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Climate change impacts: Understanding the synergetic interactions using graph computing

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Abstract

In this study we provide a computerized graph structure for synthesizing and displaying the data on a region's ecosystem-economic system. By applying Mathematica-based graph modelling we create a causal network of the synergistic impact mechanism among certain climate related factors. Our computational approach identifies a climate factor that affects most immediately or most strongly the others. Important factors are indicated through the use of graph theoretical tools. Our graph-based approach and its computational aspects allow for factor ranking(s) according to their importance to the network both numerically and visually, for certain settlement types. Our contribution provides quantitative estimates of impacts and adaptation potentials of five potential effects of climate change (migration, flooding- landslides-fire, air and water pollution, human health and energy-water-other resources) which play a substantial role at the synergistic impact mechanism. Results allow having a picture of the structure of synergistic impact mechanism in a glimpse. Specifically, visual output is created to detect i) the causal relationships of the synergetic mechanism under study ii) the most influential factor(s) in the synergistic mechanism and iii) classify the factor's roles (based on the degree of their impact) within the coping mechanism.

Keywords: Graph theory; vertex centrality; Mathematica; climate related factors; environmental economics computation.

JEL Classification: C63; C88; P28; Q51; Q54; Q58.

1. Introduction

We conduct an analysis of environmental impacts referring to certain categories of settlements. We consider settlements as ecosystems vulnerable to climate-change related factors. One factor could have an environmental impact on many more. Within the framework of the synergistic mechanism of environmental effects we find that network-based measures may provide important insights into recognizing the key factors in a given ecosystem. Understanding the influence of climate change on human settlements and the associated socio-economic effects is a major challenge (Halkos, 2013; Halkos and Matsiori, 2012).

In a previous computational approach of the same issue (Halkos and Tsilika, 2014), infinite matrix representations of influence patterns per settlement type were constructed. In the present approach, the synergistic impact mechanism is captured in one graph-theoretic formulation. Similar graph structures for economic models has been computed in (Alkemade et al., 2002; Cerina et al., 2015; Halkos and Tsilika, 2016a; b).

In the proposed graph structure, each environmental factor corresponds to a vertex and the synergy from one factor to another constitutes a (possibly weighted) directed edge. This way, we create a causal network of the synergistic impact mechanism among certain climate related factors.

The issue of finding the “important” nodes in the causal network of synergistic effects is first confronted. Important nodes are indicated through the use of graph theoretical tools. Nodes (factors) with a key role in the causal network of the synergistic impact mechanism have high centrality indicators. Usually indicators of centrality reveal the ideal route from a source to a target in order to find a shortest path or to maximize flow (Blöchl et al., 2011). Here, indicators of centrality identify

the most important vertices within a graph. The question of which nodes are the most central has multiple answers. Definition of “central” varies by context or purpose (Freeman, 1979; Aroche-Reyes, 1996; Friedkin 1991; Everett and Borgatti, 2004; Borgatti, 2005; Borgatti and Everett, 2005; Borgatti and Everett, 2006). In some cases the number of connections is the best centrality measure, in other cases “central” is relative to rest of network. In our analysis, we evaluate each indicator of centrality as an influence metric and give its interpretation in the environmental context we set. Extending and exploiting this information, we proceed in identifying “key” factors and rank the factors’ roles in a given synergistic impact mechanism. A certain algorithm for vertex coloring is employed for visual testing of linkage criteria.

The visual output of this study is the ultimate result, since we succeed to evaluate the synergetic interactions through a pseudo-geometric visualization, in a self-explanatory approach, free of any mathematical formulations, arguments and/or any other justification.

2. Visualizing Interactions among Climate Related Factors for three Settlement Types

In this section, we justify our assumptions for three types of settlements (i.e. urban settlements, riverine coastal steplands and resource dependent settlements) on the findings of IPCC (McCarthy et al., 2001), par. 7.6.2. Specifically, we take the interactions between migration, phenomena of flooding- landslides- fire, air and water pollution, human health and energy-water-other resources, as featured in a tabular format in the IPCC report (McCarthy et al., 2001) chapter 7.

