CM 615: Climate Change Impacts & Adaptation

Invited Lecture

Climate Impacts, Risk and Vulnerability

Lecture prepared by

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Oppenheimer et al., 2014: Emergent risks and key vulnerabilities. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1039-1099.

Impacts: (also referred to as **consequences** and **outcomes**)

The term ‘**impacts**’ is used primarily to refer to the effects on natural and human systems of extreme weather and climate events and of climate change. Impacts generally refer to effects on lives, livelihoods, health, ecosystems, economies, societies, cultures, services, and infrastructure due to the interaction of climate changes or hazardous climate events occurring within a specific time period and the vulnerability of an exposed society or system. The impacts of climate change on geophysical systems, include floods, droughts, and sea level rise.

Risk-based impact assessment

Conventional definition of **Risk**:

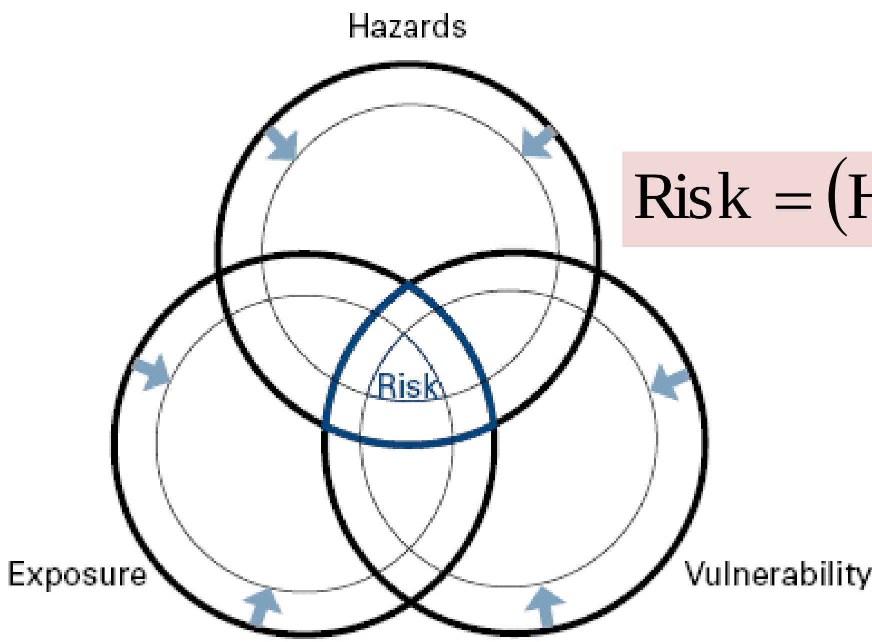
The potential for consequences where something of value is at stake and where the outcome is uncertain, recognizing the diversity of values. Risk is often represented as probability of occurrence of hazardous events or trends multiplied by the impacts if these events or trends occur.

Risk = (Probability of Events or Trends) × Consequences

However, risk results from the interaction of vulnerability, exposure, and hazard. Here the term risk is used primarily to refer to the risks of climate-change impacts.

Perception of Risk

– "Perception of Risk" by Slovic, Science, 1987, later modified by Crichton, 1999



$$\text{Risk} = (\text{Hazard}) \times (\text{Vulnerability}) \times (\text{Exposure})$$

Uncertainty

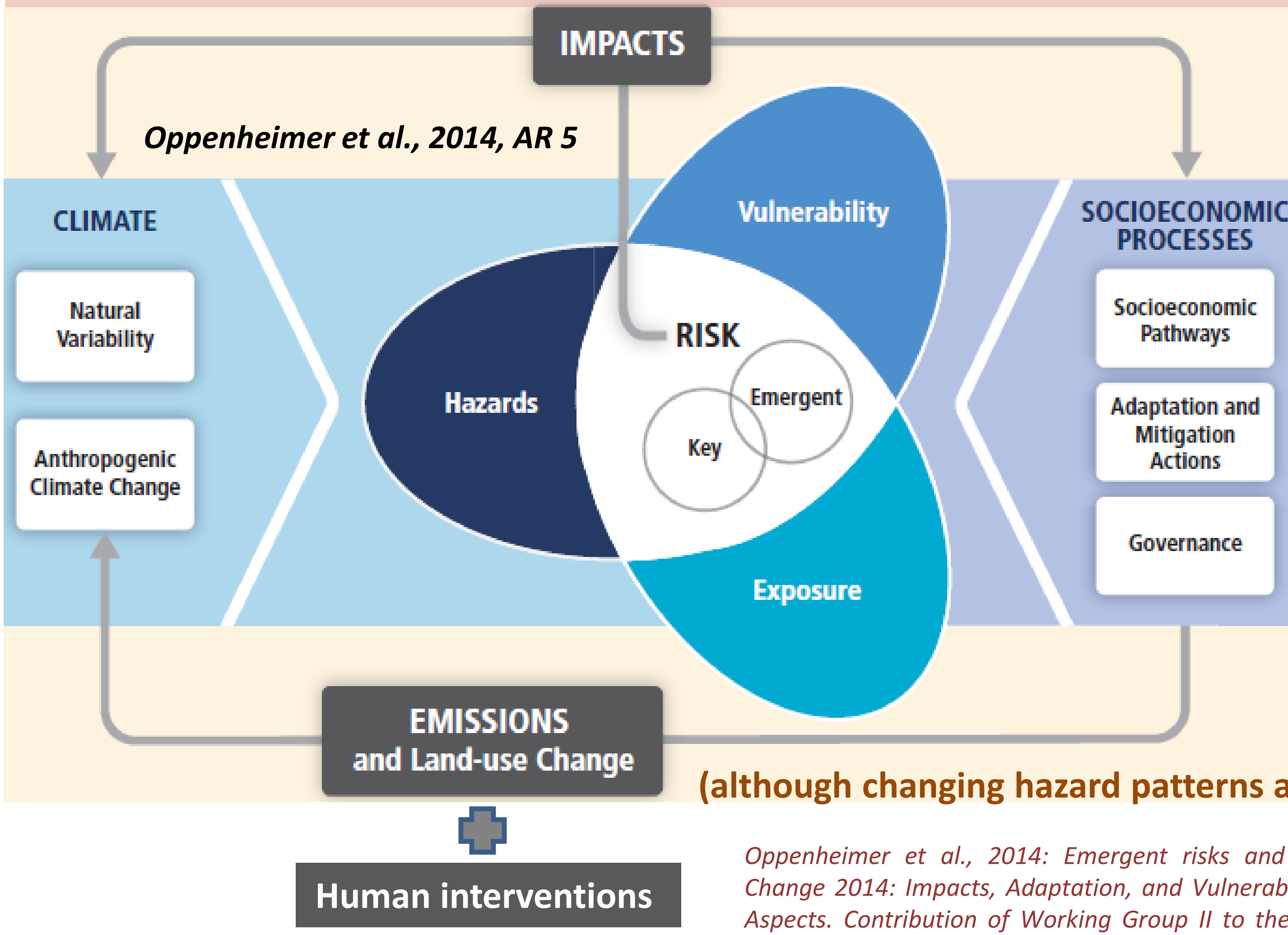
Risk adaptive / mitigative measures

(WMO/GWP, 2006)

UN 1992, Kron (2005) and Barredo et al. (2007)

Schematic of the interaction among the physical climate system, exposure, and vulnerability producing risk

Risk of climate-related impacts results from the interaction of climate-related hazards (including hazardous events and trends) with the vulnerability and exposure of human and natural systems.



Changes in both
(1) the climate system (left side)
(2) socioeconomic processes (right side) … are central drivers of the different core components (vulnerability, exposure, and hazards) that constitute risk

(although changing hazard patterns also play a role)

Oppenheimer et al., 2014: Emergent risks and key vulnerabilities. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change

Hazard

The potential occurrence of a natural or human-induced physical event or trend or physical impact that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems, and environmental resources.

Major Natural Hazards

1. Hurricanes
2. Droughts
3. Floods

Hydro-meterological
(including climatological)

4. Landslides
5. Earthquakes
6. Volcanoes
7. Tsunami

Geophysical

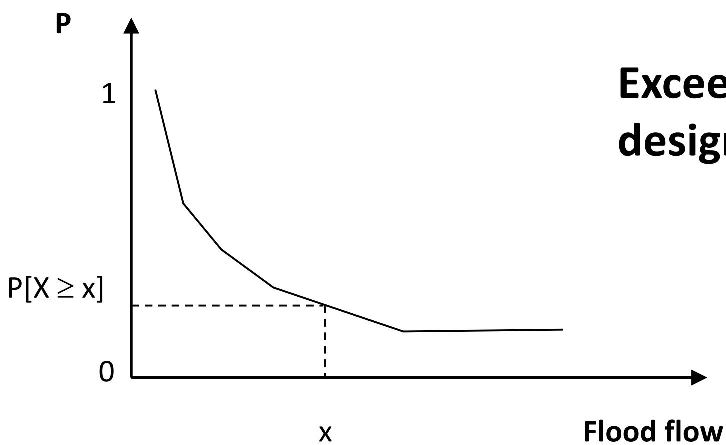
"Droughts and floods are particularly destructive, because they erode the ability of marginal groups to improve their livelihoods and economic perspectives (longer-term effects). Generally, economic costs associated with the disasters are increasing……" identified by CRED (2004)
a WHO collaborating centre - "*Thirty Years of Natural Disasters*", World Bank (2005)

Example Hazard Analysis (Apel et al. 2006, 2008)

The threat/susceptibility of a region due to the physical environment

Hazard describes the physical threat of a flood occurring

- ✓ Essential because vulnerability is negligent if it is not directly exposed to the hazard
- ✓ Hazards are represented by flood lines



Exceedance probability of a design flood x ......

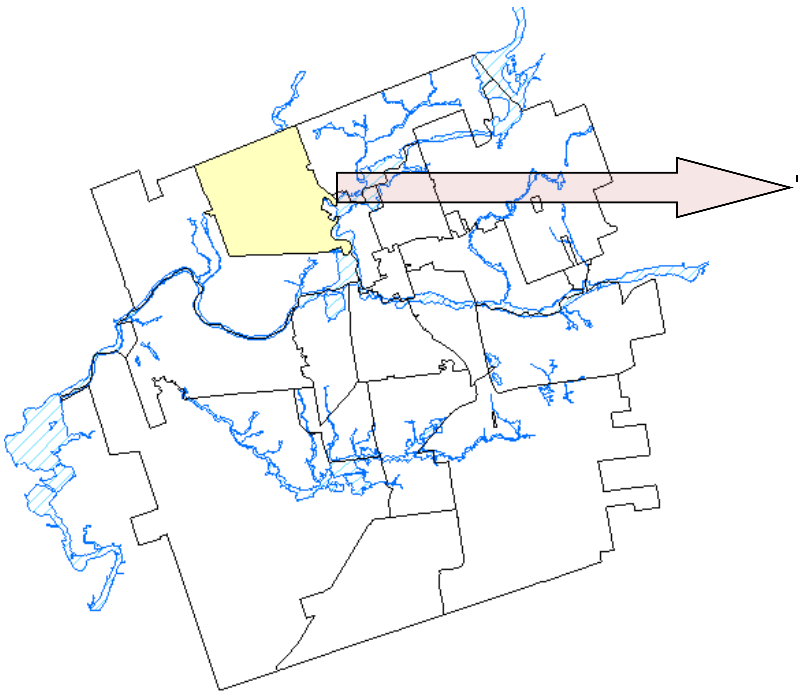
$$P[X \geq x] = 1 - F(x)$$

Return period......

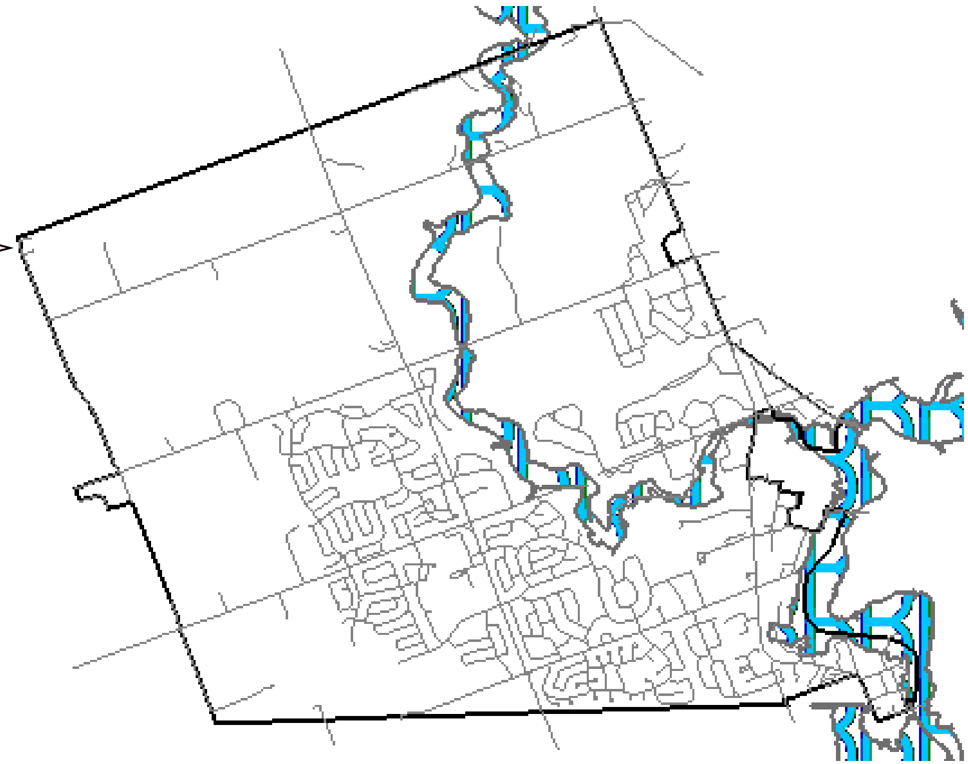
$$T_x = 1/\, P[X \geq x] = 1/[1 - F(x)]$$

A flood line of a particular return period is the line joining the extreme points in space exposed to a flood of the same return period

Example Hazard Analysis



100-yr Flood Line for an area



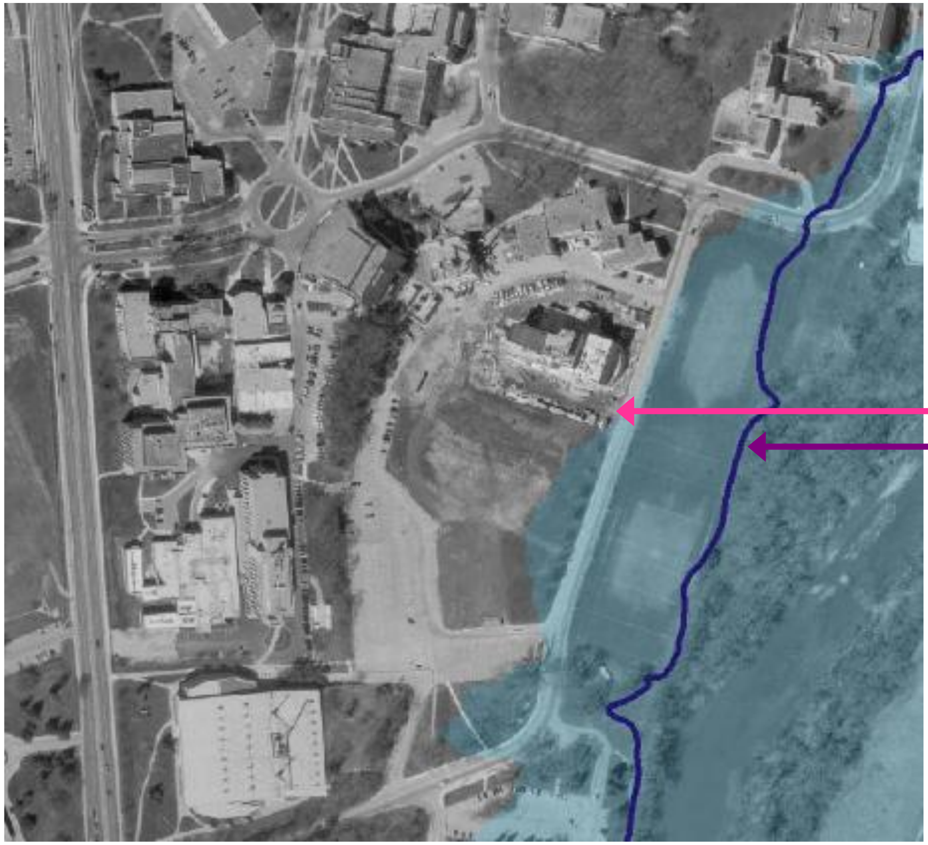
100-yr Flood Line for the shaded region

$$\text{Risk} = (\text{Hazard}) \times (\text{Vulnerability}) \times (\text{Exposure})$$

Climate change

.....Peck et al. 2008

Example Hazard Analysis (under changing climatic conditions)



Implications

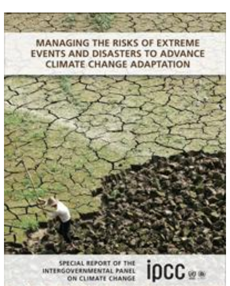
100-yrs

.....Simonovic, 2009

Climate Extreme (extreme weather or climate event): The occurrence of a value of a weather or climate variable above (or below) a threshold value near the upper (or lower) ends of the range of observed values of the variable. For simplicity, both extreme weather events and extreme climate events are referred to collectively as 'climate extremes.'

