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THE ROLE OF SCALE IN RESEARCH ON THE HIMALAYA–GANGES–BRAHMAPUTRA INTERACTION

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ABSTRACT This paper investigates the role of scale in research on the link between the Himalaya–Ganges–Brahmaputra fluvial system and floods in Bangladesh. Fifty-two studies, ranging from one hectare to near continental scales, were reviewed for variables selected in analysis and research designs. Three overall patterns of scale dependence were identified. The first is dominated by the precision with which scales and study area are defined. Local studies tend to have temporal and spatial scales which are explicitly defined while continental scale studies are dominated by general and abstract or implicitly defined scales. The second pattern indicates that local scale studies tend to focus upon physical variables such as rainfall, runoff, and mass wasting, while research at the regional and continental scales focuses on natural resource topics such as land-use change and flood mitigation policy. The third pattern identifies the degree to which studies attempt to scale up to larger regions from local scale studies. Specifically, this final pattern identifies a scale independent model which upscales stream discharge/sediment load across all three scales. The topics examined and research results presented are clearly scale dependent. It is proposed that scale perspectives are partially responsible for shaping opposing theories in the debate over the causes of flooding in Bangladesh. In conclusion, three strategies are outlined that may assist future research to incorporate multi-scale analysis of flooding in Bangladesh.

RÉSUMÉ *Le rôle de l'échelle dans la recherche sur l'interaction entre l'Himalaya, le Ganges et le Brahmaputra.* Cet article examine le rôle de l'échelle dans la recherche sur le rapport entre le système fluvial de l'Himalaya, du Ganges et du Brahmaputra, et les inondations au Bangladesh. Cinquante deux études, portant sur des superficies d'un hectare à pratiquement la taille du continent, ont été examinées en termes des variables sélectionnées pour l'analyse et la recherche. Trois modes principaux de dépendance de l'échelle ont été identifiés. Le premier est dominé par la précision à laquelle les échelles et la zone d'étude sont définies. Les études locales tendent à utiliser des échelles de temps et d'espace définies explicitement, alors que les études à l'échelle du continent sont dominées par des échelles générales et abstraites, ou définies implicitement. Le deuxième mode indique que les études locales tendent à se concentrer sur des variables physiques telles que la pluviosité, le ruissellement et le mouvement de masse, alors que la recherche aux niveaux régional et continental se concentre sur des sujets du type «ressource naturelle» tels que les changements de l'exploitation des terres et la politique d'atténuation des inondations. Le troisième mode identifie le degré auquel les études essaient de s'étendre à de plus grandes régions à partir des études locales. En particulier, ce dernier mode identifie un modèle indépendant de l'échelle qui étend les débits de cours d'eau et les charges solides aux trois échelles. Les sujets examinés et les résultats de recherche présentés sont nettement indépendants de l'échelle. Cet article suggère que les perspectives d'échelle sont partiellement responsables de l'élaboration de théories opposées dans le cadre de la discussion des causes d'inondations au Bangladesh. En conclusion, l'article présente trois stratégies susceptibles d'aider les futures recherches à incorporer une analyse à échelles multiples des inondations au Bangladesh.