Our previous visual approach (Halkos and Tsilika, 2014) is summarized in Figure 1. In visual outputs of Mathematica’s environment, matrix cells with different shades of gray show the degree of influence of the synergistic effect. Our color rule

says that a white cell states no interaction; grey-shaded cells signify interactions of variant influences. A dark shade is related to an intense impact.

In the pattern constructs below, while white cells are steadily white, all other cells, depending on the geographic, seasonal and/or sectoral level, fluctuate their shades regionally. The derived matrix patterns are representative of every type of settlement. Rows and columns of matrices in Figure 1 feature five environmental factors with a serial number from 1 to 5. Serial numbers 1-5 represent Migration (1), Flooding, Landslides, Fire (2), Air and Water Pollution (3), Human Health (4) and Energy, Water, other Resources (demand) (5).

Relevant concepts and notions are agriculture, forestry, transportation, infrastructure, extinction of species and loss of ecosystems, heat waves etc. The IPCC report 2001 states that “in the 20th century, global temperatures increased in the range of $0,6\pm 0,2^{\circ}$ C and provide a number of possible effects of global warming on climate like extreme weather events (with very possible summer droughts in continental areas, higher heat waves, etc), tropical storm intensity (hurricanes, etc), decomposition of methane hydrates, etc”.

The visual approach presented in this paper, employs graphs with vertices the climate-related factors and edges their in-between interactions. Figure 2a, b, c provide a topological view of the matrix patterns of Figure 1. In all figures, we consider synergy effects that occur with equal probability in any climate related factor and consequently, we construct unweighted graphs. We assume a flow process in which no link is repeated (only the immediate synergistic effects are considered) and, synergy flows by parallel duplication (Borgatti, 2005). We do not approach the system with a dynamic model-based view; the dynamic flow context is out of the scopes of the present study since i) a secondary (undefined) synergistic mechanism

takes place after the first activation of the synergistic mechanism and ii) priority has been given to prevention measures and policy interventions based out mostly on the primary synergistic mechanism. Following Borgatti's (2005) categorization, we study the case of "diffusion by replication". We consider shortest paths (i.e., the geodesic distances) in the sense of direct/immediate impacts.

Figure 1: Matrix of synergistic effects for urban settlements, riverine coastal steplands and resource dependent settlements