Definition of climate extremes may be : *(i)probability-based or (ii)threshold-based*

(i) Probability-based: Typical indices that are seen in the scientific literature include the number, percentage, or fraction of days with maximum temperature (Tmax) or minimum temperature (Tmin), below the 1st, 5th, or 10th percentile, or above the 90th, 95th, or 99th percentile, generally defined for given time frames (days, month, season, annual) with respect to the 1961-1990 reference time period.



IPCC, 2012: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK, and New York, NY, USA, 582 pp. [IPCC SREX 2012]

Climate Extreme (extreme weather or climate event):

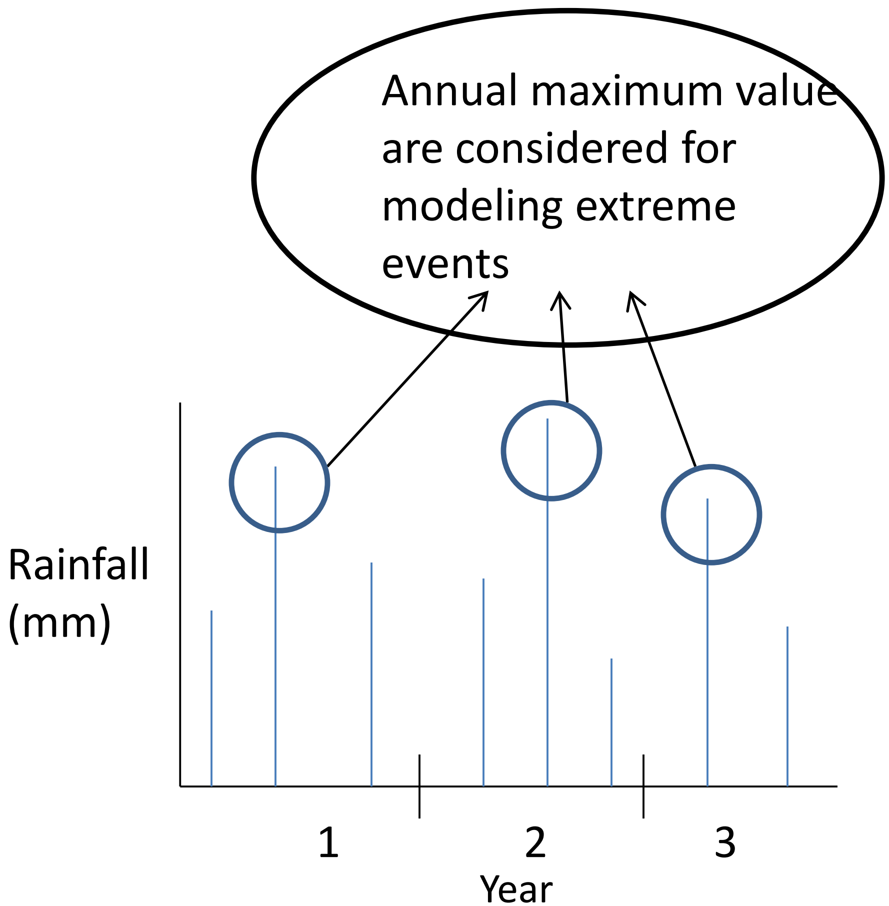
Threshold-based: Two different approaches can be used to estimate the parameters for such probability distributions. In the block maximum approach, the probability distribution parameters are estimated for maximum values of consecutive blocks of a time series (e.g., years). In the second approach, instead of the block maxima the estimation is based on events that exceed a high threshold (peaks over threshold approach). Both approaches are used in climate research.

Limitations in the definition of both probability-based or threshold-based climate extremes and their relations to impacts:

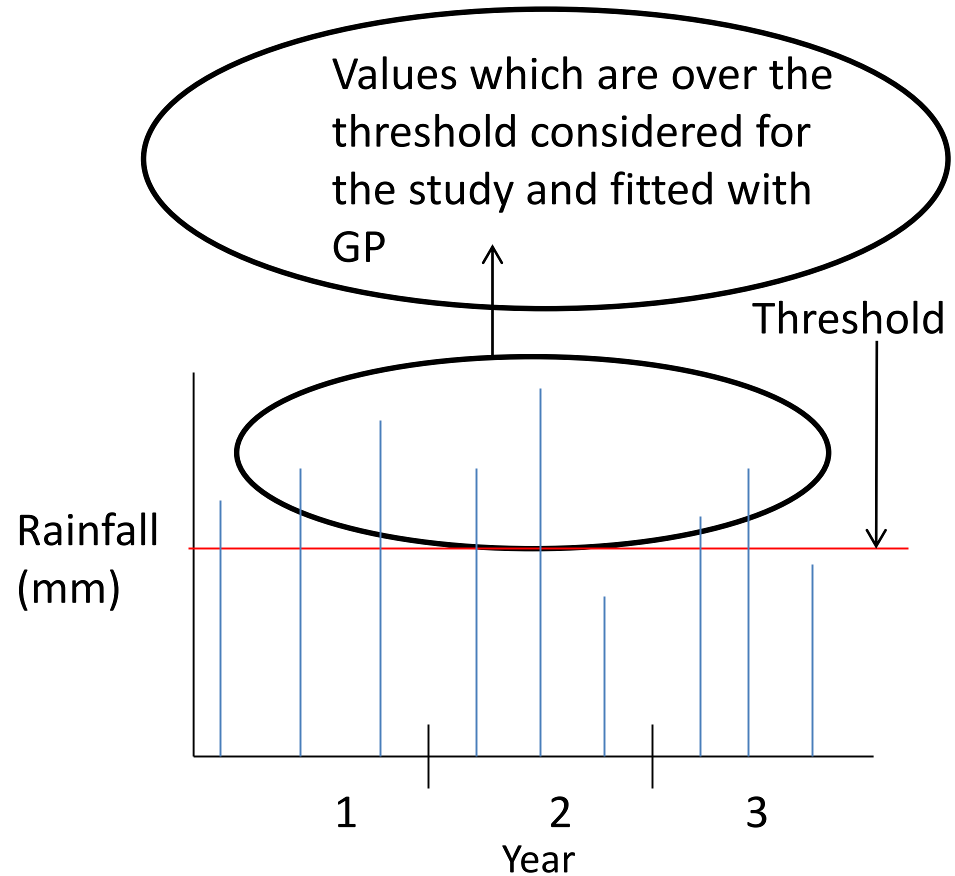
• An event from the extreme tails of probability distributions is not necessarily extreme in terms of impact.

• Impact-related thresholds can vary in space and time, that is, single absolute thresholds (e.g., a daily rainfall exceeding 25 mm or the number of frost days) will not reflect extremes in all locations and time periods (e.g., season, decade).

Climate Extreme (extreme weather or climate event):



(1) Block (Annual) maxima approach



(2) Peak over threshold approach

Vulnerability: The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt. General definitions of vulnerability used in risk assessment due to natural hazards and climate change:

Working definitions(s): Vulnerability is...	Source
The degree of loss to a given element at risk or a set of elements at risk resulting from the occurrence of a natural phenomenon of a given magnitude and expressed on a scale from 0 (no damage) to 1 (total damage)	[1]
The conditions determined by physical, social, economic, and environmental factors or processes, which increase the susceptibility of a community to the impact of hazards	[2]
The characteristics of a person or group in terms of their capacity to anticipate, cope with, resist and recover from impacts of a hazard	[3]
The intrinsic and dynamic feature of an element at risk that determines the expected damage/ harm resulting from a given hazardous event and is often even affected by the harmful event itself. Vulnerability changes continuously over time and is driven by physical, social, economic and environmental factors	[4]
The degree to which geophysical, biological and socio-economic systems are susceptible to, and unable to cope with, adverse impacts of climate change	[5, 6]

Vulnerability: General definitions of vulnerability used in risk assessment due to natural hazards and climate change (contd.)

[1] UNDRO. Natural disasters and vulnerability analysis: report of Expert Group Meeting. Geneva: Office of the United Nations Disaster Relief Co-ordinator; (1979). http:// www23.us.archive.org/details/naturaldisasters00offiaccessed 25 August 2012).

[2] UNISDR. Living with Risk. A global review of disaster reduction initiatives: United Nations; (2004). http://www.unisdr.org/files/657_lwr21.pdfaccessed 20 August 2012).

[3] Blaikie, P. At risk : natural hazards, people's vulnerability, and disasters. London; New York: Routledge; (1994).

[4] Birkmann, J. Indicators and criteria for measuring vulnerability: theoretical basis and requirements. In: Birkmann J, (ed.). Measuring vulnerability to natural hazards towards disaster resilient societies. Tokyo: United Nations University; (2006). , 55-77.

[5] Schneider, S. H, Semenov, S, Patwardhan, A, & Burton, I. Magadza CHD, Oppenheimer M, et al. Assessing key vulnerabilities and the risk from climate change. Climate Change (2007). Impacts, Adaptation and Vulnerability. Approaches to Disaster Management - Examining the Implications of Hazards, Emergencies and Disasters Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. In: Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE, (eds.). Cambridge, UK; 2007. , 779-810.

[6] Füssel, H-M, & Klein, R. T. Climate Change Vulnerability Assessments: An Evolution of Conceptual Thinking. Climatic Change (2006). , 75(3), 301-329.

Vulnerability *(contd.)*

- *"…. refers to a condition of the vulnerable: it is their weakness, their exposure, their defenselessness or their instability''*

  *[*Campbell JR (1997) Human dimensions of global change: a New Zealand perspective. Paper Presented at APN/SASCOM/GCTE Workshop on Living with Global Change: The Human Dimensions of Global Change in Asia and the Pacific, National Physical Laboratory, New Delhi, 20–23 Jan 1997*]*

- *''Vulnerability here refers to exposure to contingencies and stress, and difficulty in coping with them. Vulnerability has two sides: an external side of risks, shocks, and stress to which an individual or household is subject; and an internal side which is defenselessness, meaning a lack of means to cope without damaging loss''.*

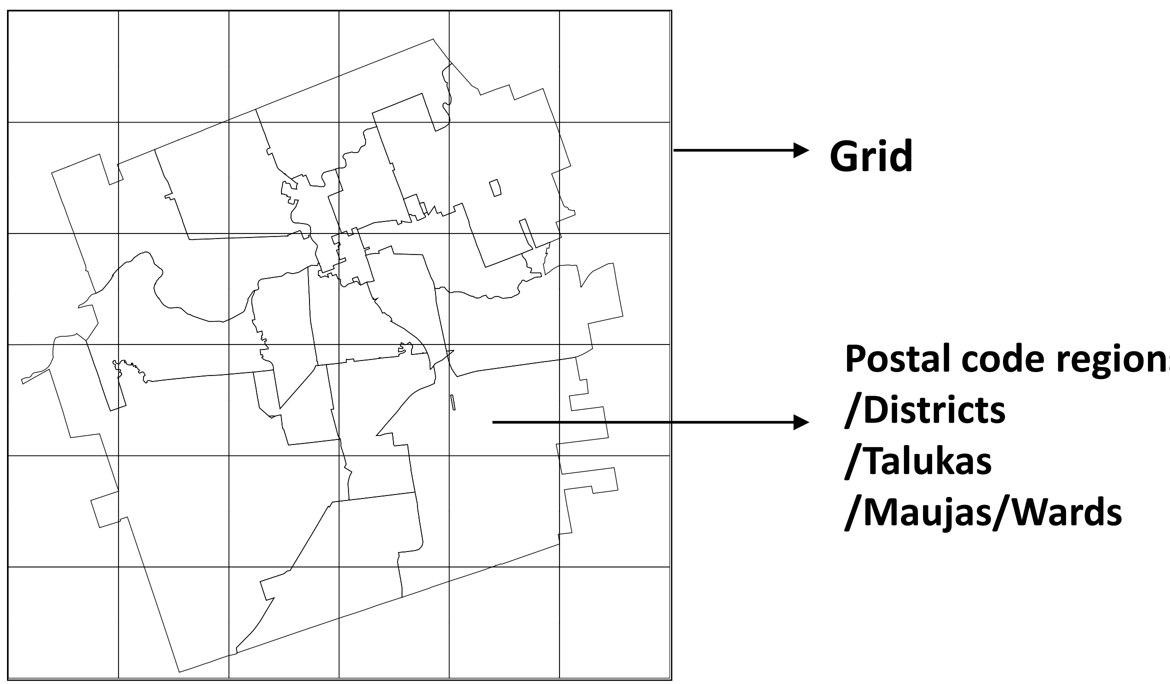
  [Chambers R (1989) Editorial introduction: vulnerability, coping and policy, IDS Bulletin, Vol. 20, No. 2, Institute of Development Studies, Sussex]

Vulnerability *is defined as measure of a region's susceptibility to damage in natural hazards.*

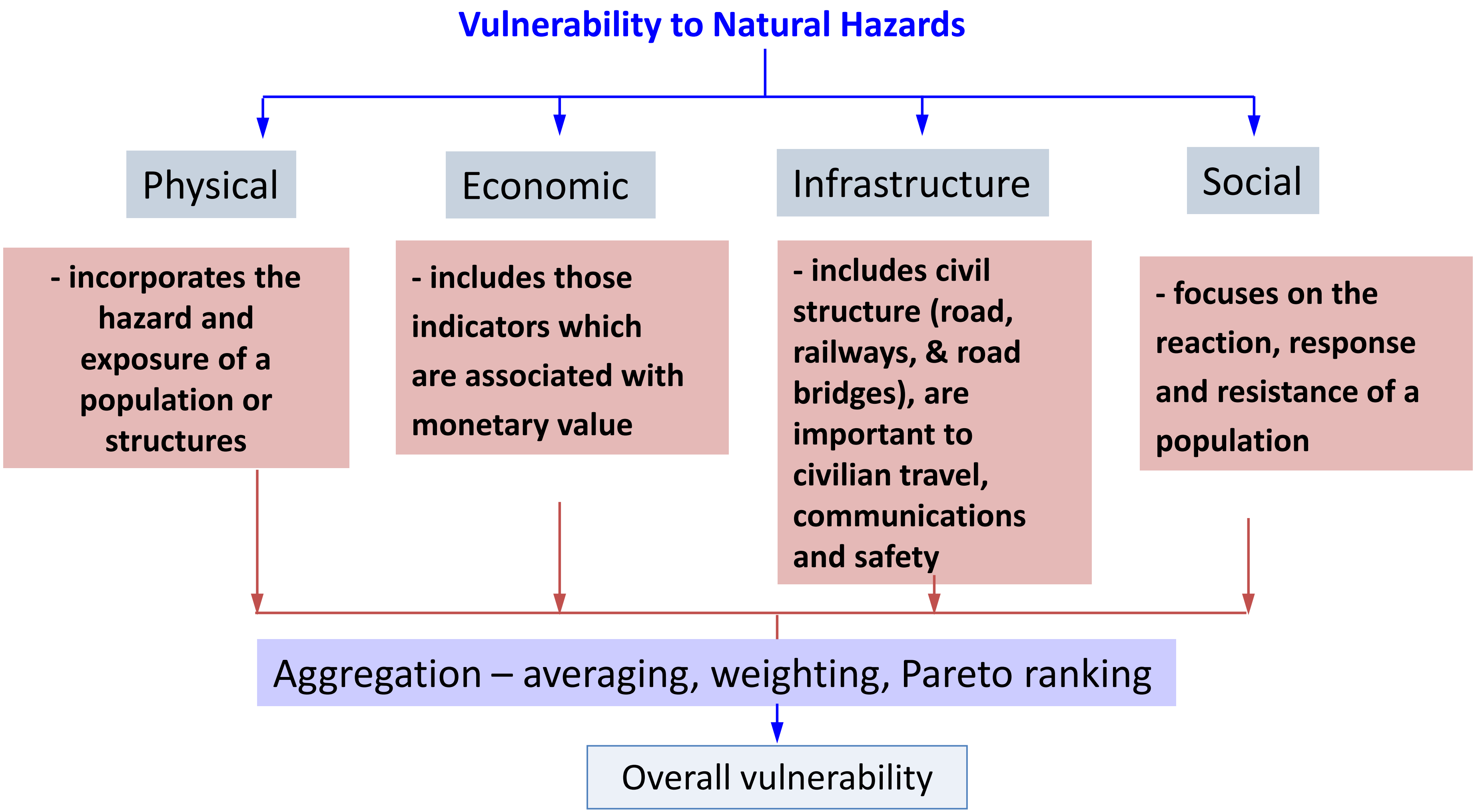
It also includes population susceptibility to physical, mental or emotional damage.

…. Pls Note: Although the number of overall deaths caused by natural disasters is decreasing, the number of those affected in terms of disruptions to daily life, loss of livelihoods, and deepening poverty continues to increase [The Organisation for Economic Co-operation and Development (OECD)]

A typical region for vulnerability analysis



Classifying Vulnerability



A list of Vulnerability indicators

Categories of vulnerability	*Indicators*	*Source*[1]
Economic	Gross Domestic Product per inhabitant at purchasing power parity	WB
	Human Poverty Index (HPI)	
	Total debt service (% of the exports of goods and services),	UNDP
	Inflation, food prices (annual %),	WB
	Unemployment, total (% of total labor force)	ILO
Type of economical activities	Percentage of arable land	FAO
	Percentage of urban population	UNPOP
	Percentage of agriculture's dependency for GDP	WB
	Percentage of labor force in agricultural sector	FAO
Dependency and quality of the environment.	Forests and woodland (in percentage of land area),	FAO
	Percentage of irrigated land	
	Human Induced Soil Degradation (GLASOD)	FAO
		UNEP
Demography	Population growth,	UNPOP
	Urban growth,	GRID[2]
	Population density,	GRID[3]
	Age dependency ratio,	WB

Agricultural vulnerability

Population under 6 years of age Population 60+ years Female population

[1] FAOSTAT (Food and Agriculture Organisation, FAO) / GRID: UNEP/Global Resource Information Database / WB: World Development Indicators (World Bank) / UNDP: Human Development Report (UNDP) / ILO: International Labour Office / UNPOP: UN Dep. Of Economic and Social Affairs/Population Division. Most of the data were reprocessed by the UNEP Global Environment Outlook team. Figures are available at the GEO Data Portal (UNEP), http://geodata.grid.unep.ch, CRED: Université Catholique de Louvain (as of 2002), EM-DAT: The OFDA/CRED International Disaster Database, http://www.cred.be/

(Contd.)

