disadvantage is the high input data demand. In the past computational  
525 demand was a big disadvantage, but nowadays with the development of cloud and cluster  
526 computing capabilities over the internet, this disadvantage is reduced. However this is only  
527 true in case of larger, better-funded organisations that have good computer power to create  
528 cluster of computers, and not yet true for small consultancy companies or water boards who  
529 cannot dedicate cluster of computers for a specific modelling task. Due to the high  
530 computation resources demands, in case of 2D and 3D models, the calibration of physically  
531 or semi-physically based models can still be a tremendous effort.

532

533 In the present study the data on flooding was scarce, however the 2D physically based model  
534 was able to predict well the extent of flood, which shows that even in an ungauged catchment  
535 if the model is properly build, confidence in the construction of such a model does not  
536 require calibration (Cunge et al, 1980) and the results are good for design. A model based on  
537 the physics of the phenomena can be used to produce synthetic data to be used with a simple  
538 forecasting model (Van Steenbergen et al., 2012).

539 One of the important tasks of the decision makers in flood situations is not only to take  
540 management decision but also to properly disseminate knowledge to involved stakeholders,  
541 including the general public. The objectives of knowledge dissemination is to offer simple  
542 and clear information, which can prepare the public for the future and also can actively  
543 involve the stakeholders in flood management planning. The information should be  
544 delivered in relevant spatial and temporal scales. A physically based model has the advantage  
545 that can offer all types of information on a very fine spatial resolution, at a level of a street,  
546 or a house, in a familiar and easily recognisable user interface. It is very important that the  
547 decision makers use thoroughly verified results, rather than results characterised by  
548 uncertainties, because the stakeholders and the public are taking often quick evacuation  
549 measures based on such information.

550

## 551 **5.2 The parametric approach**

552 The FVI approach regarding the *information on the mechanism and cause of flooding* has  
553 some limitations, what is given from this approach are the indicators values for river  
554 discharge, topography, closeness to the river, the amount of rainfall, dikes and levees.  
555 Considering these indicators the FVI approach can only evaluate the flood vulnerability,  
556 cannot tell the extent of flooding nor the expected inundation area through the physical and  
557 environmental component. The application of this approach takes less preparation time than  
558 physically-based model construction, calibration and simulation.

559

560 The FVI approach regarding the *information on the health and safety implications to the*  
561 *affected population* is well designed; the approach shows through the social vulnerability  
562 indicators the exact population exposed to floods, the ones which are susceptible (youngest  
563 and eldest), if these people are aware and prepare, if they have and know how to interpret a  
564 warning system, which of the roads can act as an evacuation road. The social flood



565 vulnerability index expresses whether the population of that specific area has experienced  
566 floods, the number of people working in the emergency service and the number and locations  
567 of shelters in the area. The social FVI provides a greater understanding of how people might  
568 be affected, which can feed into emergency services and evacuation strategy development.

569

570 The FVI approach regarding the *information on the economic damages and losses to the*  
571 *affected areas* gives basic damage estimation. The economic component is related to income  
572 or issues which are inherent to economics that are predisposed to be affected (Gallopini  
573 2006).

574

575 Many economic activities can be affected by flooding events, among them are agriculture,  
576 fisheries, navigation, power production, industries, etc. The loss of these activities can  
577 influence the economic prosperity of a community, region or a country. The FVI can assess  
578 the economic vulnerability using a single number, though this number cannot evaluate the  
579 exact damage and losses but instead the index shows the number of industries in the area and  
580 their closeness to the river and also the amount of investment in counter measures and the  
581 number of flood insurances in that specific area.

582

583 *How easily the information of the FVI approach is communicated?*

584

585 From experts undertaking the study to the decision makers it can be said that the use of the  
586 FVI approach improves the decision-making process by identifying the vulnerability of flood  
587 prone areas. The FVI approach will direct decision-makers to a simplified usage and simpler  
588 understanding of the vulnerability; the FVI approach can be seen as a tool for decision  
589 making to direct investments to the most appropriate sectors and also to help in the decision-  
590 making process relating to flood defence, policies, measures and activities. The FVI  
591 approach allows, irrespective of uncertainties, relative comparisons to be made between case  
592 studies. While a level of uncertainty is inherent in FVI, the use of it in operational flood  
593 management is highly relevant for policy and decision makers in terms of starting adaptation  
594 plans. It offers a more transparent means of establishing such priorities, which inevitably are  
595 considered as highly political decisions. It may also be considered as a means to steer flood  
596 management policy in a more sustainable direction. However, as individual information is  
597 lost in the aggregation process, it needs to be retrieved by a more in-depth analysis of each  
598 process in order to design policies and their implementation.