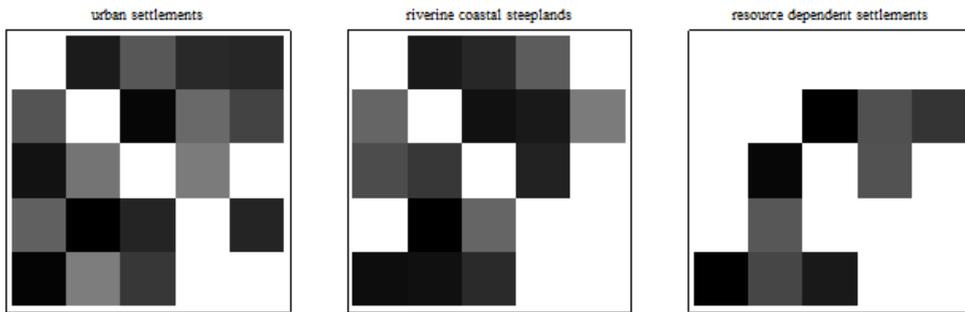
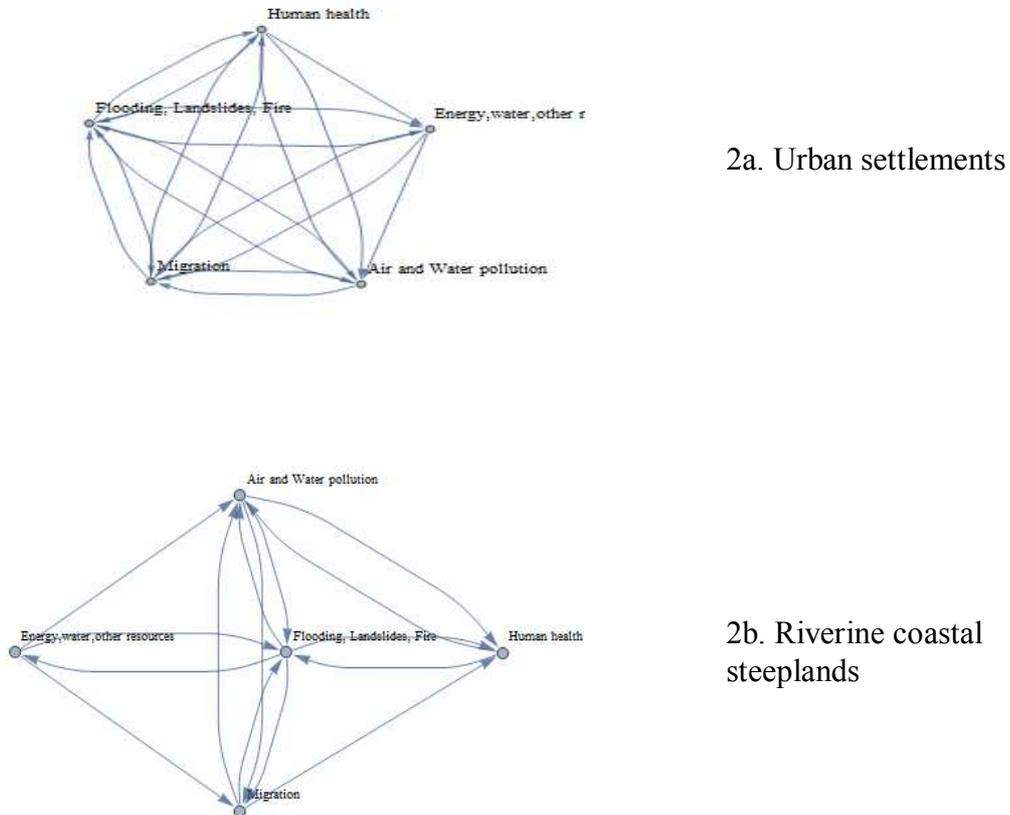
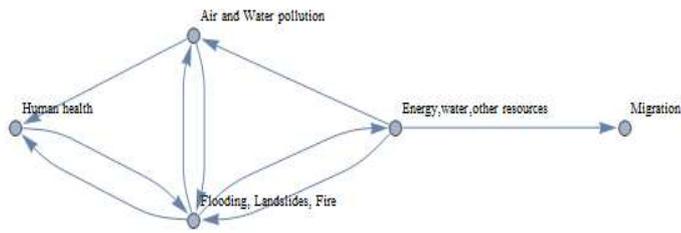


Figure 2: Graph illustration of the interactions of climate-related factors





2c. Resource dependent settlements

3. Computational Description of our Methodology

Graphs are built from vertices and edges directly in a symbolic form. The computer input for the graph construction is the so-called adjacency matrix. In the network analysis context, the adjacency matrix displays relationships between objects. Matrix inputs 1 and 0 indicate whether two objects are related or not.

In this study, the adjacency matrix is generated from climate hypotheses for types of settlements that are conceptualized verbally in the IPCC report (McCarthy et al., 2001, par. 7.6.2). Let $A=(a_{ij})$ be the adjacency matrix representing the synergistic effects of the climate related phenomena. Elements $a_{ij}=1$ if a phenomenon i has an impact on phenomenon j and $a_{ij}=0$ otherwise. The one and only task of a potential user of our codes, is, to synthesize the adjacency matrix of the ecosystem under study and assign it in the appropriate built-in Mathematica functions. Following IPCC (2001) report, the study of the synergistic effects, results in the following adjacency matrices.

The most influential node of the network is traced using indicators of centrality. The ranking of the nodes' impact is made by computing different kinds of centrality indices (to be analyzed in the next section).

Table 1: Adjacency matrix of urban settlements

| | Migration | Flooding, Landslides , Fire | Air and Water Pollution | Human Health | Energy, Water, Other Resources |
|-----------------------------------|-----------|-----------------------------------|----------------------------|-----------------|-----------------------------------|
| Migration | 0 | 1 | 1 | 1 | 1 |
| Flooding, Landslides , Fire | 1 | 0 | 1 | 1 | 1 |
| Air and Water Pollution | 1 | 1 | 0 | 1 | 0 |
| Human Health | 1 | 1 | 1 | 0 | 1 |
| Energy, Water, Other Resources | 1 | 1 | 1 | 0 | 0 |