Vulnerability indicators (contd.)

Categories of vulnerability	*Indicators*	*Source*[1]
Health and sanitation	Average calorie supply per capita,	FAO
	Percentage of people with access to adequate sanitation,	WHO/ UNICEF
	Percentage of people with access to safe water (total, urban, rural)	WHO/ UNICEF
	Number of physicians (per 1,000 inh.),	
	Number hospital beds	WB
	Life expectancy at birth for both sexes	WB
	Under five years old mortality rate	UNPOP
		UNPOP
Politic	Index of Corruption	WB
Early warning capacity	Number of Radios (per 1,000 inh.)	WB
Education	Illiteracy Rate,	WB
	School enrolment,	UNESCO
	Secondary (% gross),	UNESCO
	Labor force with primary, secondary or tertiary education	WB
Development	Human Development Index (HDI)	UNDP

<u>Critical facilities</u>:
Number of hospitals
Fire stations
Blood bank

<u>Critical facilities</u>:
Schools

[1] FAOSTAT (Food and Agriculture Organisation, FAO) / GRID: UNEP/Global Resource Information Database / WB: World Development Indicators (World Bank) / UNDP: Human Development Report (UNDP) / ILO: International Labour Office / UNPOP: UN Dep. Of Economic and Social Affairs/Population Division. Most of the data were reprocessed by the UNEP Global Environment Outlook team. Figures are available at the GEO Data Portal (UNEP), http://geodata.grid.unep.ch, CRED: Université Catholique de Louvain (as of 2002), EM-DAT: The OFDA/CRED International Disaster Database, http://www.cred.be/

Example: Vulnerability Index

The vulnerability index (VI_i) corresponding to each indicator for i^{th} FSA is calculated using the following equation, which standardizes each vulnerability index value ranging from 0.0 to 1.0:

$$VI_i = (V_i / V^{\max})$$

$$VI_i = \frac{V_i - V^{\min}}{V^{\max} - V^{\min}}$$

.... More logical

... ensures values within [0, 1]; always non-negative and includes minimum value

Vulnerability to Climate Change

In the context of climate change, vulnerability may be expressed as the combination of three components: (a) Adaptive Capacity, (b) Sensitivity and (c) Exposure *[Oppenheimer, 2014, AR5]*

Adaptive capacity: represents the potential to implement adaptation measures that help avert potential impacts

Sensitivity: describes the human-environmental conditions that can worsen or ameliorate the hazard, and/or trigger an impact

Exposure: can be interpreted as the direct danger (that is the stressor*), and the nature and extent of change to a regions climate variables (for example, temperature, precipitation and extreme weather events)

**Stressors: Events and trends, that have an important effect on the system exposed and can increase vulnerability to climate-related risk. [Oppenheimer, 2014, AR5]*

Vulnerability to Climate Change (contd.)

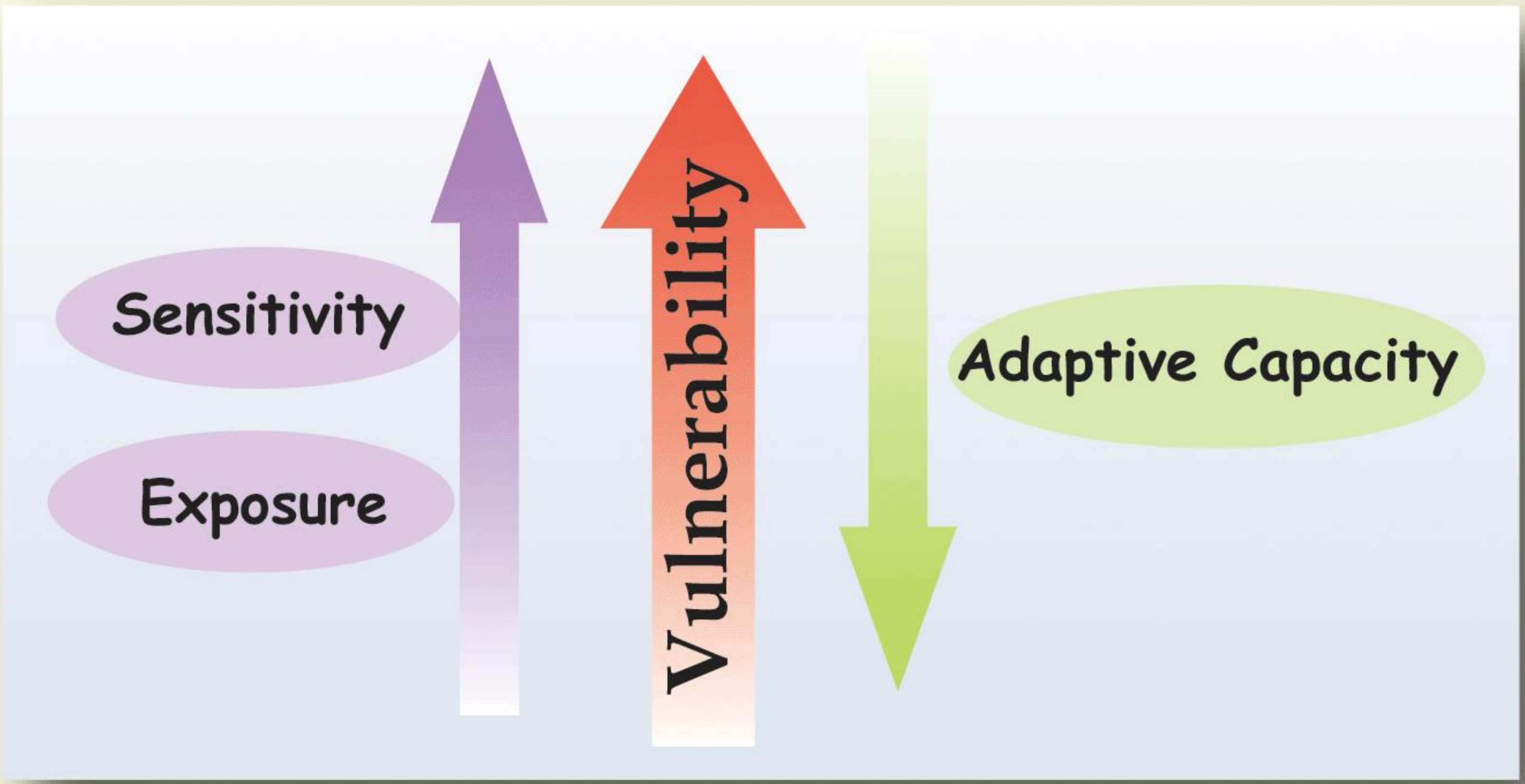
Example indicators: for the three components: (a) Adaptive Capacity, (b) Sensitivity and (c) Exposure

Climate change effect indicators in Livelihood Vulnerability Index

Indicators	Dimensions	Sub-dimensions
Adaptive Capacity	Socio-demographic profile	Dependency ratio
		Percentage of female headed household
	Livelihood strategies	Percentage of household with orphans
		Percent of households dependent solely on agriculture as income source
	Social network	Percent of households dependent solely on agriculture as income source
		Average agricultural Livelihood Diversification Index
Sensitivity	Health	Average time to nearest health centre
		Percent of households with family member with chronic illness
	Food	Percent of households dependent solely on family farm for food
		Percentage of households struggle to find food to support whole year
	Water	Percentage of households reported to have water availability problem
		Percent of households that utilize a natural water source
Exposure	Natural disaster and Climate variability	Percentage of households reporting injury or death of a family member due to climate related disaster
		Percentage of households reported their natural resource base reduced

Khajuria and Ravindranath (2012)

Climate Vulnerability is determined by three factors



- First two components (Exposure+Sensitivity) together represent the <u>**Potential Impact**</u>
- The <u>**Adaptive Capacity**</u> is the extent to which <u>these impacts</u> can be averted
- Thus, <u>**Vulnerability (V)**</u> = Potential Impact (PI) – Adaptive Capacity (AC)

V = f (PI –AC)

.... IPCC vulnerability framework

Vulnerability

'The degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes'

+ −

Potential Impacts PI

'All impacts that may occur given a projected change in climate, without considering adaptation'

Adaptive Capacity AC

'The ability of a system to adjust to climate change (including climate variability and extremes) to moderate potential damages, to take advantage of opportunities, or to cope with the consequences'

+ +

Exposure E

'The nature and degree to which a system is exposed to significant climatic variations'

Sensitivity S

'The degree to which a system is affected, either adversely or beneficially, by climate-related stimuli. The effect may be direct (e.g. a change in crop yield in response to a change in the mean, range or variability of temperature) or indirect (e.g. damages caused by an increase in the frequency of coastal flooding due to sea level rise'

The signs under the arrows mean that ***high*** exposure, ***high*** sensitivity and ***low*** adaptive capacity induce ***high*** vulnerability.

McCarthy, J.J., Canziani, O.F., Leary, N.A., Dokken, D.J. and White, K.S. (eds.) 2001 Climate change 2001: impacts, adaptation and vulnerability. Cambridge University Press, Cambridge, UK.

- Vulnerability is a function of exposure, sensitivity and adaptive capacity
- Potential impacts are a function of just exposure and sensitivity
- Vulnerability is a function of potential impacts and adaptive capacity

$$V(es, x, s, t) = f(\ E(es, x, s, t), S(es, x, s, t), AC(es, x, s, t)\ )$$

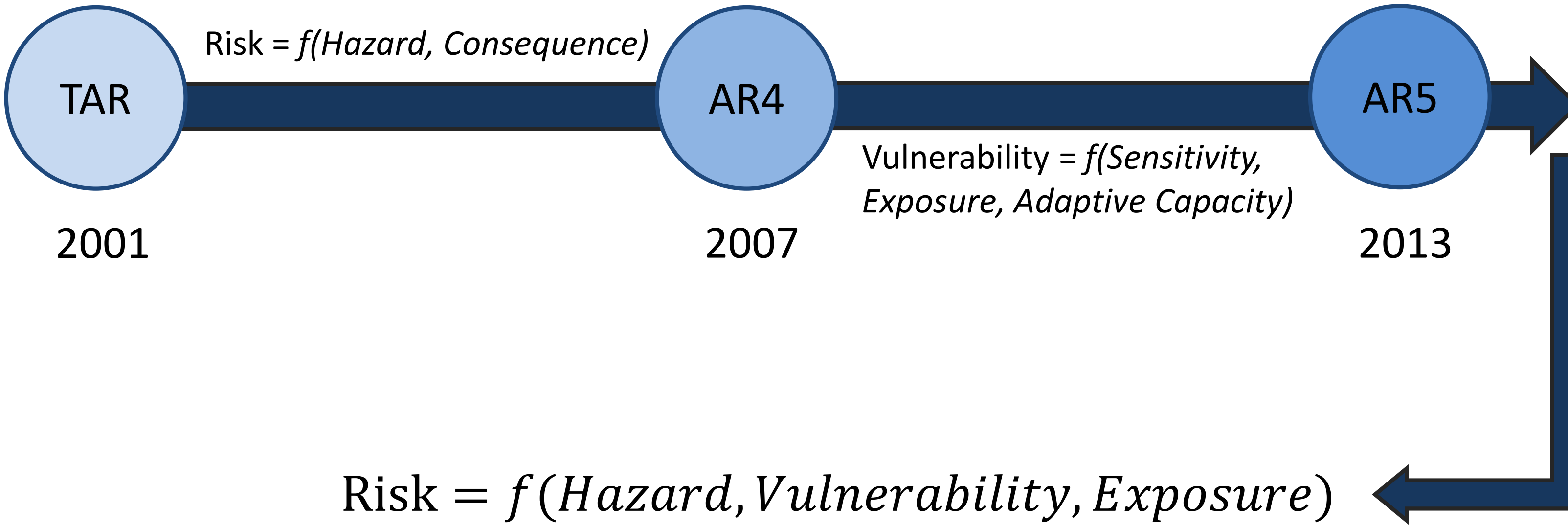
$$PI(es, x, s, t) = f(\ E(es, x, s, t), S(es, x, s, t)\ )$$

$$V(es, x, s, t) = f(\ PI(es, x, s, t), AC(es, x, s, t)\ )$$

where V = vulnerability, E = exposure, S = sensitivity, AC = adaptive capacity and PI = potential impact, es = ecosystem service, x = a grid cell, s = a scenario, t = a time slice

(ecosystem services are "the benefits people obtain from ecosystems")

Intergovernmental Panel on Climate Change (IPCC)



$$\text{Risk} = f(Hazard, Vulnerability, Exposure)$$

Examples of <u>climate change vulnerability assessment models</u> used in the literature where sub-indices for exposure (E), sensitivity (S), and adaptive capacity (AC) are first calculated prior to combining these sub-indices into an overall vulnerability score:

Model #	Equation	References
M1	$V=E + S + AC$	(Borden et al. 2007; Perch-Nielsen 2010; Corobov et al. 2013)
M2	$V=E + S - AC$	(Antwi-Agyei et al. 2012; Cinner et al. 2012; Silva and Lucio 2014)
M3	$V=E \times S \times AC$	(Ferrier and Haque 2003)
M4	$V=E \times S \div AC$	(Cinner et al. 2012; Balica et al. 2009)
M5	$V=(E - AC) \times S$	(Hahn et al. 2009; Shah et al. 2013)

V vulnerability score or ranking, *E* exposure score or ranking, *S* sensitivity score or ranking, *AC* adaptive capacity score or ranking

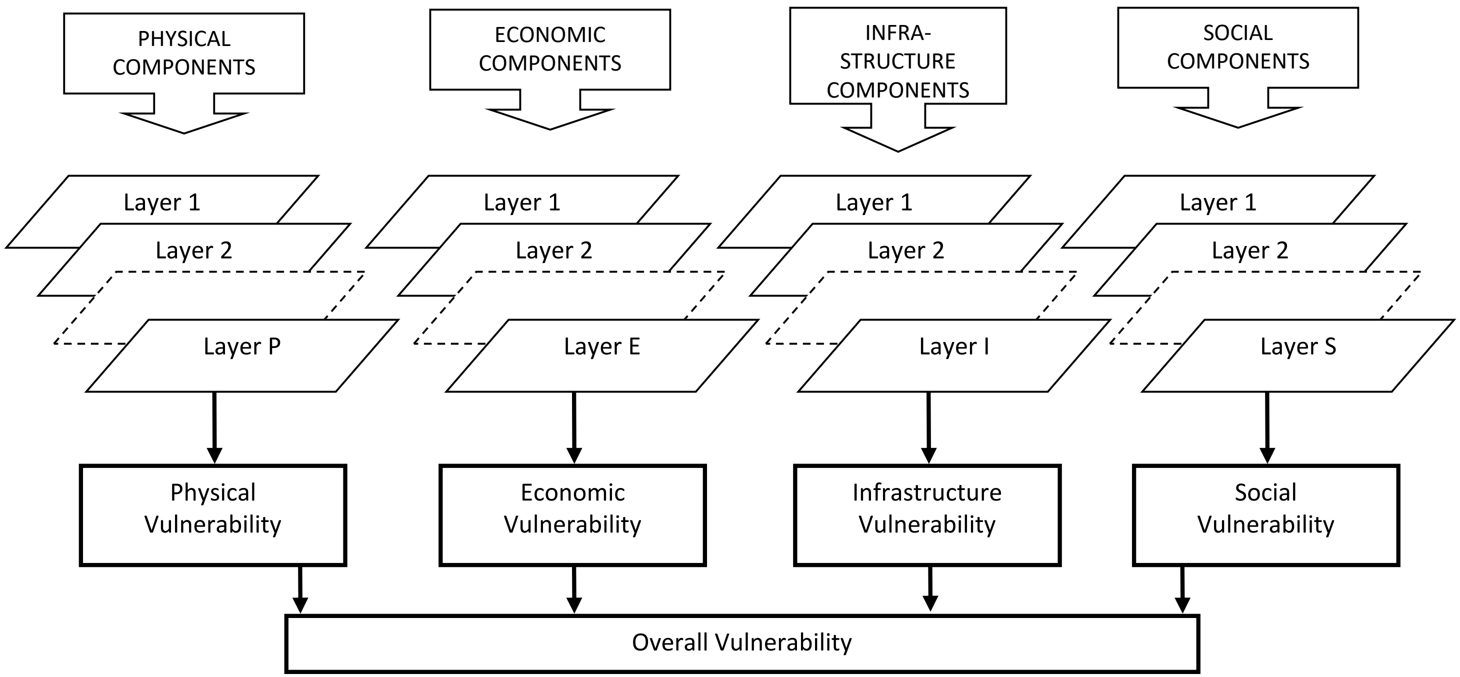
Luh et al. 2015

Vulnerability Index (VI) =

$$a + \frac{(X - X_{\min}) \times (b - a)}{(X_{max} - X_{\min})}$$

where *X* is the total number of an indicator value for a specific unit area, X_{min} is the minimum number of all units, X_{max} is the maximum number of all units, and *a* and *b* define the range within which all *VI* values fall (may be 0.1 and 1, respectively).

Process for deriving overall vulnerability using GIS



…. The concepts are applicable to any climate hazards (natural or human-induced)

Vulnerability to Climate Change

During the last decades, various schools of thinking proposed different conceptual models with the final aim of developing methods for measuring vulnerability.