ZUSAMMENFASSUNG *Erforschung von maßstabgetreuer Wechselwirkung im Himalaya-Ganges-Brahmaputra Gebiet.* Diese Arbeit untersucht in welchen Größenordnungen die Wechselwirkung zwischen dem Himalaya-Ganges-Brahmaputra Flußsystem und den Hochwasserereignissen in Bangladesh abläuft. Mittels 52 Studien, die Maßstäbe von einem Hektar bis hin zu kontinentalen Größenordnungen einschlossen, wurden Variable ausgewählt, die zur Analyse und Forschung gebraucht werden. Dabei konnte die Skalenabhängigkeit in drei Gruppen geordnet werden. Die erste wird von der Genauigkeit bestimmt, mit der Skalengrößen und Gebietsdetails angegeben sind. Studien vor Ort werden im allgemein mit klar-definierten zeitlichen und räumlichen Skalen durchgeführt; kontinentale Studien dagegen geben nur typische oder abstrakte Größenordnungen an, und dies oft auch nur indirekt. Die zweite Gruppe zeigt, daß lokale Studien sich auf physikalische Variable, wie Regenmenge, Abfluß und Erosionsrate konzentrieren; wogegen Studien auf regionaler und kontinentaler Basis die Naturressourcen in den Mittelpunkt stellen, die auf die Landnutzung Einfluß haben und die das Überschwemmungsausmaß kontrollieren. Die dritte Gruppe ergibt sich aus dem Genauigkeitsgrad, mit dem Ergebnisse von lokalen Studien sich auf größere Gebietsskalen extrapolieren lassen. Diese letzte Gruppe definiert ein Modell, das maßstabgetreu Größenordnung, Abflußmenge und Sedimentfracht für alle drei Gruppen angeben kann. Die untersuchten Themen und die beschriebenen Forschungsergebnisse sind eindeutig skalenabhängig. Da der Wert korrekter Skalierung oft unerkannt blieb, wird die Debatte über Überschwemmungsursachen in Bangladesh mit z.T. widersprüchlichen Theorien geführt. Zum Abschluß werden drei Strategien vorgestellt, die bei zukünftiger Erforschung der Hochwasserursachen in Bangladesh eine multi-skalige Analyse befürworten.

INTRODUCTION

Scale, spatial and temporal, has been identified as an important, yet often overlooked, variable in the research of many of the Earth's processes (Meentemeyer, 1989; Weins, 1989). In terms of the hydrologic cycle, the spatial scale or size of the study area selected can limit and determine the relevant variables as well as influence the nature of research designs (Mather, 1978). For instance, a flood may be caused by a thunderstorm with a 10-km radius, or a mature extra-tropical cyclone with a 1,000-km radius (Hirschboeck, 1988). In the use of hydrological models, spatial aggregation of hydrologic variables at different scales changes empirical results and model performance (Shelton, 1989). In addition, high variability in hydrologic characteristics of small river basins makes generalizations about larger river basins, in the same region, nearly impossible (Pilgrim, 1983).

According to Ives (1987) and Ives and Messerli (1989), generalization about regional hydrologic trends and extrapolation of the characteristics of micro-scale river basins to macro-scale river basins is the central issue which is creating the current debate over the cause of flooding in Bangladesh. The Theory of Himalayan Environmental Degradation (THED), the conventional theory, extrapolates the impacts of deforestation from micro-scale mountain watersheds to the macro-scale watersheds of the Ganges and Brahmaputra (Eckholm, 1976; Denniston, 1993).

The alternative theory to the THED does not deny the presence of environmental degradation in the Himalaya; rather, the theory claims the impacts of such degradation cannot be extrapolated to the entire Ganges and Brahmaputra river basins (Hamilton, 1987; Ives, 1987; Ives and Messerli, 1989). In particular, environmental degradation of micro-scale watersheds in the Himalaya results in a significant increase in stream sediment load, yet an insignificant change in stream discharge. For meso-scale watersheds, human impact is still uncertain in quantitative terms, but the high variability of natural factors is believed to dominate stream discharge and sediment load. At the macro-scale watershed, human alteration of watersheds in the highland areas (Himalaya) is insignificant when compared to human alteration of lowland areas (Bangladesh).

The purpose of this paper is to investigate the impact of spatial scales selected in research designs directed to analyses of the link between the Himalaya–Ganges–Brahmaputra fluvial system and floods in Bangladesh. Research studies presented in open academic literature (including academic journals, books, and conference proceedings) which pertain to the Himalaya–Ganges–Brahmaputra fluvial system are compared based on the scales selected. Moreover, the variables selected and analysis methods used are also compared. Patterns, similarities, and differences displayed by these studies are presented. Finally, potential research strategies are proposed which address gaps in the current research, especially with respect to the scales selected.