Table 2: Adjacency matrix of riverine coastal steplands

| | Migration | Flooding, Landslides , Fire | Air and Water Pollution | Human Health | Energy, Water, Other Resources |
|-----------------------------------|-----------|-----------------------------------|----------------------------|-----------------|-----------------------------------|
| Migration | 0 | 1 | 1 | 1 | 0 |
| Flooding, Landslides , Fire | 1 | 0 | 1 | 1 | 1 |
| Air and Water Pollution | 1 | 1 | 0 | 1 | 0 |
| Human Health | 0 | 1 | 1 | 0 | 0 |
| Energy, Water, Other Resources | 1 | 1 | 1 | 0 | 0 |

Table 3: Adjacency matrix of resource dependent settlements

| | Migration | Flooding, Landslides , Fire | Air and Water Pollution | Human Health | Energy, Water, Other Resources |
|-----------------------------------|-----------|-----------------------------------|----------------------------|-----------------|-----------------------------------|
| Migration | 0 | 0 | 0 | 0 | 0 |
| Flooding, Landslides , Fire | 0 | 0 | 1 | 1 | 1 |
| Air and Water Pollution | 0 | 1 | 0 | 1 | 0 |
| Human Health | 0 | 1 | 0 | 0 | 0 |
| Energy, Water, Other Resources | 1 | 1 | 1 | 0 | 0 |

For the presentation and better understanding of our evaluation, we use a vertex coloring methodology (<http://reference.wolfram.com/language/ref/ClosenessCentrality.html>), exploiting the values of the vertex centrality measures.

In our computer experiments we use the following Mathematica functions (Wolfram Language and System): for the graph model construction the `AdjacencyGraph` and `WeightedAdjacencyGraph` functions, for graph metrics and measures evaluation the `DegreeCentrality`, `ClosenessCentrality`, `PageRankCentrality`, `EigenvectorCentrality` functions¹. `HighlightGraph [g, { $\alpha_1, \alpha_2, \dots$ }]` function highlights the α_i that can be vertices, edges, or subgraphs of g . Similar source codes are given in (Halkos and Tsilika 2016a; b).

4. Vertex Centralities

Centrality is a way to address the importance of a vertex in a given network. It is defined as how actively this vertex interacts with others. There are several ways to calculate the centrality of a vertex as degree centrality, closeness centrality, eigenvector centrality, page-rank centrality, betweenness centrality etc (see indicatively Harary et al., 1965; Freeman, 1979; Friedkin 1991; Everett and Borgatti, 2004; Borgatti, 2005; Borgatti and Everett, 2005; Borgatti and Everett, 2006; Everett and Borgatti, 2005; Aldasoro and Angeloni 2015).

Definition 1. Closeness centrality is a measure to check if a node is close to other nodes. Closeness centrality² for a graph g is given as $\{1/l_1, 1/l_2, \dots\}$ where l_i is the average distance from vertex i to all other vertices connected to i . If d is the distance matrix then the average distance l_i from vertex i to all connected vertices is given by

¹ A Mathematica implementation is available on request.

² Since centrality indices are computed in Mathematica, definitions of centrality are given as stated in the *Mathematica Book*.

$(\sum_j d_{ij})/k$, where the sum is taken over all finite d_{ij} and k is the number of vertices connected to i . The closeness centrality for isolated vertices is taken to be zero.

Definition 2. (The simplest concept) Degree centrality is defined as the number of the direct neighbors of the vertices. Degree centrality measures the immediate/direct impact. The degree can be interpreted in terms of the immediate risk of a node for catching whatever is flowing through the node. We usually define two separate measures of degree centrality, namely indegree and outdegree. Indegree centrality reveals whether the vertex in question is a source (more outflows than inflows) or a receiver (more inflows than outflows). In our environmental study, a source is a threatening factor (able to trigger more climate change effects) and a sink a vulnerable one (is likely to be triggered by other climate change effects).

Observing the adjacency matrix of urban settlements, the obvious result from the first, second and fourth row is that the corresponding environmental factor (migration, flooding- landslides- fire, human health) has a dominant impact within the coping mechanism of environmental effects. Quantifying this result, we evaluate closeness centrality (we select closeness centrality out of a variety of centrality measures following Borgatti, 2005; Borgatti and Everett, 2005; Friedkin, 1991) for the associated graph, to certify that the (same) highest closeness centrality corresponds to the first, second and fourth climate-related factor. The performance of our methodology is summarized in Tables 4, 5. Results concern only closeness centralities, but can be adjusted for any other centrality measure.