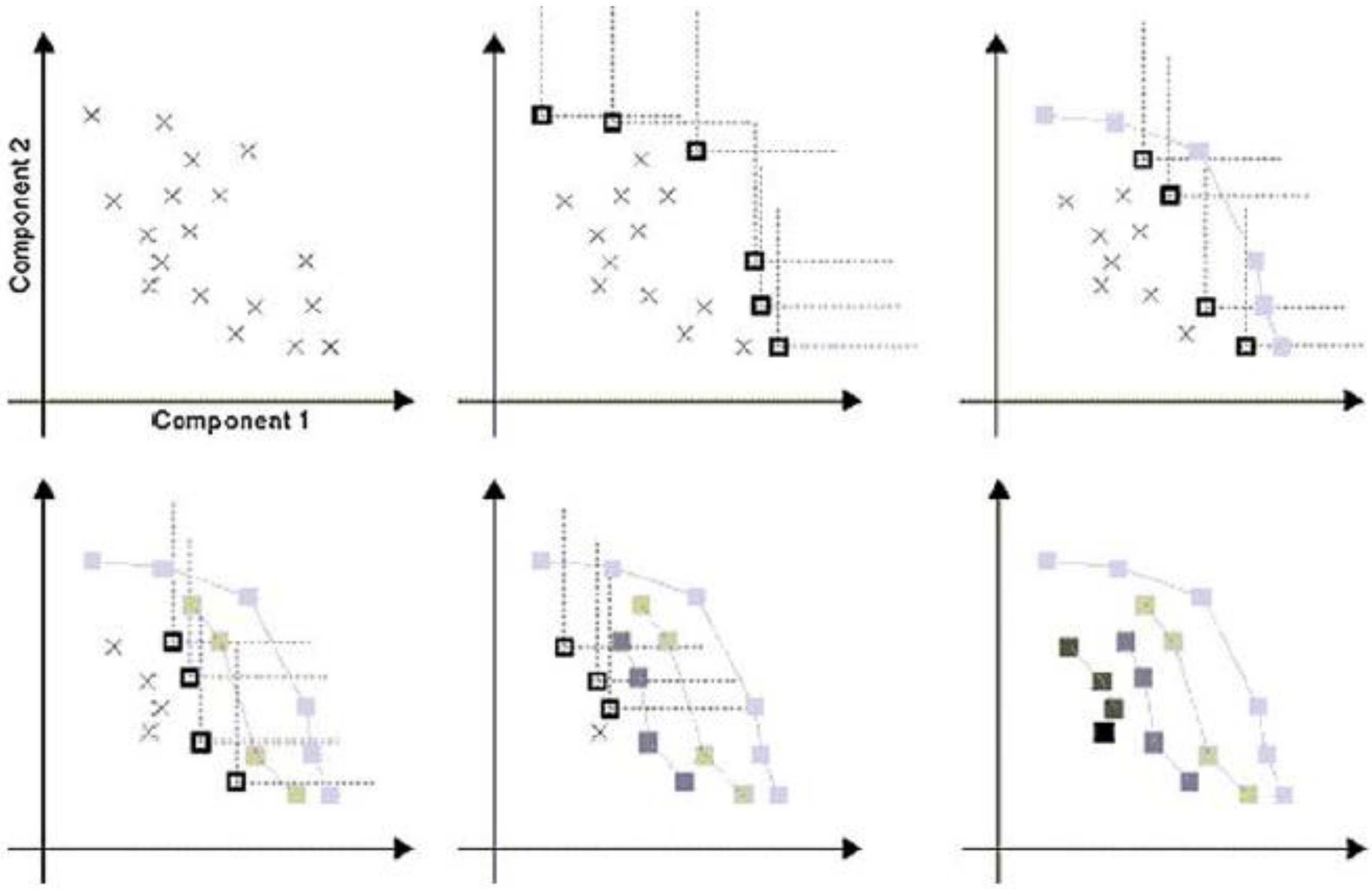
- The double structure of vulnerability
- Vulnerability within the context of hazard and risk
- Vulnerability in the context of global environmental change community
- Presure and Release Model
- Holistic approach to risk and vulnerability assessment

Aggregation methods

An overall vulnerability index requires a method of aggregation to aggregate indicators of vulnerability.

- Averaging
- Weighting
- Ranking
- Scoring
- Analytic Hierarchy Process (AHP) and Fuzzy AHP
- Pareto Ranking
- Data Envelopment Analysis (DEA)

Aggregation methods: Pareto Ranking Process (Rygel, 2006)



The Pareto ranking process (Rygel, 2006)

Aggregation methods: Analytic Hierarchy Process

- The Analytic Hierarchy Process (AHP) was proposed by Prof. T. L. Saaty (1977).

- The basis of this technique is that humans are more capable of making relative judgments than absolute judgments.

- The basic idea of the approach is to convert subjective assessments of relative importance to a set of overall scores or weights.

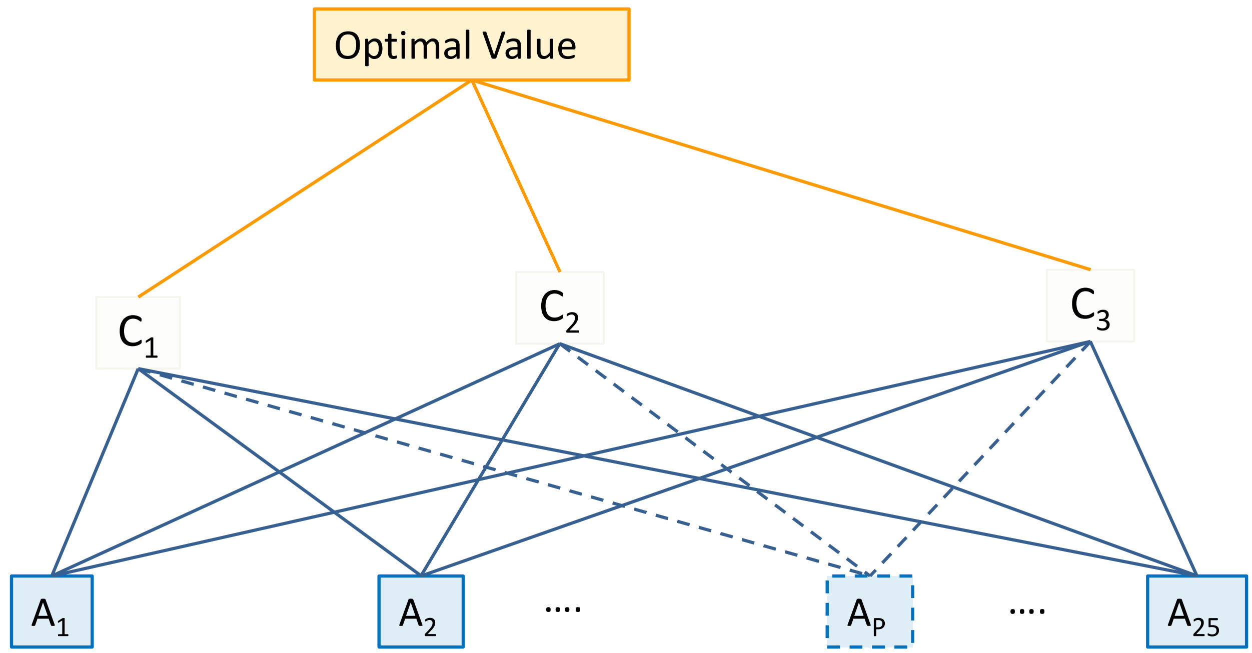
- Most widely used method (Zahedi 1986)

Aggregation methods: Analytic Hierarchy Process (contd.)

Level 1
Focus….

Level 2
Criteria / Attributes….

Level 3
Units/Alternatives….

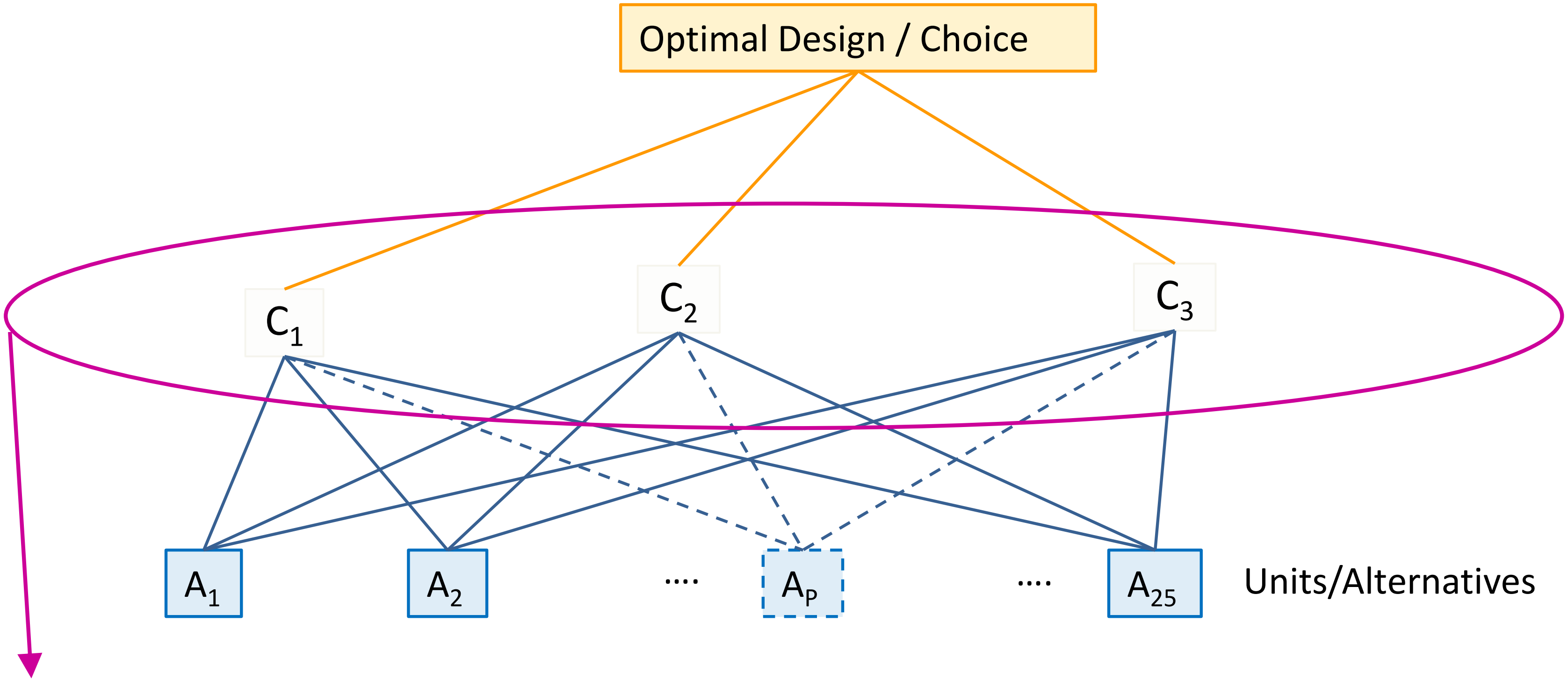


- <u>Pairwise Comparisons of Attributes</u>
- <u>Pairwise Comparisons of Units/Alternatives</u>

Aggregation methods: Analytic Hierarchy Process (contd.)

Step 1: Pairwise Comparison or Factor Evaluation of Attributes

In order to help a DM, Saaty (1980) created a 9-point intensity scale of importance between two criteria / attributes



$(C_1 : C_2) = (2:1)$ … i.e., C_1 is more important

$(C_1 : C_3) = (7:1)$

$(C_2 : C_3) = (3:1)$

Consistency ??

Aggregation methods: Analytic Hierarchy Process (contd.)

Step 1: Pairwise Comparison or Factor Evaluation of Attributes

Nine-point Intensity Scale (Saaty 1980)

If $a_{ij} = W_A/W_B = \alpha$

Then $a_{ji} = 1/\alpha$

$\alpha \neq 0$

Preference Level **[if A is …. as (than) B]**	**Intensity Scale**
Equally preferred	1
Equally to moderately preferred	2
Moderately preferred	3
Moderately to strongly preferred	4
Strongly preferred	5
Strongly to very strongly preferred	6
Very strongly preferred	7
Very strongly to extremely preferred	8
Extremely preferred	9

Intermediates (2, 4, 6, 8) can be used to represent compromises between preferences (Saaty 1980)

Aggregation methods: Analytic Hierarchy Process (contd.)

Step 1: Pairwise Comparison or Factor Evaluation of Attributes

DM1	C1	C2	C3
C1	1.00	2.00	7.00
C2	0.50	1.00	3.00
C3	0.14	0.33	1.00

DM2	C1	C2	C3
C1	1.00	5.00	4.00
C2	0.20	1.00	1.00
C3	0.25	1.00	1.00

(C_1 Equally to moderately preferred than C_2) ..
In Saaty's scale this ratio is (2:1)

DM3	C1	C2	C3
C1	1.00	5.00	7.00
C2	0.20	1.00	2.00
C3	0.14	0.50	1.00

DM4	C1	C2	C3
C1	1.00	7.00	5.00
C2	0.14	1.00	2.00
C3	0.20	0.50	1.00

Consistency test: when the judgments are based on DM's choice

Aggregation methods: Analytic Hierarchy Process (contd.)

Step 2: Consistency Test for Pairwise Comparison Matrices

….. [Steps given in Islam and Abdullah (2006)]

DM1	C1	C2	C3	Geomean	Priority
C1	1.00	2.00	7.00	2.41	0.62
C2	0.50	1.00	3.00	1.14	0.29
C3	0.14	0.33	1.00	0.36	0.09
Total				3.92	

$$\prod_{j=1}^{n} a_{ij}^{1/n}$$

(3×3)

(3×1)

Matrix Multiplication

Weighted Sum Vector	Consistency Vector
1.85	3.00
0.88	3.00
0.28	3.00

W.S.V / Priority

Arithmetic average gives the maximum eigenvalue (principal eigenvalue), λ_{max} = 3.00

Aggregation methods: Analytic Hierarchy Process (contd.)

Step 2: Consistency Test for Pairwise Comparison Matrices

- Following Saaty (1977) - a pairwise comparison matrix (reciprocal matrix) with positive entries is consistent iff λ_{max} = n (n is the number of attributes being compared).

- The deviation from consistency termed as Consistency Index (CI)

$$= [(\lambda_{max} - n)/(n-1)]$$

λ_{max}	3.00
n	3
CI	0.0013

- Similarly Avg. Random Index (ARI) is generated from randomly generated reciprocal matrix from the scale 1 to 9

  At ORNL, scientists generated an average RI for matrices of order 1 – 15 using a sample size of 100 (Saaty 1990)

Aggregation methods: Analytic Hierarchy Process (contd.)

Step 2: Consistency Test for Pairwise Comparison Matrices

n	ARI
1	0
2	0
3	0.58
4	0.9
5	1.12
6	1.24
7	1.32
8	1.41
9	1.45
10	1.49
11	1.51
12	1.48
13	1.56
14	1.57
15	1.59
20	1.63
25	1.65

(Saaty 1990)

(Stein and Mizzi 2007)

Consistency Ratio (CR) = $\left.\dfrac{CI}{ARI}\right|_n$

CR ≤ 0.10 acceptable (Saaty 1990)

Aggregation methods: Analytic Hierarchy Process (contd.)

Step 2: Consistency Test for Pairwise Comparison Matrices

DM2	Geomean	Priority	Wt. Sum Vec.	Consist. Vec.	Lambda	3.01
C1	2.71	0.69	2.08	3.01	CI	0.0028
C2	0.58	0.15	0.45	3.01	CR	0.0048
C3	0.63	0.16	0.48	3.01		
Total	3.93					

DM3	Geomean	Priority	Wt. Sum Vec.	Consist. Vec.	Lambda	3.01
C1	3.27	0.74	2.23	3.01	CI	0.0071
C2	0.74	0.17	0.50	3.01	CR	0.0122
C3	0.41	0.09	0.28	3.01		
Total	4.42					

DM4	Geomean	Priority	Wt. Sum Vec.	Consist. Vec.	Lambda	3.12
C1	3.27	0.74	2.32	3.12	CI	0.0595
C2	0.66	0.15	0.47	3.12	CR	0.1025
C3	0.46	0.11	0.33	3.12		
Total	4.39					

Aggregation methods: Analytic Hierarchy Process (contd.)

Step 2: Consistency Test for Pairwise Comparison Matrices

(Aczel and Satty 1983, Forman and Peniwati 1998, Moreno-Jimenez 2002)

DM 1-4	C1	C1	C1	GM	Priority	Wt. Sum Vec.	Consist. Vec.	λ	3.01
C1	1.00	4.33	5.60	2.89	0.70	2.12	3.01	CI	0.0074
C2	0.23	1.00	1.86	0.75	0.18	0.55	3.01	CR	0.0127
C3	0.18	0.54	1.00	0.46	0.11	0.34	3.01		
Total				4.11					

Geometric Mean of DM 1 to 4

Aggregated Priority of Attributes

CR ≤ 0.10

Aggregation methods: Analytic Hierarchy Process (contd.)

Step 3: Pairwise Comparisons of Alternatives /Units

C1	A1	A2	...	...	A25
A1	1.00	2.00	...	...	5.00
A2	0.50	1.00	...	...	4.00
...	...	...	...	...	...
...	...	...	...	...	...
A25	0.20	0.25	...	...	1.00

w.r.t. C_1

C2	A1	A2	...	...	A25
A1	1.00	2.00	...	...	5.00
A2	0.50	1.00	...	...	4.00
...	...	...	...	...	...
...	...	...	...	...	...
A25	0.20	0.25	...	...	1.00

w.r.t. C_2

C3	A1	A2	...	...	A25
A1	1.00	2.00	...	...	5.00
A2	0.50	1.00	...	...	4.00
...	...	...	...	...	...
...	...	...	...	...	...
A25	0.20	0.25	...	...	1.00

w.r.t. C_3

The pairwise comparison matrices may be derived numerically..