TABLE 1
Research articles categorized into three spatial scales

Study no.	Area	Authors
Local scale		
1	0.8-1.0 ha	Mathur *et al.* 1976
2	Three Villages	Saksena *et al.* 1995
3	~10 km²	Smadja 1992
4	~30 km²	Froehlich *et al.* 1990
5	55 km²	Rawat and Rawat 1994a
6	55 km²	Rawat and Rawat 1994b
7	113 km²	Fleming 1983
8	30-200 km²	Pandey *et al.* 1983
9	200 km²	Virgo and Subba 1994
10	231 km²	Haque and Hossaim 1988
11	~375 km²	Sarkar 1987
12	600 km²	Valdiya and Bartarya 1991
13	600 km²	Bartarya and Valdiya 1989
14	~1200 km²	Gilmour *et al.* 1987
Regional scale		
15	~3200 km²	Das and Chakravarti 1988
16	5,522 km²	Garg and Dun 1971
17	5,000-47,000 km²	Hofer 1993
18	5,000-57,000 km²	Bagchi 1987
19	~29,600 km²	Tiwari *et al.* 1986
20	45,000 km²	Wohl 1995
21	47,480 km²	Sharma *et al.* 1991
22	141,577 km²	Metz 1991
23	141,577 km²	Schreier *et al.* 1990
24	142,776 km²	Brammer 1990a
25	142,776 km²	Brammer 1990b
26	142,776 km²	Barrett 1990
27	142,776 km²	Paul and Rasich 1990
28	142,776 km²	Pearce 1991
29	345,848 km²	Jha *et al.* 1988
30	Central Himalaya	Reiger 1977
31	Central Himalaya	Nautiyal and Babor 1985
32	Darjeeling Himalaya	Froehlich and Starkel 1993
33	Tehri Garwal	Bandyopadhyay 1992
34	Uttar Pradesh	Sharma 1984
35	Uttar Pradesh	Singh and Singh 1986
Continental scale		
36	523,000 km²	Ahmad 1993
37	580,000 km²	Goswami 1985
38	Himalaya	Ives and Messerli 1989
39	Himalaya	Bandyopadhyay and Gyawali 1994
40	Himalaya	Hamilton 1987
41	Himalaya	Narayana 1987
42	Himalaya	Myers 1986
43	Himalaya	Subramaniam 1979
44	Himalaya	Karan and Iijima 1985
45	India	Bowonder 1982
46	India	Narayana and Babu 1983
47	India	Singh *et al.* 1992
48	Ganges R. Basin	Abbas and Subramaniam 1984
49	Ganges R. Basin	Quinn and Harrington 1992
50	Ganges R. Basin	Chaphekar and Mhatre 1986
51	Highland-Lowland	Singh 1991
52	Highland-Lowland	Eckholm 1976

TABLE 2
Research topics and scale research design

Study no.[1]	Research topic	Scale Research Design
Local scale		
1	Runoff Processes	Upscaling
2	Fuel Wood Usage	Upscaling
3	Human and Climate Slope Impact	Mapping
4	Slope and Channel Processes	Upscaling
5	Sediment Load	Upscaling
6	Stream Discharge	Upscaling
7	Cost/Benefit Analysis	Systematic Regionalization
8	Runoff, Sediment, Nutrients	Upscaling
9	Land-use Change	Mapping
10	Natural Hazard Perception	Upscaling
11	Soil Loss	Mapping
12	Hydrogeology	Upscaling
13	Landslides and Erosion	Upscaling
14	Soil Hydraulics	Upscaling
Regional scale		
15	Forest Conservation	Systematic Regionalization
16	Soil Erosion	Systematic Regionalization
17	Stream Discharge	Upscaling
18	Land-use Change	Mapping
19	Geo-forestry	Mapping
20	Flood Estimation	Upscaling
21	Stream Discharge; Sediment	Upscaling
22	Environmental Conservation	Scale Linking
23	GIS Analysis	Scale Linking
24	Flood Description	Systematic Regionalization
25	Flood Mitigation Policy	Scale Linking
26	Flood Description	Systematic Regionalization
27	Flood Damage Assessment	Systematic Regionalization
28	Flood Mitigation Policy	Systematic Generalization
29	Sediment Load	Upscaling
30	Sociology of Deforestation	Systematic Generalization
31	Population and Forest Resources	Systematic Generalization
32	Slope and Channel Processes	Systematic Generalization
33	Political Movements	Scale Linking
34	Ecological Inventory	Mapping
35	Deforestation	Systematic Generalization
Continental scale		
36	Environmental Impact Assess.	Systematic Generalization
37	River Basin Geomorphology	Upscaling
38	Himalayan Conservation	Systematic Regionalization/Scale Linking
39	Himalayan Water Resources	Scale Linking
40	Highland-Lowland Interaction	Scale Linking
41	Soil Conservation	Systematic Regionalization/Scale Linking
42	Deforestation	Systematic Generalization
43	Stream Discharge and Sediment	Upscaling
44	Environmental Degradation	Systematic Regionalization
45	Deforestation	Systematic Generalization
46	Soil Erosion	Systematic Regionalization
47	Soil Erosion	Mapping/Systematic Regionalization
48	Stream Discharge and Sediment	Upscaling
49	Water Resource Planning	Systematic Regionalization
50	Human Impact on Environment	Systematic Regionalization
51	Geographic Monitoring	Scale Linking
52	Environmental Degradation	Systematic Generalization