599

600 **From decision maker to the public:**

601 Hence it is useful to have an *easy-to-apply* and *communicating* instrument that can help give  
602 an overview of the main points by having one single and comparable number, the FVI. The  
603 FVI is necessary, but not sufficient, for decision making and therefore should be used in  
604 combination with other decision-making tools. This should specifically include participatory  
605 methods with the population of areas identified as vulnerable and should also include a team  
606 of multidisciplinary thematic specialists and knowledgeable societal representatives and  
607 those with expert judgments.

608

609 **6. Conclusions**

610 The two approaches, modelling and parametric, have been applied to a data-scarce area - the  
611 Budalangi settlement. Examining the **approaches** in the context of this study leads to the  
612 following conclusions:

- 613 1. FVI does not assess flood risk directly, but does contribute to assessing flood risk.  
614 Vulnerability takes a step further and covers other aspects, such as: social aspects,  
615 environmental damage and infrastructure resilience.
- 616 2. The deterministic approach has a better science base, but limited evaluation of  
617 vulnerability;
- 618 3. FVI gives a wider evaluation, but is less rigorous. Therefore FVI is useful in a larger-  
619 scale vulnerability assessment, but a deterministic approach is better for more focused  
620 studies. In fact FVI could be used to decide where a deterministic model is  
621 necessary.

622 The Flood Vulnerability Index as analysed in the research provides a quick, reliable  
623 evaluation of flood vulnerability and in fact is the only method for assessing the vulnerability  
624 to flooding of a particular geographical area. The fact that indicators are used, allows for  
625 comparison of flood vulnerability in different areas as well as the identification of which  
626 indicators can determine the relative level of flood vulnerability. FVI can measure trends in  
627 the changing natural and human environments, helping identify and monitor priorities for  
628 action. These features, alongside the ability to identify the root causes of increased  
629 vulnerability, provide key information at a strategic level for flood risk planning and  
630 management. However the results would provide neither sufficient information nor the  
631 required level of detail for input into engineering designs or project level decisions.

632  
633 FVI can provide an insight into the most vulnerable locations. It can analyse the complex  
634 interrelation among a number of varied indicators and their combined effect in reducing or  
635 increasing flood vulnerability in a specified location. It is very useful when there is a large  
636 level of uncertainty and decision makers are faced with a wide array of possible actions that  
637 could be taken in different scenarios, in this case the FVI can present readily understood and  
638 readily communicated results that can decision-makers in identifying the most effective  
639 measures to be taken. In this way the proposed measures can be prioritised for areas that are  
640 at greatest risk. Uncertainty is not removed, but is integrated into the assessment. On the  
641 other hand this complexity is also a negative point, since it takes a long time and good  
642 knowledge of the area and the system behind the FVI to be able to implement it.

643  
644 As all with models, this FVI model is a simplification of reality and its application should be  
645 compensated for with thorough knowledge and expert-based analysis. The difficulties that  
646 the quantification of social indicators poses to the calculation may constitute a considerable  
647 weakness of the model. The FVI is a useful tool to identify the most vulnerable elements of  
648 the water resource system and safety chain components (Pro-action, prevention, preparation,  
649 response and recovery).

650  
651 Obviously such a parametric model is limited by the accuracy and availability of good  
652 datasets. A number of the indicators are very hard to quantify especially when it comes to  
653 the social indicators. On the other hand, such a model can give a simplified way of  
654 characterising what in reality is a very complex system. Such results will help to give an

655 indication of whether a system is resilient, susceptible or exposed to flooding risks and help  
656 identify which measures would reap the best return on investment under a changing climate  
657 and population and development expansion. The important point is that such a model is used  
658 as one tool among others within the whole process of deciding on a roadmap for flood  
659 assessment.

660

661

662

663

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