Aggregation methods: Analytic Hierarchy Process (contd.)

Step 3: Pairwise Comparisons of Alternatives / Units

C1	A1	A2	...	...	A25
A1	1.00	2.00	...	...	5.00
A2	0.50	1.00	...	...	4.00
...	...	...	...	...	...
...	...	...	...	...	...
A25	0.20	0.25	...	...	1.00

w.r.t. C_1

C2	A1	A2	...	...	A25
A1	1.00	2.00	...	...	5.00
A2	0.50	1.00	...	...	4.00
...	...	...	...	...	...
...	...	...	...	...	...
A25	0.20	0.25	...	...	1.00

w.r.t. C_2

C3	A1	A2	...	...	A25
A1	1.00	2.00	...	...	5.00
A2	0.50	1.00	...	...	4.00
...	...	...	...	...	...
...	...	...	...	...	...
A25	0.20	0.25	...	...	1.00

w.r.t. C_3

Step 4: Consistency Test for Pairwise Comparison Matrices

Aggregation methods: Analytic Hierarchy Process (contd.)

Step 5: Overall Weight Evaluation

Attribute/ Criteria Matrix

Unit	C1	C2	C3
A1	0.08	0.09	0.08
A2	0.07	0.07	0.06
A3	0.06	0.05	0.05
A4	0.07	0.07	0.07
A5	0.05	0.04	0.04
A6	0.06	0.05	0.05
A7	0.08	0.10	0.11
A8	0.06	0.07	0.07
A9	0.06	0.06	0.06
A10	0.06	0.05	0.05
A11	0.06	0.08	0.07
A12	0.04	0.03	0.04
A13	0.05	0.05	0.05
A14	0.03	0.03	0.03
A15	0.03	0.03	0.03
A16	0.02	0.02	0.02
A17	0.02	0.03	0.03
A18	0.02	0.02	0.02
A19	0.01	0.02	0.02
A20	0.01	0.02	0.02
A21	0.01	0.02	0.02
A22	0.01	0.01	0.01
A23	0.01	0.01	0.01
A24	0.01	0.01	0.01
A25	0.01	0.01	0.01

Aggregated Priority

Criteria	Priority Weight
C1	0.70
C2	0.18
C3	0.11

Overall Weight Evaluation

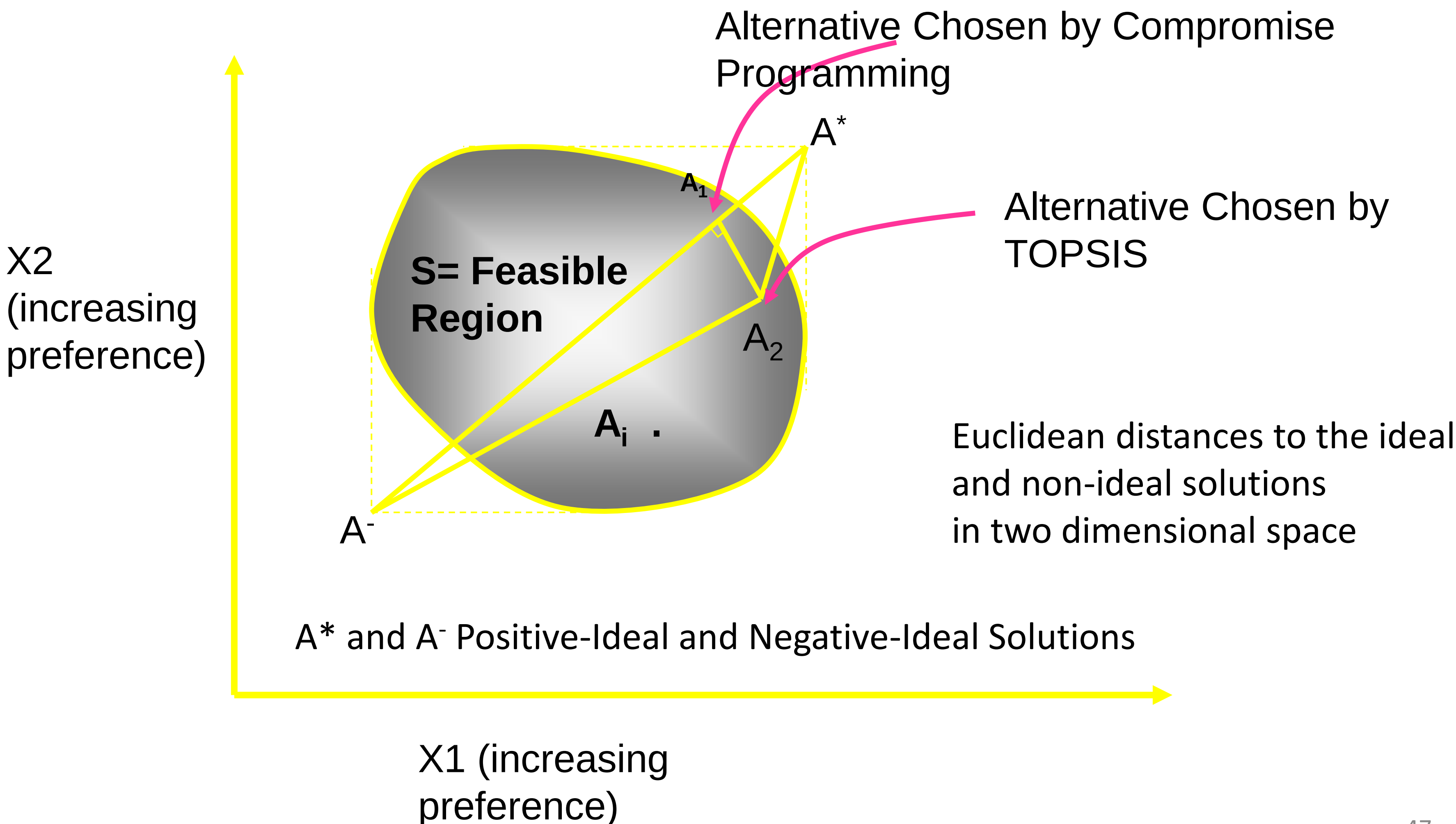
Unit	Weight	Rank
G1	0.083	2
G2	0.070	4
G3	0.056	10
G4	0.072	3
G5	0.044	12
G6	0.059	8
G7	0.089	1
G8	0.065	5
G9	0.057	9
G10	0.060	7
G11	0.063	6
G12	0.039	13
G13	0.048	11
G14	0.029	14
G15	0.026	15
G16	0.021	17
G17	0.024	16
G18	0.017	18
G19	0.014	21
G20	0.015	19
G21	0.015	20
G22	0.011	22
G23	0.010	23
G24	0.008	24
G25	0.007	25

One more ranking / aggregation technique….

Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)

- Developed by Zeleny (1982) and enriched by Yoon (1987)

Distance Measure based Methods



The step by step exposition of TOPSIS methodology

1. Calculate the Normalized Ratings (vector normalization)

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^{2}}} \quad , i=1,....,m; j=1,...,n.$$

2. Calculate the Weighted Normalized Ratings

$$a_{ij} = w_j r_{ij}$$

..... AHP weights may be applied

The step by step exposition of TOPSIS methodology

3. Identification of Positive-Ideal and Negative-Ideal Solutions (PIS & NIS)

$$D^{+} = \left\{ a^{+}{}_{1}, a^{+}{}_{2}, \ldots\ldots\ldots, a^{+}{}_{j}, \ldots\ldots\ldots, a^{+}{}_{n} \right\}$$

$$= \left\{ (\max_{i} a_{ij} \,\middle|\, j \in J_{1}), (\min_{i} a_{ij} \,\middle|\, j \in J_{2}) \,\middle|\, i = 1, \ldots\ldots\ldots, m \right\}$$

$$D^{-} = \left\{ a^{-}{}_{1}, a^{-}{}_{2}, \ldots\ldots\ldots, a^{-}{}_{j}, \ldots\ldots\ldots, a^{-}{}_{n} \right\}$$

$$= \left\{ (\min_{i} a_{ij} \,\middle|\, j \in J_{1}), (\max_{i} a_{ij} \,\middle|\, j \in J_{2}) \,\middle|\, i = 1, \ldots\ldots\ldots, m \right\}$$

where J_1 is a set of benefit attribute and J_2 is a set of cost attributes and $J_1 + J_2 = n$

The step by step exposition of TOPSIS methodology

4. Calculate Separation Measures

$$D^{+}_{i} = \sqrt{\sum_{j=1}^{n} (a_{ij} - a^{+}_{j})^{2}} \qquad \text{i = 1,.....,m}$$

$$D^{-}_{i} = \sqrt{\sum_{j=1}^{n} (a_{ij} - a^{-}_{j})^{2}} \qquad \text{i = 1,.....,m}$$

5. Calculate Similarities to Positive-Ideal Solution

$$R^{*}_{i} = \frac{D^{-}_{i}}{(D^{+}_{i} + D^{-}_{i})} \qquad \text{i = 1,.....,m}$$

6. Choose an alternative with maximum R_i^*

Example: TOPSIS (derived from Yoon and Hwang 1997)

UIUC wants to select a student to receive a fellowship award from six applicants. The criteria, maximum points, score, scale are shown below :

Profiles of Graduate Fellowship Applicants

Applicants	GRE	GPA	College Rating	Recommendation Rating	Interview Rating
A	690	3.1	9	7	4
B	590	3.9	7	6	10
C	600	3.6	8	8	7
D	620	3.8	7	10	6
E	700	2.8	10	4	6
F	650	4.0	6	9	8

Suppose the university sets the importance weights for the 5 attributes as :
(0.3, 0.2, 0.2, 0.15, 0.15)

Which candidate will receive the fellowship ??

Example: TOPSIS

Step 1: Since each attribute is measured on a different scale, an attribute normalization is required.

$$
\begin{array}{c}
\\ A \\ B \\ C \\ D \\ E \\ F
\end{array}
\begin{array}{c}
\begin{array}{ccccc} \quad X_1 & \quad X_2 & \quad X_3 & \quad X_4 & \quad X_5 \end{array} \\
\begin{bmatrix}
0.4381 & 0.3555 & 0.4623 & 0.3763 & 0.2306 \\
0.3746 & 0.4472 & 0.3596 & 0.3226 & 0.5764 \\
0.3809 & 0.4128 & 0.4109 & 0.4301 & 0.4035 \\
0.3936 & 0.4357 & 0.3596 & 0.5376 & 0.3458 \\
0.4444 & 0.3211 & 0.5137 & 0.2150 & 0.3458 \\
0.4127 & 0.4587 & 0.3082 & 0.4838 & 0.4611
\end{bmatrix}
\end{array}
$$

where the first element r_{11} was obtained from:

$$0.4381 = 690/\sqrt{(690^2 + 590^2 + \ldots + 650^2)}$$

Example: TOPSIS

Step 2: The chosen weights of (0.3, 0.2, 0.2, 0.15, 0.15) are multiplied with each column of the normalized rating matrix.

$$
\begin{array}{c}
A \\ B \\ C \\ D \\ E \\ F
\end{array}
\begin{bmatrix}
0.1314 & 0.0711 & 0.0925 & 0.0564 & 0.0346^{-} \\
0.1124^{-} & 0.0894 & 0.0719 & 0.0484 & 0.0865^{*} \\
0.1143 & 0.0826 & 0.0822 & 0.0645 & 0.0605 \\
0.1181 & 0.0871 & 0.0719 & 0.0806^{*} & 0.0519 \\
0.1333^{*} & 0.0642^{-} & 0.1027^{*} & 0.0323^{-} & 0.0519 \\
0.1238 & 0.0917^{*} & 0.0616^{-} & 0.0726 & 0.0692
\end{bmatrix}
$$

where the first element v_{11} was calculated as (0.1314 = 0.3 × 0.4381)

Step 3: PIS and NIS

Since all the chosen attributes are of benefit (the higher, the more preference). $A^* = (0.1333, 0.0917, 0.1027, 0.0806, 0.0865)$

$A^- = (0.1124, 0.0642, 0.0616, 0.0323, 0.0346)$

Example: TOPSIS

Step 4: The separation measures from A* are computed first:

$$S_A^* = \sqrt{\sum_{j=1}^{5} (v_{Aj} - v_j^*)^2}$$

$$= [(0.1314 - 0.1333)^2 + \ldots + (0.0346 - 0.0865)^2]^{½} = 0.0617$$

Separation measures from A* of all alternatives are:

(0.0617, 0.0493, 0.0424, 0.0490, 0.0655, 0.0463)

The separation measures from A^- :

$$S_A^- = \sqrt{\sum_{j=1}^{5} (v_{Aj} - v_j^-)^2}$$

$$= [(0.1314 - 0.1124)^2 + \ldots + (0.0346 - 0.0346)^2]^{½} = 0.0441$$

Separation measures from A^- of all alternatives are:

(0.0441, 0.0608, 0.0498, 0.0575, 0.0493, 0.0609)

Example: TOPSIS

Step 5: Similarities to PIS: $C_A^* = S_A^- / (S_A^* + S_A^-)$

$$= 0.0441/(0.0617 + 0.0441) = 0.4167.$$

Three Sets of Preference Rankings

	S^*		S^-		C^*	
Applicants	*Value*	*Rank*	*Value*	*Rank*	*Value*	*Rank*
A	0.0617	5	0.0441	6	0.4167	6
B	0.0493	4	0.0608	2	0.5519	2
C	0.0424	1	0.0498	4	0.5396	4
D	0.0490	3	0.0575	3	0.5399	3
E	0.0655	6	0.0493	5	0.4291	5
F	0.0463	2	0.0609	1	0.5681	1

Similarities to PIS:

$$= (0.4167, 0.5519, 0.5396, 0.5399, 0.4291, 0.5681).$$

Exposure: The presence of people, livelihoods, species or ecosystems, environmental functions, services, and resources, infrastructure, or economic, social, or cultural assets in places and settings that could be adversely affected.

Example of two exposure indicators – Land use and Soil type

The land use and soil permeability are two physical watershed characteristics which affect the flood flow (hazard comp.) (Sullivan et al., 2004)

Impact of land use on 'Exposure'

- **7 different categories of land use:**

1. Open space
2. Commercial
3. Residential
4. Parks and recreational
5. Government and institutional
6. Resource and industrial
7. Water body

- Mathematically the flood exposure of land use for i^th ward is expressed as:

$$E_i^{Land} = \sum_{l=1}^{n} [DI_l \times (A_i^l / A_i)]$$

- The standardized value of exposure for land use pertaining to the i^th ward:

$$E_{iStd}^{Land} = \frac{E_i^{Land} - E_{iMin}^{Land}}{E_{iMax}^{Land} - E_{iMin}^{Land}}$$

Impact of soil permeability on 'Exposure'

- 4 different categories of soil type:

  1. Low
  2. Low-medium
  3. Variable
  4. High

Decreasing chance of accumulation of water on the soil surface

Imply decreasing chance of flooding

- Mathematically the flood exposure of soil permeability for i^{th} ward is expressed as:

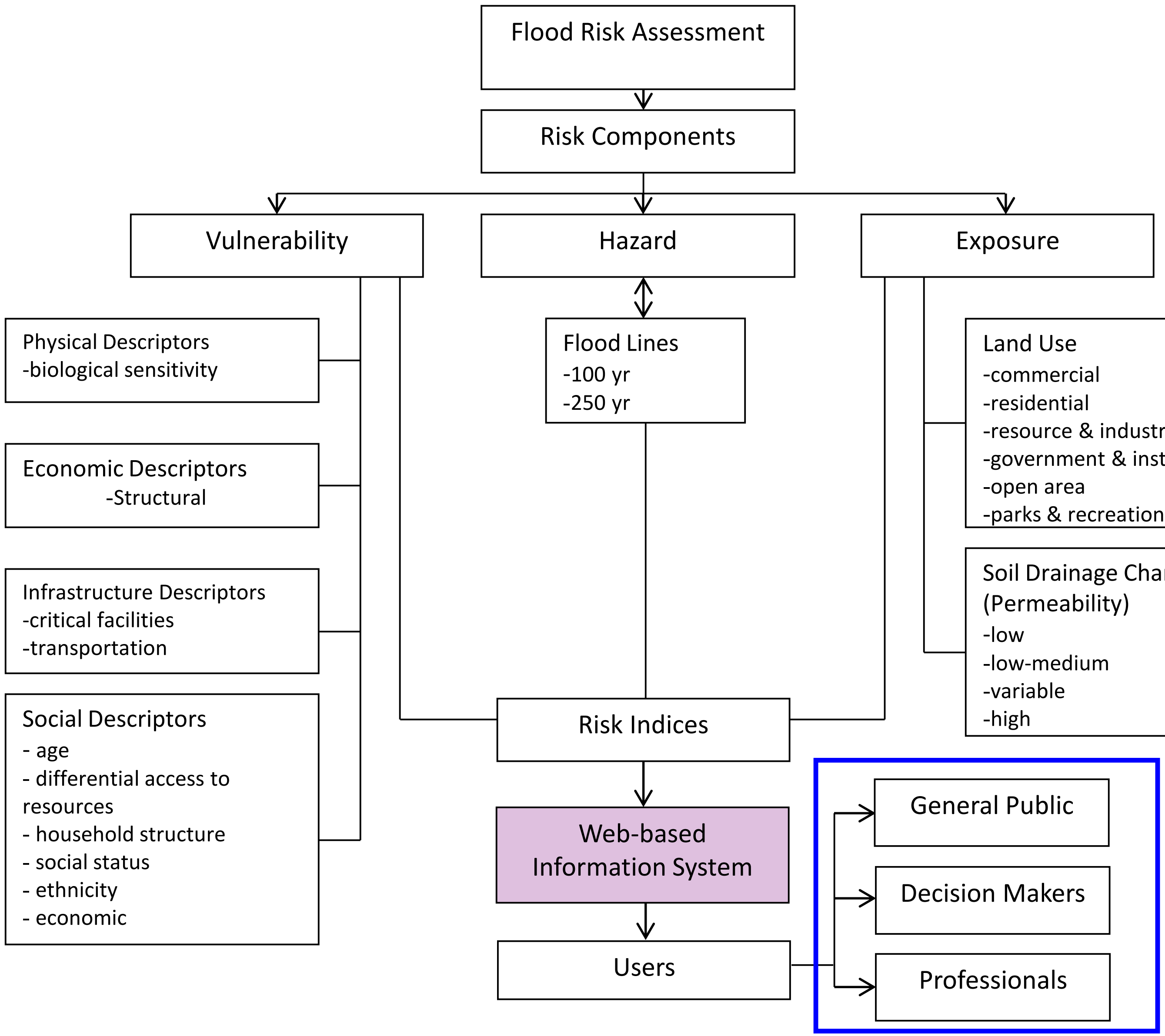
$$E_i^{Soil} = \sum_{p=1}^{m} [DI_p \times (A_i^p / A_i)]$$