Nodes whose centrality index is 1 are “centres of the structure”. The more central a node is, the closer it is to all other nodes. In a self-explanatory visual scheme, Mathematica automatically highlights the vertex (vertices) with the highest closeness centrality (Figure 3a, b, c). In Figure 4, blue shaded vertices stand for

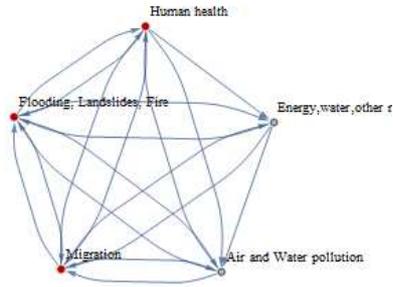
factors with a null to small share of environmental impacts, while red shaded vertices represent factors having a significant degree of influence on the synergetic mechanism. The closeness centrality for isolated vertices is taken to be zero (blue colored vertex). The closeness centrality for vertices connected to all the other vertices of the graph is taken to be one (red colored vertex).

Table 4: Summary table of influence indices of environmental factors per type of settlement (based on closeness centralities)

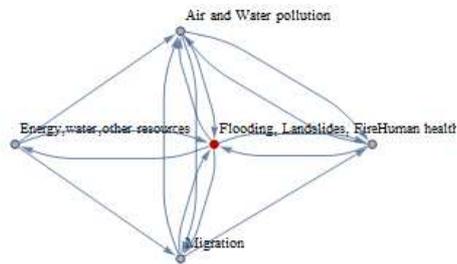
| Type of settlement / environmental effect | Migration | Flooding, Landslides, Fire | Air and Water Pollution | Human Health | Energy, Water, other Resources |
|--|------------------|-----------------------------------|--------------------------------|---------------------|---------------------------------------|
| Urban Settlements (US) | 1 | 1 | 0.8 | 1 | 0.8 |
| Riverine Coastal Steeplands (RCS) | 0.8 | 1 | 0.8 | 0.6667 | 0.8 |
| Resource Dependent Settlements (RDS) | 0 | 0.8 | 0.571429 | 0.5 | 0.8 |

When performing an “impact analysis”, i.e. evaluating how environmental factors influence each other and the synergistic mechanism system-wise, it may not be assumed that matrix A is a strict 0-1 matrix or that has constant input. The proposed methodological approach can be generalized for weighted graph models, where in place of the adjacency matrix, a matrix X with entries real numbers, representing connection strengths, is employed. (x_{ij}) matrix is the matrix that captures all the repercussions between the five factors and consists of the indicators of impact. For random weighted matrix of synergistic effects, nonzero entries are computer generated numbers from Mathematica’s random number generator `RandomReal[{1, 2}]`. In this case, the climate-related factor with the dominant impact cannot be indicated from the tabular formulation, as happened previously.

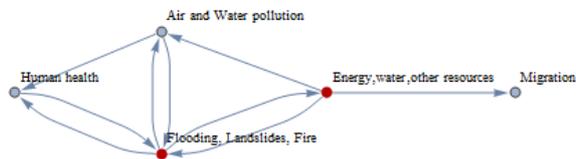
Figure 3: Highlighting the maximum closeness centrality



3a. Urban settlements



3b. Riverine coastal stepplands



3c. Resource dependent settlements

Figure 4: Variations of closeness centrality through temperature map colors (blue=0 to red=1)