[1]References for each study are shown on Table 1.

METHODS

SCALE CATEGORIZATIONS AND COMPARISONS

The interaction between the Himalaya–Ganges–Brahmaputra fluvial system and floods in Bangladesh has been researched by many disciplines, using a wide variety of methodologies and research emphases as well as a wide range in spatial scales. This paper analyzes research that addressed any facet of the relationship between environmental degradation, hillslope hydrology, and flooding in the Himalaya–Ganges–Brahmaputra region. A total of fifty-two studies were identified and then ranked in ascending order by size of the study area (Table 1).

The size of the study area was taken directly from the article text or approximated from maps within the article. In some instances, a specific area was not provided. In such cases, an approximation of the spatial scale was determined from other information presented, such as place/region names and references to previous work. As a first step, each article was classified within one of the three scale categories: local, regional, and continental. The categories approximate the three scale categories (micro-, meso-, and macro-) suggested by Ives and Messerli (1989) as significant within the context of the link between the Himalaya–Ganges–Brahmaputra fluvial systems.

The local scale category represents micro-scale drainage basins, villages, and small town political divisions. The regional scale category represents meso-scale drainage basins, and physiographic regions, states, and smaller individual nations (Nepal, Bangladesh). The continental scale category represents the Ganges and Brahmaputra drainage area, the Himalaya, or a combination of both. Of the 52 studies, 14 are local, 21 are regional, and 17 are continental scale (Table 1).

In addition to study area, the research topics, designs, and models produced were examined in each article and described by key words (Table 2). These key words were used in identification of patterns within each and across all of the three scale categories.

RESEARCH CONTENT COMPARISONS

Comparisons among the research studies could be facilitated by first separating topics into two categories, physical and natural resources. Physical research represents analysis of specific Earth processes, absent of cultural, socioeconomic, and political phenomena. Natural resource research topics represent human–environment interactions, including physical, cultural, socioeconomic, and political phenomena.

In addition, five different methods or approaches to dealing with scale in the research designs were identified in the 52 articles (Table 2). The first, "upscaling," refers to the characterization of an entire study area based upon numerous point measurements. The point measurements range from stream discharge (Subramaniam, 1979) to individual household interviews (Haque and Hossaim, 1988) and randomly sampled air photos (Virgo and Subba, 1994). A second approach, termed "mapping," refers to the characterization of an area by representing selected phenomena across the entire study area through the construction of maps. Mapping techniques may include ground survey (Smadja, 1992) and air photo analysis (Tiwari *et al.*, 1986).

Two other types of scale research design focus upon the representation of phenomena and processes across space. The category termed "systematic regionalization" identifies spatial heterogeneity within the given study area, based on the processes or phenomenon in question. Examples include identification of climatic regions (Narayana and Babu, 1987), identification of different flooding regions (Brammer, 1990a), and identification of agricultural regions (Bagchi, 1987). A fourth category, termed "systematic generalization," refers to the representation of a process or phenomena as occurring uniformly across the entire study area, with little or no spatial heterogeneity. Examples of this include assumption of consistent population growth and fuelwood demand across the study area (Nautiyal and Babor, 1985), assumption of consistent sociological motivation for deforestation across the study area (Reiger, 1977), and the general description of slope and channel response to deforestation (Froehlich and Starkel, 1993). Data presented as averages for the region are commonly reported in systematic generalization.