- The standardized value of exposure for soil permeability pertaining to the i^{th} ward:

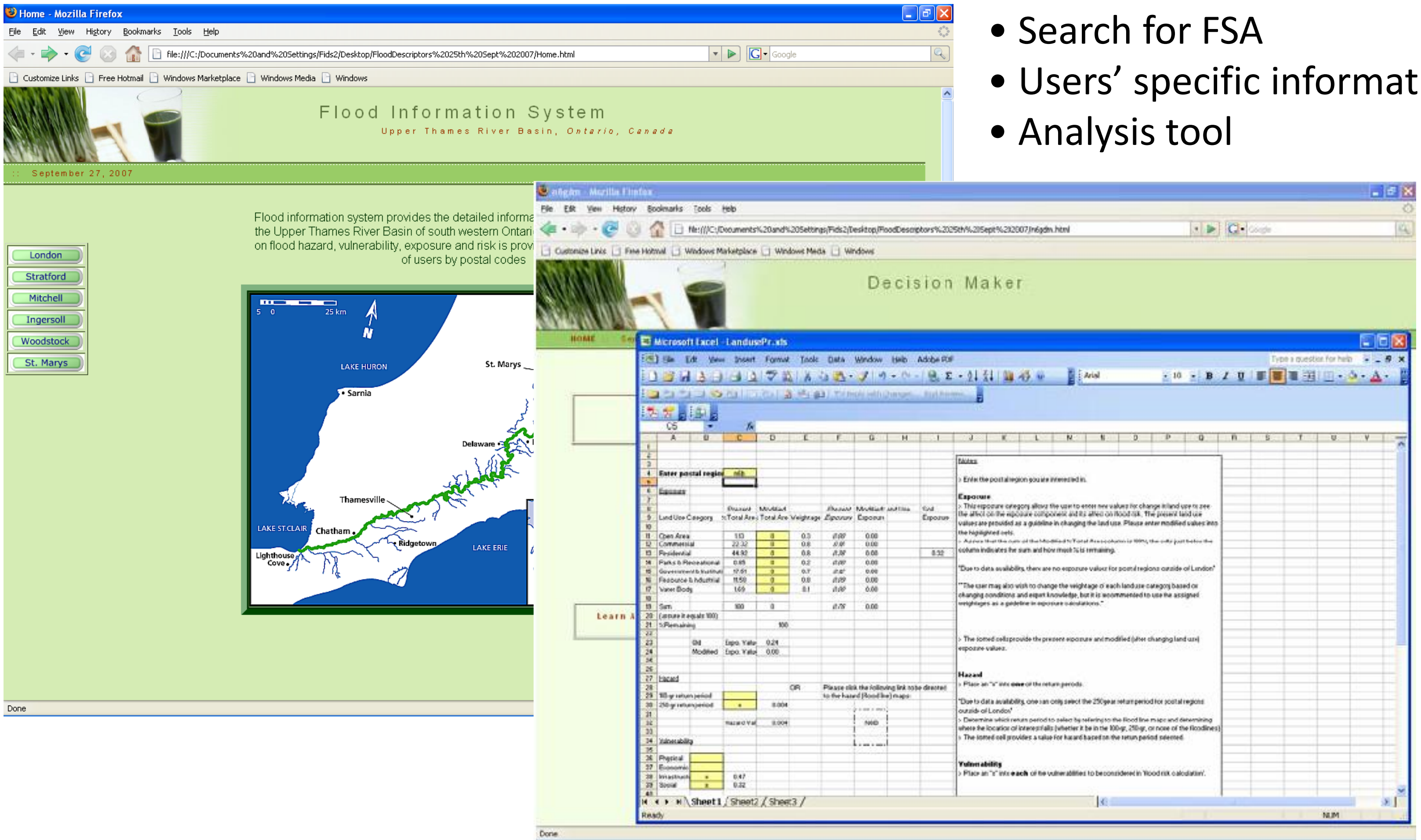
$$E_{iStd}^{Soil} = \frac{E_i^{Soil} - E_{iMin}^{Soil}}{E_{iMax}^{Soil} - E_{iMin}^{Soil}}$$

Web-based Flood Information System

(Holz et al, 2006, Peck et al. 2008, Black et al. 2008; Karmakar et al. 2010)



Web-based Flood Information System



- Search for FSA
- Users' specific information
- Analysis tool

Screenshot of the home page of a web-based flood information system

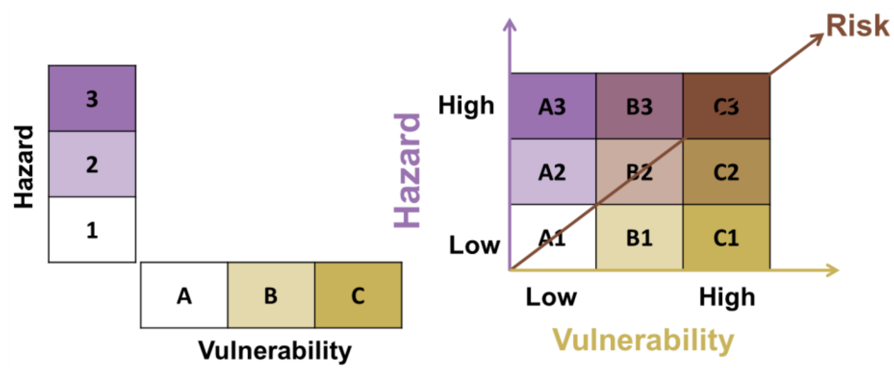
Univariate risk mapping

- This is the traditional method of mapping in which only one variable is considered.
- DEA method has been applied to calculate the magnitude of risk from hazard and vulnerability.

Bivariate risk mapping

Bivariate colour mapping has been extensively used in climate research (Teuling et al., 2011), where two variables can be displayed simultaneously.

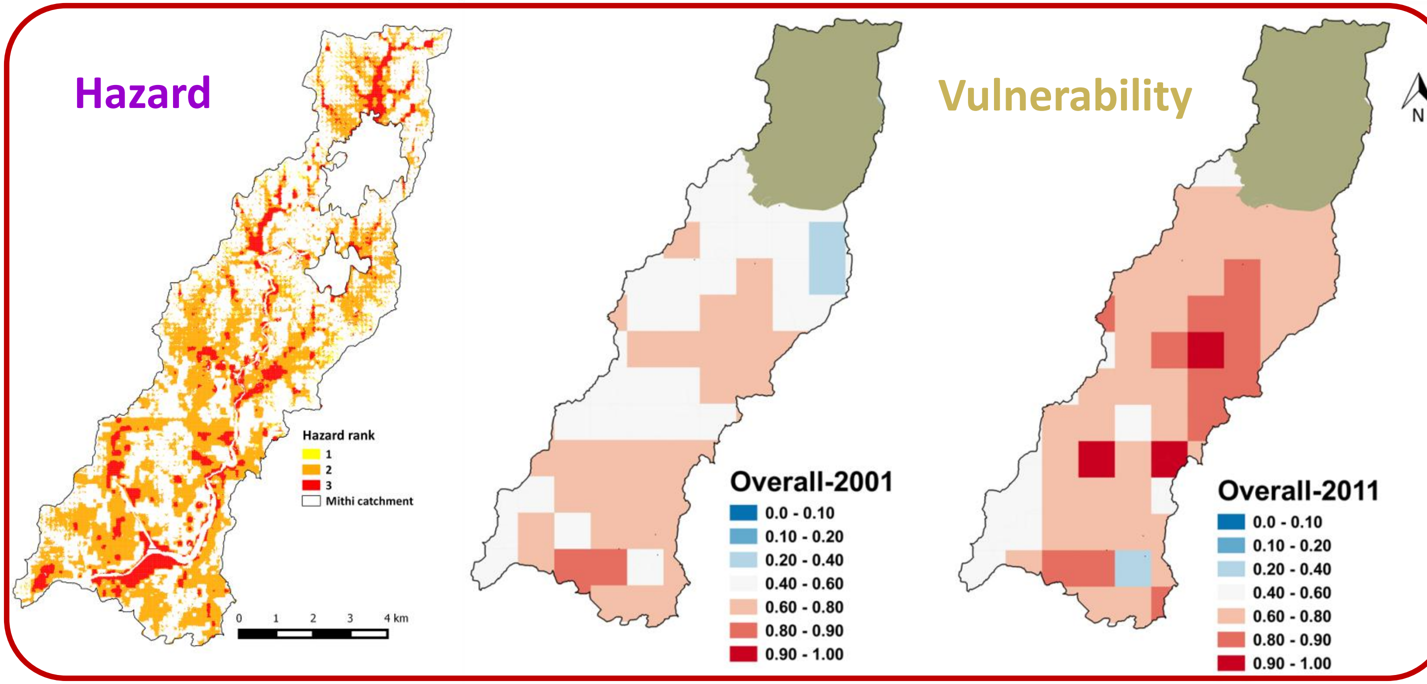
3x3 colour scheme

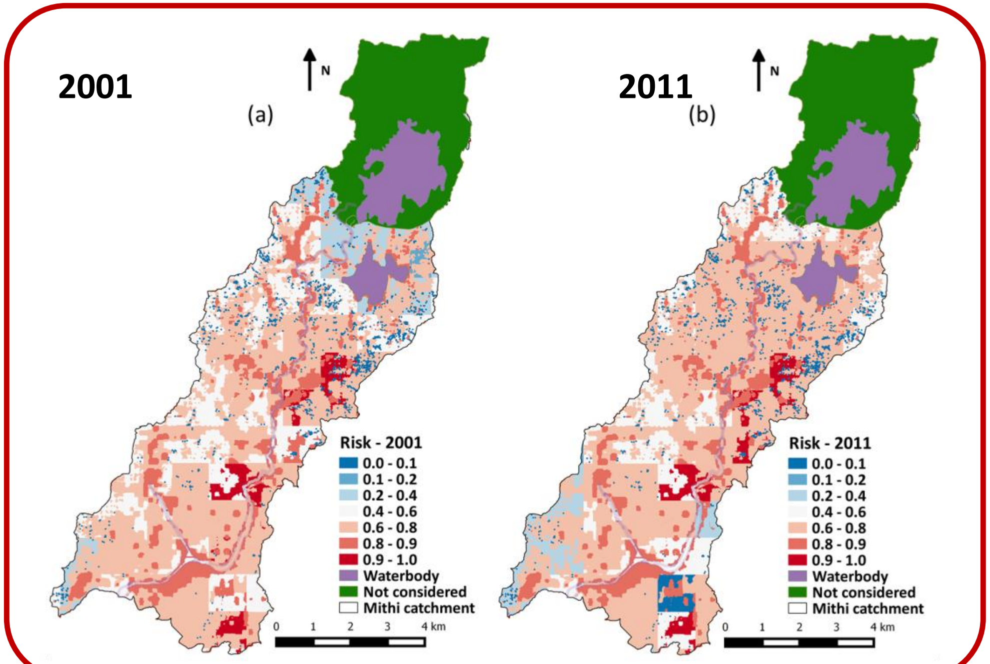


- Degree or spatial pattern of cross-correlation between hazard and vulnerability.
- Improved readability and accuracy of data representation

Univariate risk mapping

6 h design rainfall



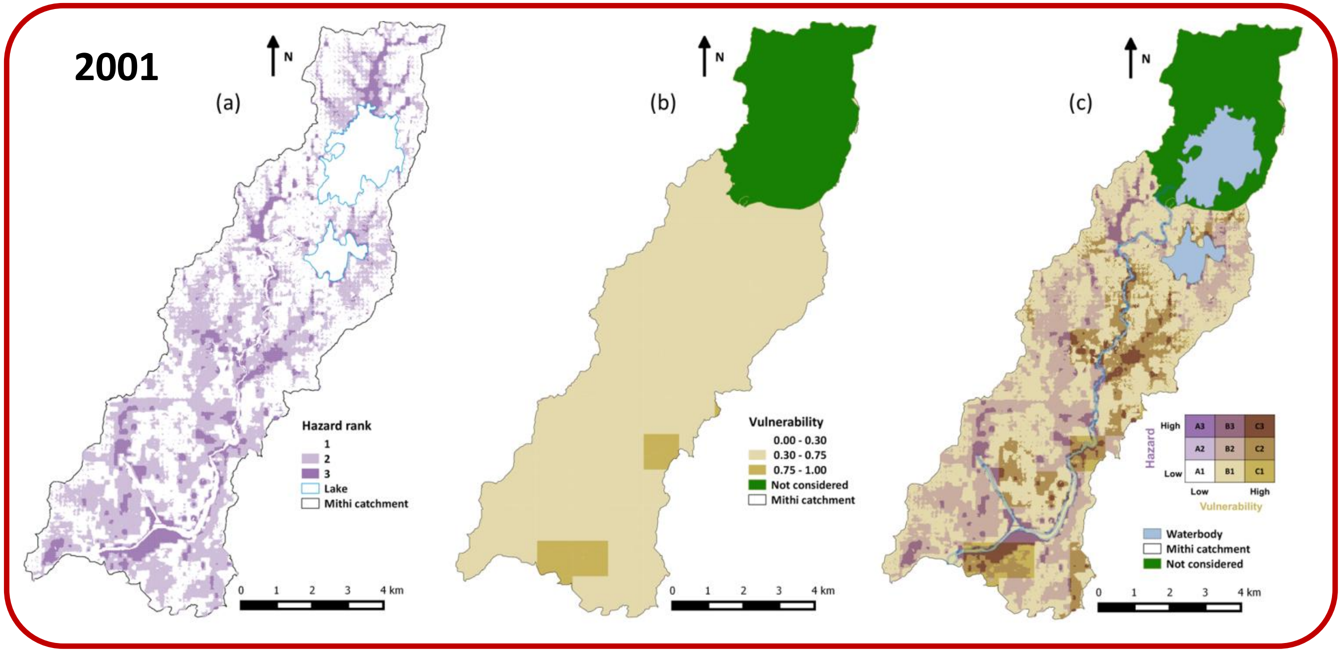


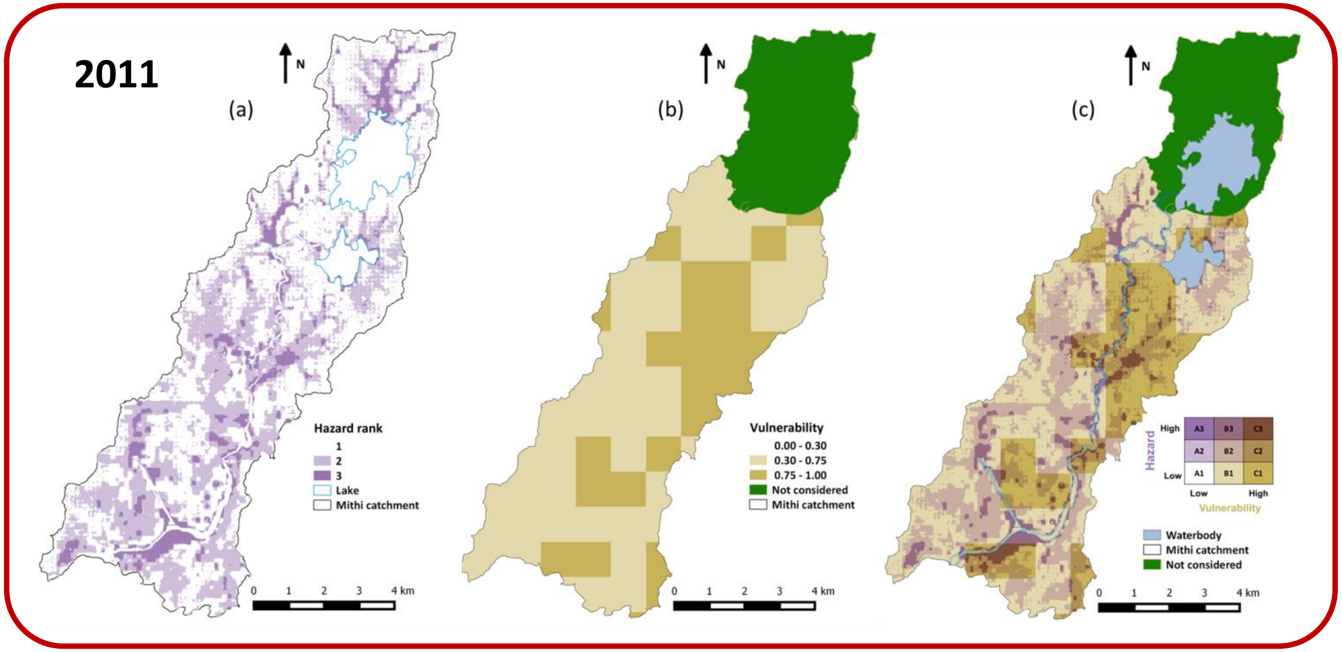
Flood risk map of Mithi catchment generated using DEA with 6 h design rainfall
and vulnerability as in: (a) Year 2001; (b) Year 2011