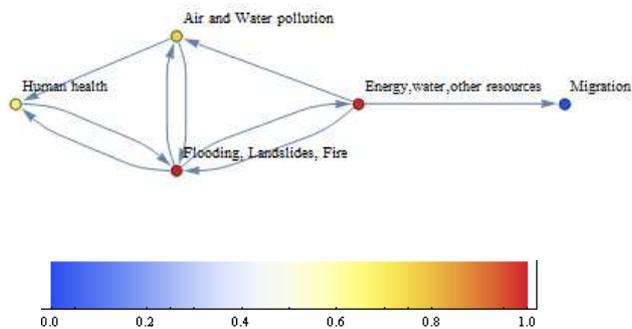


Table 5: Factor rankings according to closeness centrality

| Rank | Factor in US* | Factor in RCS** | Factor in RDS*** |
|-------------|--|--|--|
| 1 | Migration Flooding, Landslides, Fire Human Health | Flooding, Landslides, Fire | Flooding, Landslides, Fire Energy, Water, other Resources |
| 2 | Air and Water Pollution Energy, Water, other Resources | Migration Air and Water Pollution Energy, Water, other Resources | Air and Water Pollution |
| 3 | | Human Health | Human Health |
| 4 | | | Migration |

*Urban settlements **Riverine coastal steplands ***Resource dependent settlements

5. Evaluation and Discussion

In this study, the knowledge from different fields is combined for the purpose of dealing with the issue of climate change. When we define the matrix of synergistic effects, we take into account the seasonal, spatial/regional differences, the local climate variability. Then, in our graph-inspired model, we perform the proposed “impact analysis”, as presented in sections 3, 4. The resulting images raise awareness of the risks that emerge. In a first step, domino effect prediction and measurement of the transmission of risk within the climate related synergistic impact mechanism is made. Secondly, an evaluation of the evolution of environmental danger is achieved.

Our computational methodology highlights the most crucial factors in a given ecosystem. In the case of urban settlements, Figure 3a and Table 4 reveal three key factors which strongly influence the underlying mechanism. In riverine coastal steplands (Figure 3b), only one factor has a strong influential role within the associated synergistic mechanism. Consequently, less prevention measures are needed in the second case. In another way of thinking, seeing closeness centrality as an index of reception speed (Borgatti, 2005), since environmental factors in resource dependent

settlements have lower centrality values than other types of settlements (see the entries in “RDS” line of Table 4), a slower spread of climatic impacts and vulnerabilities is expected. Therefore, urban settlements (interpreting “US” line of Table 4) carry a higher systemic risk compared to resource dependent settlements. Results in Table 5 help a decision maker set priorities at the country level.³

In the light of an anticipated future risk, activities aiming in risk and vulnerability reduction and/or adaptation policies should take place. Using our information, local government or local community could prepare an early warning system, proceed with pre-disaster actions, (i.e. emergency evacuation, emergency shelters, drain cleaning, disease surveillance, public awareness etc) and prepare for surprises (REC 2004; Revi et al., 2014; Dasgupta et al., 2014; Adger et al., 2014). Effective policy interventions (as slope stabilization, watershed management upstream, land use management, standards enforced on housing quality) could intercept a potential crisis, a massive disaster, the damage of an upcoming “environmental domino effect”. The effectiveness of such responses depends on an advanced understanding of the specific vulnerabilities, uncertainties, and priorities of the synergetic mechanism under study.

A range of measures responding to risks reduces also the associated social costs, damage costs, climate change costs (Parry et al., 2007, par. 7.5; Halkos, 2014). The use of policy rules is discussed among others by Amman and Kendrick (1999; 2003), Amman and Duraiappah (2004).

³ For the implementation of environmental management systems standards in corporate decision making see Evangelinos and Halkos (2002), Halkos and Evangelinos (2002).

6. Conclusions

Our approach focuses on an integrated computational framework that models the structured mechanism of environmental impacts in an ecosystem. The output produced visually pinpoints the impact of each factor and identify at a glance, environmentally important factors.

In our computational experiments, the interactions between migration, phenomena of flooding- landslides- fire, air and water pollution, human health and energy-water-other resources, are depicted in a graph. The matrix of their interconnections is our basis for our computational methodology. Given the linkages between the five studied climate related phenomena, we construct symbolic graphs as visual and accurate representations of the mechanism of environmental impacts at a regional level.

Centrality measures are the graph theoretic metrics for the quantitative analysis. Vertices whose centrality indicators are high seriously affect the synergetic mechanism of environmental effects and point to criticality. By these means, our computational approach provides useful information on risk mapping, early warning, risk awareness in an eco-framework, in order to set the directions for climate change control policies. Specifically, policies that maximize the socio-economic benefits and avoid climate change damage.

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