Bivariate risk mapping

6 h design rainfall

a) Flood hazard map
b) Vulnerability map
c) Flood risk map





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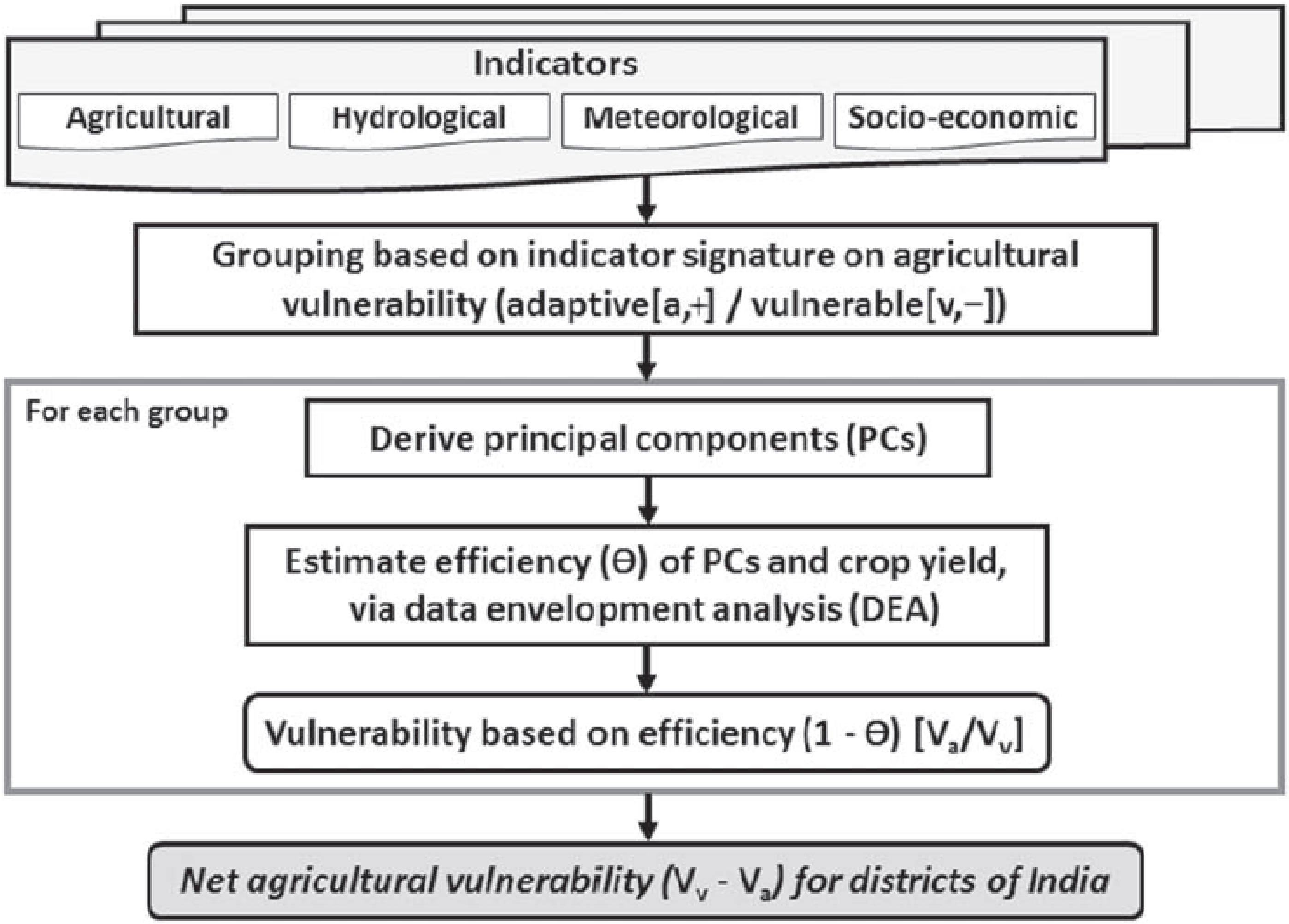
Increasing agricultural risk to hydro-climatic extremes in India

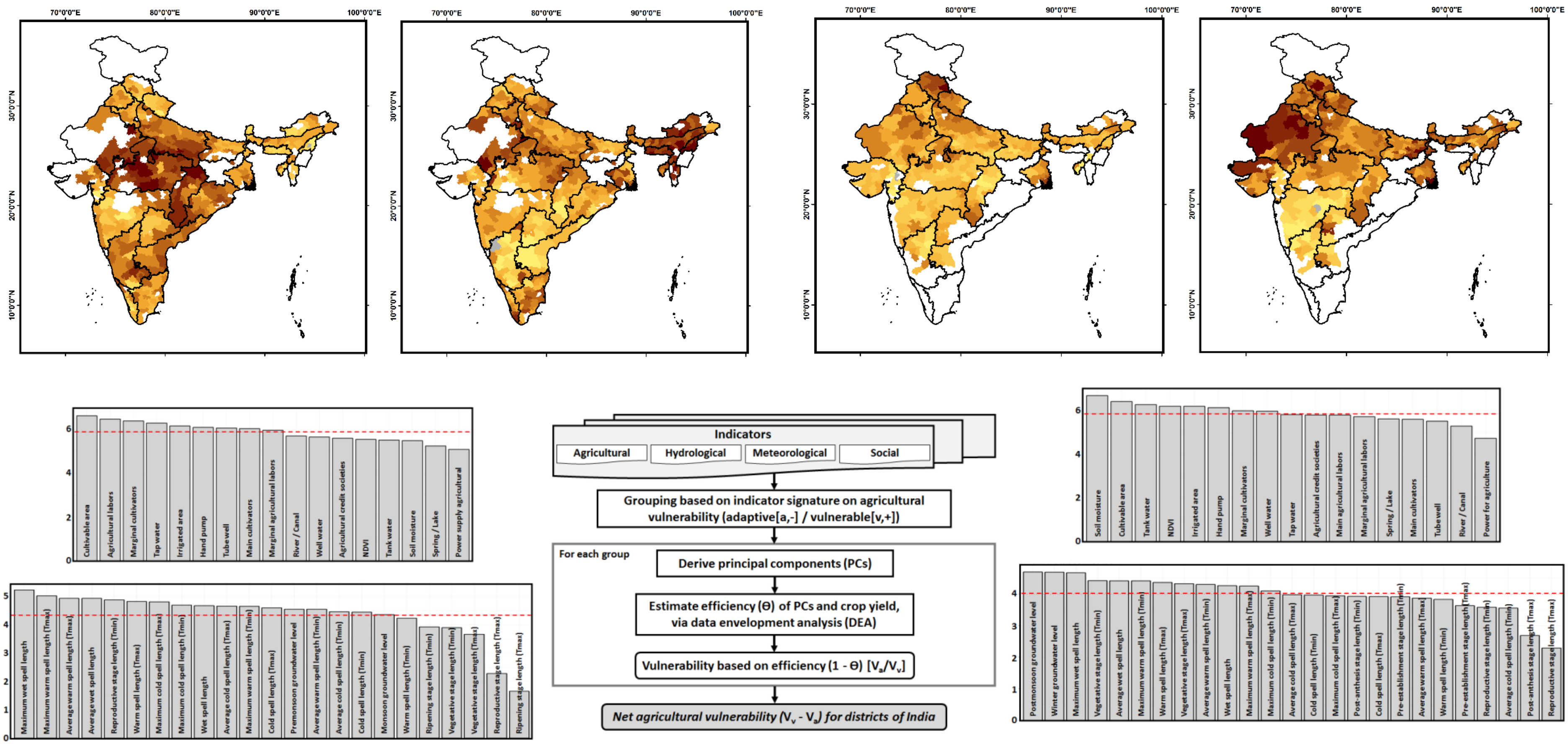
To cite this article before publication: Tarul Sharma *et al* 2019 *Environ. Res. Lett.* in press https://doi.org/10.1088/1748-9326/ab63e1

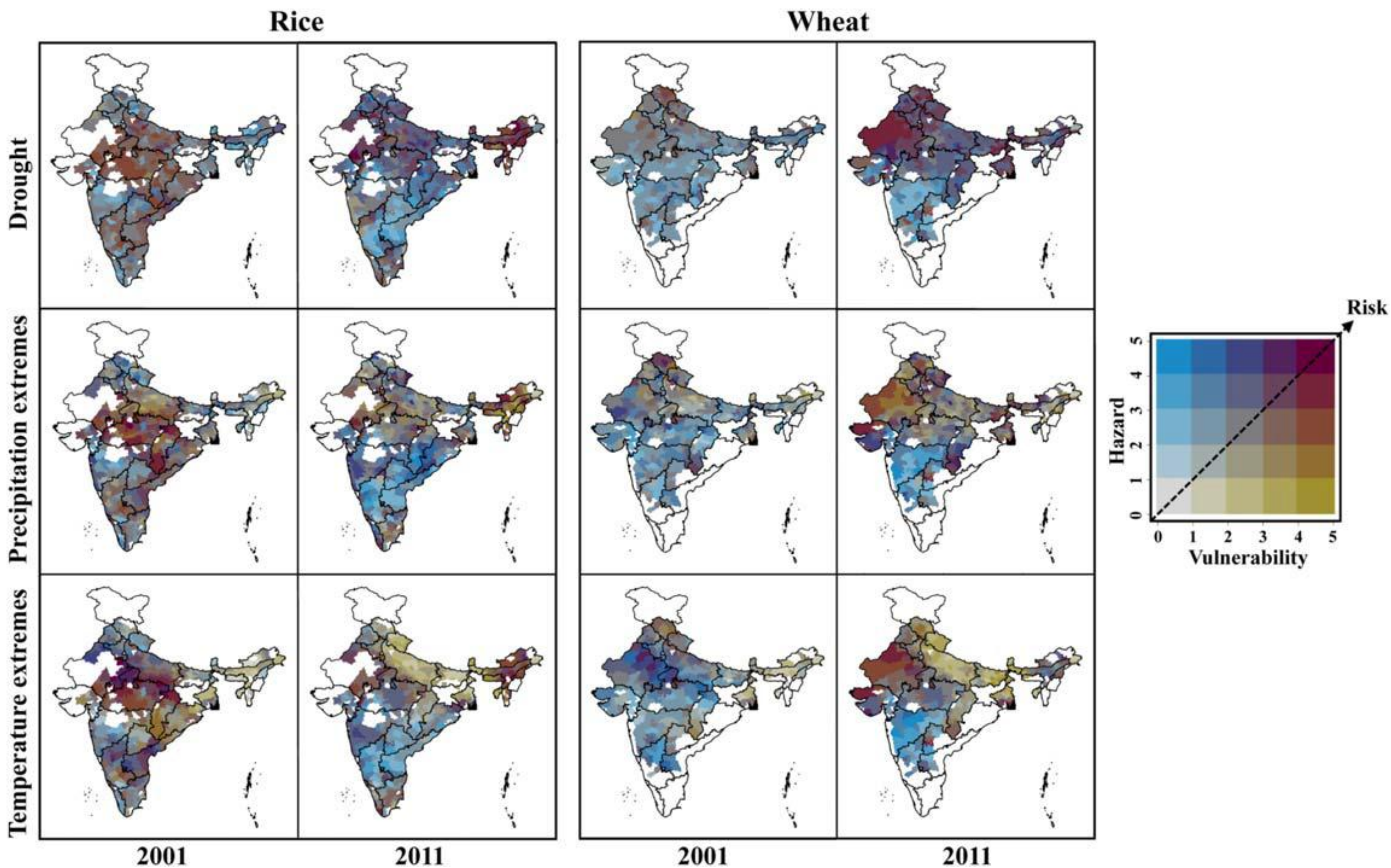


Proposed methodological framework for mapping the agricultural vulnerability (Sharma et al., 2020, ERL)

Rice vulnerability and its influencers at national scale

Wheat vulnerability and its influencers at national scale





Bivariate agricultural risk map to drought (top panel), precipitation extremes (middle panel) and temperature extremes (bottom panel) for both the rice and wheat crops in census decades 2001 and 2011. Bivariate mapping can provide an effective understanding of the individual/marginal and combined/joint intensity of both the components. The representation of agricultural risk levels is provided in the right corner of panel in the form of a choropleth, wherein the agricultural vulnerability and hydroclimatic hazard components are depicted with variable yellow and blue intensities, respectively. The combination of yellow and blue colors provides information pertaining to the agricultural risk at different levels (Sharma et al., 2020, ERL).

- Application: ***National Scale Agricultural Impacts and Vulnerability Mapping***

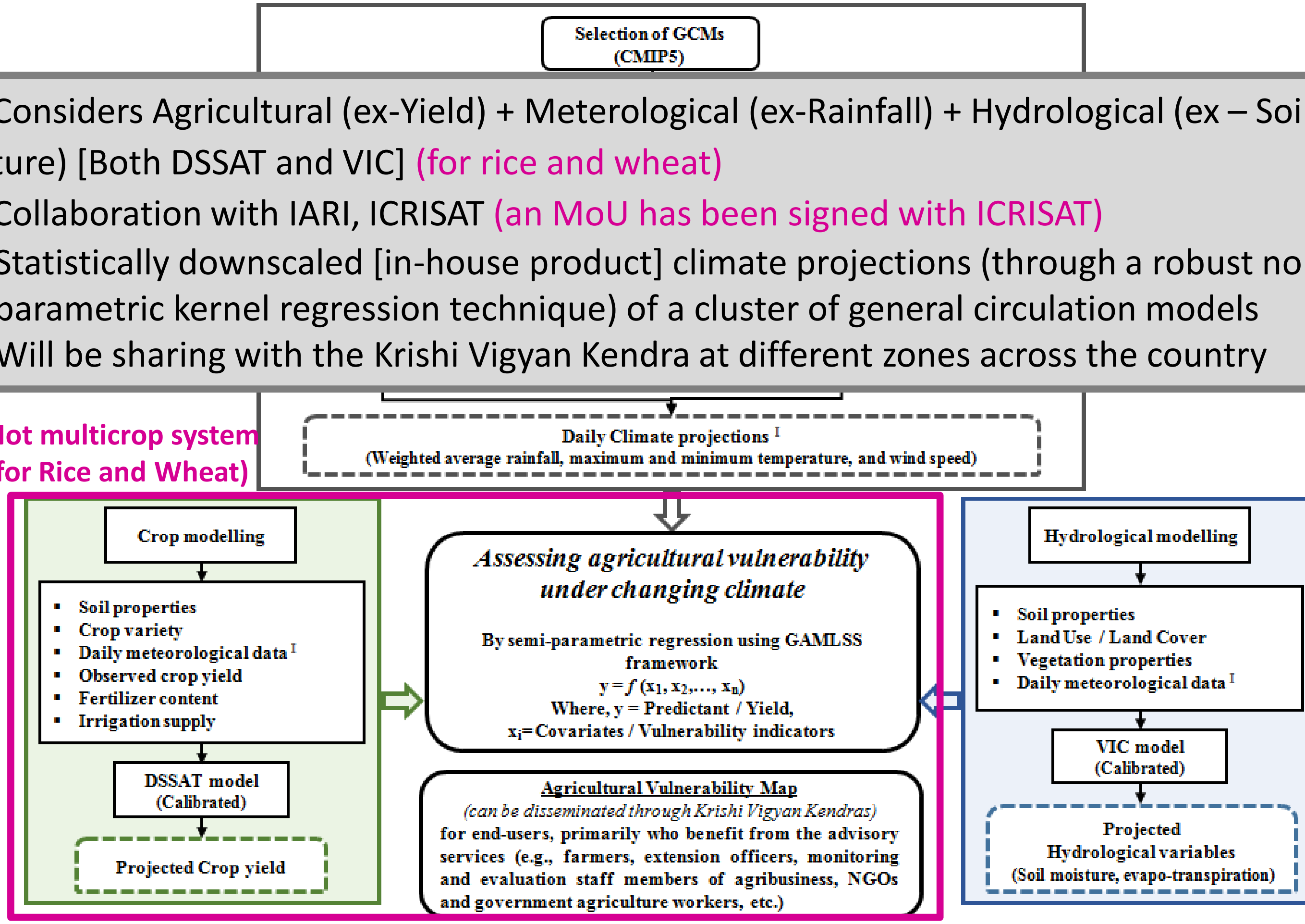
(i) Considers Agricultural (ex-Yield) + Meterological (ex-Rainfall) + Hydrological (ex – Soil moisture) [Both DSSAT and VIC] (for rice and wheat)

(ii) Collaboration with IARI, ICRISAT (an MoU has been signed with ICRISAT)

(iii) Statistically downscaled [in-house product] climate projections (through a robust non-parametric kernel regression technique) of a cluster of general circulation models

(iv) Will be sharing with the Krishi Vigyan Kendra at different zones across the country

Not multicrop system (for Rice and Wheat)



Environmental Research Letters

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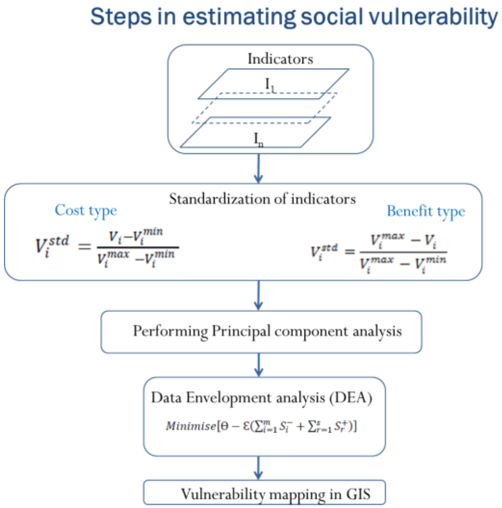
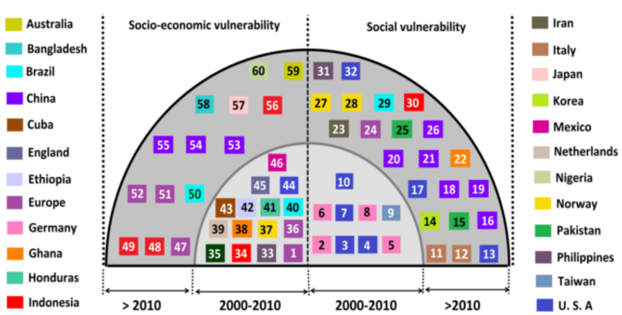
Increasing agricultural risk to hydro-climatic extremes in India

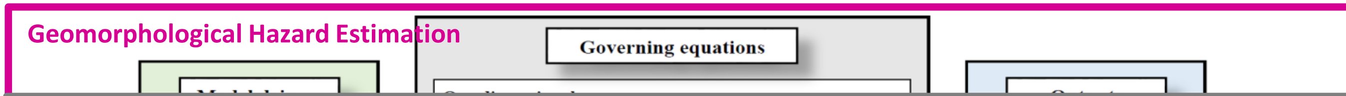
To cite this article before publication: Tarul Sharma *et al* 2019 *Environ. Res. Lett.* in press https://doi.org/10.1088/1748-9326/ab63e1

Application: *National Scale Flood Hazard and Vulnerability Mapping*

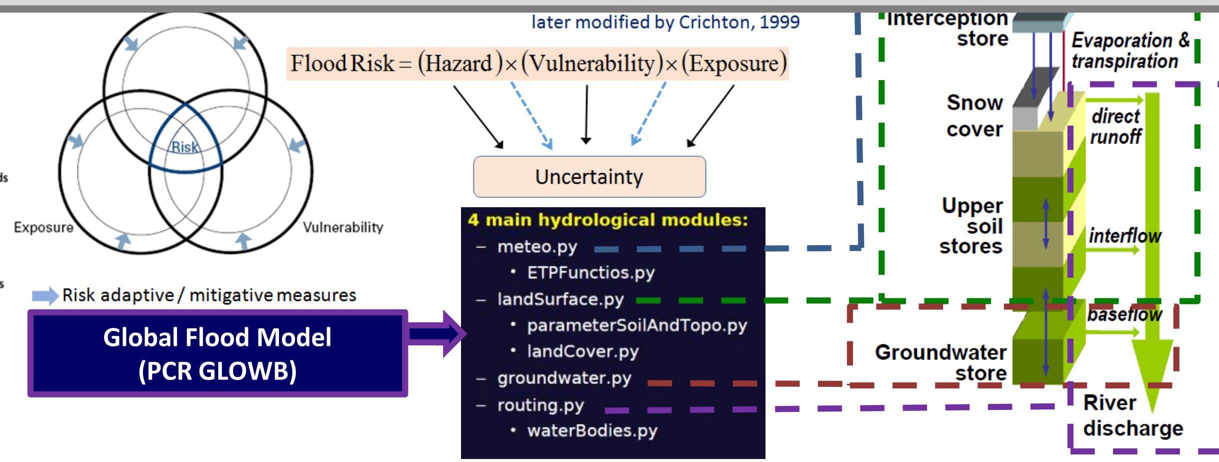




Efforts on vulnerability/risk mapping



- The flood hazard component will be derived from grided or station Level rainfall and the streamflow – First effort over India (Geomorphic & hydrodynamic)
- Most of the *Global Flood Risk Models* are open –The hydrologic community must utilize
- *Socio-economic Vulnerability Map* will be developed for the entire India
- All data inventories (pertaining to hazard, vulnerability and exposures components) - will be made available to all research and academic institutes



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A comprehensive India-wide social vulnerability analysis: highlighting its influence on hydro-climatic risk

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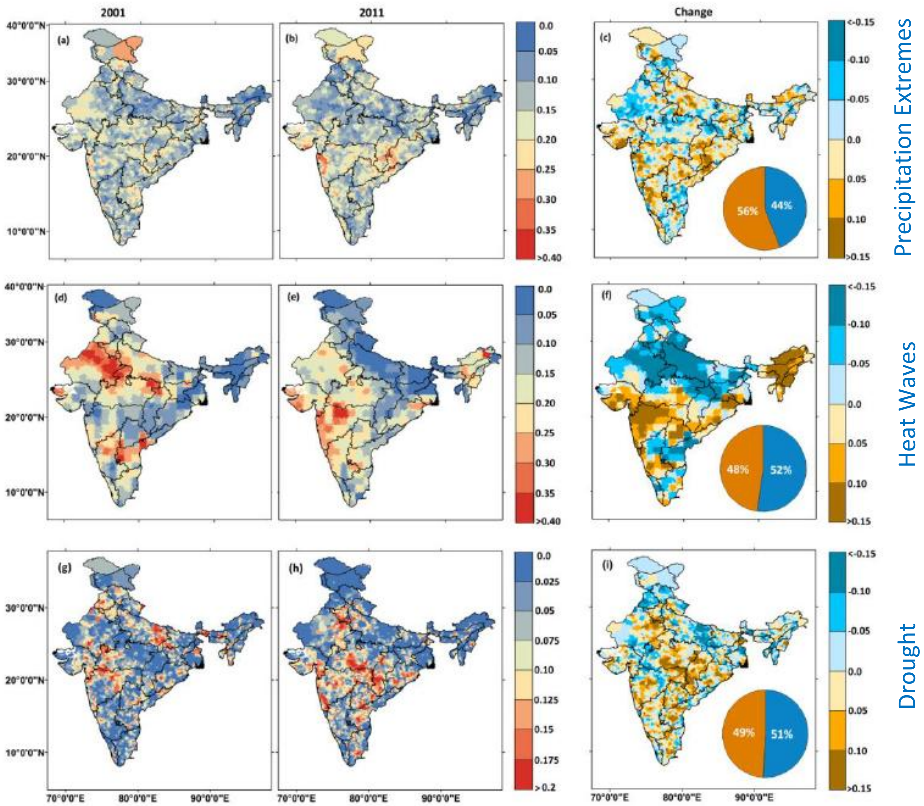
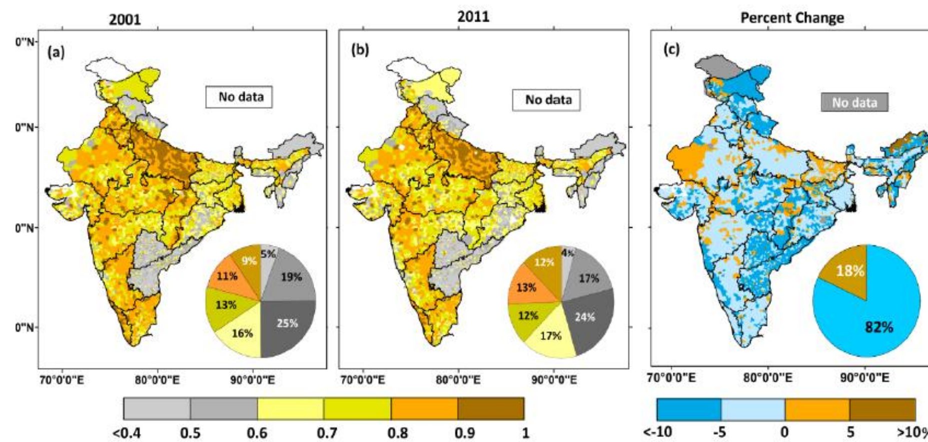
National Scale Hazard and Vulnerability Mapping



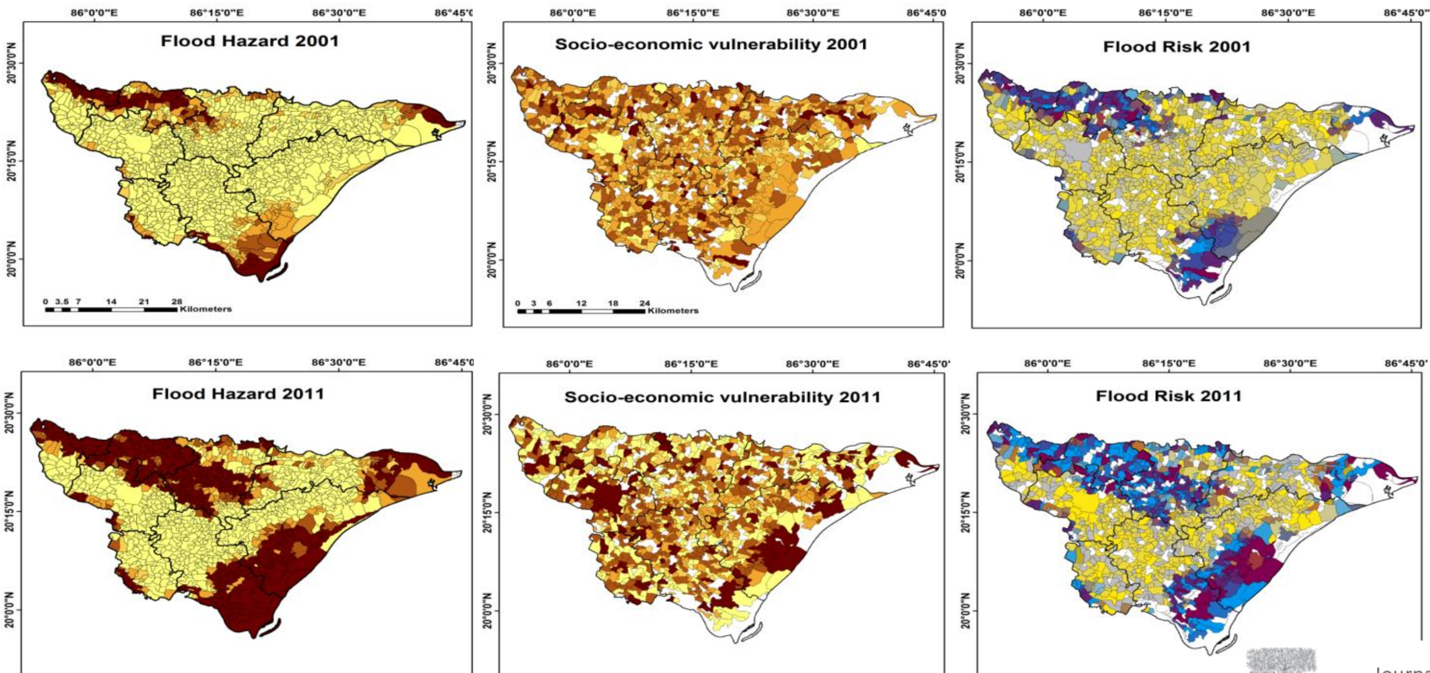
DEA based users' friendly module



Few representative social vulnerability indicators

Indicators	Justification	Resources of references	Influence to Social Vulnerability
Female Population	Increase in the female population increases difficulties in evacuation during the hazard, as the responsibility for family and children will be more.	Morrow (1999); Cutter et al. (2000, 2003). Dwyer et al. (2004); Tate et al. (2010); Ojerio et al. (2011); Schmidtlein et al. (2011); Khan (2012); Lee (2014) and Shrely et al. (2015)	Positive
Total Population	Higher the population, more difficult during the evacuation process	Mendas (2009); Tate et al. (2010); Khan (2012); Lee (2014) and Shrely et al. (2015)	Positive
Main agricultural and cultivators population	They are usually poor and will have a direct adverse effects during a disaster event. The coping will also be less, as they need to find some other jobs to fulfil their needs	WB, Shrely et al. (2015)	Positive
Children population (population < 6 years)	They require special attention during evacuation due to their high susceptibility to health problems and thereby slowing down the processes during disaster.	Guillard-Gonçalves et al. (2014); Kotzee and Reyers, (2016);	Positive
Rural Population	Usually poor and the percentage of the farmers will be higher and thereby having direct adverse effect during the disaster	World Bank (2002); Brooks et al. (2005);	Positive
Number of households	Higher households increases the vulnerability as tend to have more economically inactive dependents	Shewmake (2008); Wongbusarakum and Loper (2011); Nkondze et al. (2013); Guillard-Gonçalves et al. (2014); Shrely et al. (2015); Dumenu and Obeng, (2016)	Positive
Illeterate population	Illiterates tend to have least set of employable skills and have reduced access to information with low level of risk acknowledgement. This increases their vulnerability.	Morrow (1999), Haan et al. (2001); Leichenko and O'Brien (2002); Eriksen et al. (2007); Cutter et al. (2008); Wongbusarakum and Loper (2011); Shrely et al. (2015); Dumenu and Obeng, (2016)	Positive
Illeterate female population	Illiterate female may find it more difficult to follow any evacuation warning, and take care of the family during a disaster.	Shrely et al. (2015)	Positive
SC and ST population	They are categorized as the backward community by the government of India	Shrely et al. (2015)	Positive

Regional Flood Modeling for a Comprehensive Flood Risk Mapping



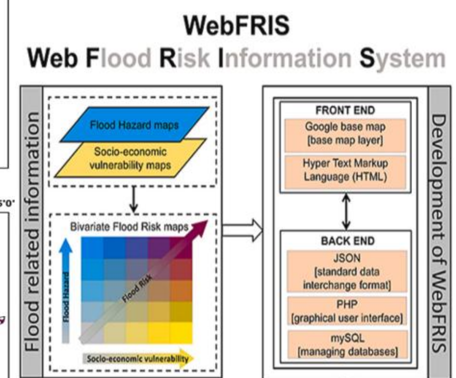


Fig. Flood hazard maps for the census years 2001 (a) and 2011 (d), Socio-economic vulnerability maps for the census years 2001 (b) and 2011 (e) and bivariate flood risk maps for census years 2001 (c) and 2011 (f) for Jagatsinghpur district, Odisha, India; The values inside choropleth cells show the percentage of area under a particular class of risk

(Mohanty et al. 2018, Mohanty et al. 2020 a, b; Mohanty and Karmakar 2021)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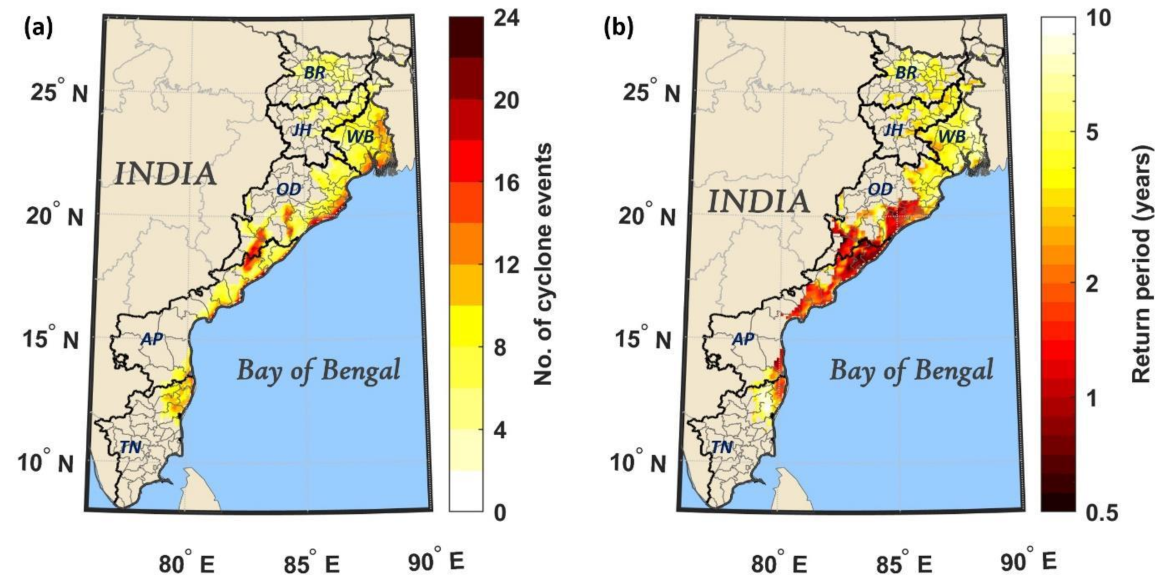
Research article

WebFRIS: An efficient web-based decision support tool to disseminate end-to-end risk information for flood management

Mohit Prakash Mohanty [a], Subhankar Karmakar [a, b, c]

Application: Conditional concurrent wind-rainfall extremes over India



Conditional concurrent wind-rainfall extremes over India. (a) Number of extreme cyclone events (i.e., duration of both wind and rainfall extreme more than 6hr) at eastern coastal states of India, and (b) Conditional return period of cyclonic events (having duration of concurrent extreme ≥ 24hr, given duration of both wind extreme and rainfall extreme ≥ 6hr) for eastern coastal states.

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Compound hazard mapping for tropical cyclone-induced concurrent wind and rainfall extremes over India

Ravi Ranjan & Subhankar Karmakar