The final type of scale research design is termed "scale linking." Scale linking represents the attempt to link processes or phenomena which occur at different scales. Examples include the linking of regional political movements to global environmental opinion (Bandyopadhyay, 1992), micro-scale farm activities to national government policy (Metz, 1991), and the effect of environmental degradation at the micro-, meso-, and macro- drainage basin levels (Schreier *et al.*, 1990).

RESULTS AND DISCUSSION

All local scale research articles, except for one, possess an explicitly defined area for the study. At the regional scale, more general or abstract definitions of the study area are presented in the studies (6 out of 21). While at the continental scale, the majority of research is conducted with general, abstract, or poorly defined areas for the study (15 out of 17).

A second pattern involves the research topics that can be identified in the research. A frequency analysis of research topics was undertaken in each category (Table 3). The local scale category is dominated by physical research (9 out of 14) versus fewer natural resource studies (5 out of 14). On the other hand, the regional scale category has only 7 physical topics versus 14 on natural resource research. At the continental scale the dominance of natural resource topics is even more pronounced (14 of 17).

Using this same type of frequency analysis, patterns of

TABLE 3
Frequency of research topics

	Local	Regional	Continental	Total
Physical	9	7	3	19
Natural Resources	5	14	14	33
Total	14	21	17	52

TABLE 4
Frequency of research designs

	Local	Regional	Continental	Total
Upscaling	10	4	3	17
Mapping	3	3	1	7
Systematic Regionalization	1	5	7	13
Systematic Generalization	0	5	4	9
Scale Linking	0	4	5	9
Total	14	21	20[1]	

[1]Three studies possessed two research designs, thus 20 instead of 17.

research design for each scale category can also be identified (Table 4). Local scale research design is dominated by upscaling (10 out of 14 articles), regional scale study research design is balanced across all five research design types (4, 3, 5, 5, 4 respectively), and only one study uses the mapping research design at the continental scale (1 out of 17 articles).

A closer analysis of the research topics of all three scale categories identifies a "scale independent" model. This model utilizes the same research topic and research design across all scale categories. For the studies reviewed, a "scale independent" model is the upscaling of stream discharge and sediment load. The model was present in all three scale categories. Thus, no matter the scale of research, stream discharge and sediment load are often extrapolated from set points to represent the entire study area.

Each of the three patterns and the scale independent model identified in this study creates implications for research of the Himalaya–Ganges–Brahmaputra interaction. The first pattern, explicitly defined local study areas and abstractly defined continental study areas, allows for varied interpretation of study results. By broadly referring to the "Himalaya" region, the author or researcher may be referring to an area perceived in various ways by readers, other researchers, and government officials. Such differing perceptions of a study area may cause improper interpretation or extrapolation of study results.

The second pattern of physical bias of research at the local scale, and natural resource factors at the regional and continental scale, may cause a disproportionate emphasis on physical or social processes as a cause of problems at either scale. Research needs to be more balanced between physical and natural resource topics within each scale category in order to identify relevant processes and their proper scale of influence. Research completed up to the present time perpetuates the concept of dominance by physical processes at the local scale and social processes at the continental scale.

The implications for research as indicated by patterns in research design are not as clear as those for study area and research topic. In fact, the patterns displayed by the three scale research design comparison are opposite of the authors' expected results. The Ives (1987) characterization of Himalaya–Ganges–Brahmaputra interaction research describes two opposing theories, the THED and the "Multi-scale" alternative. Accordingly, the authors expected the opposing theories to create a distinct division in the use of research designs across all scales. Proponents of the THED were expected to use upscaling/systematic generalization to extrapolate environmental degradation from the Himalaya to the lowlands of Bangladesh. On the other hand, the Multi-scale theory proponents were expected to utilize systematic regionalization/scale linking to illustrate the spatial heterogeneity and complexity of links between processes of the Himalaya and the Ganges–Brahmaputra lowlands.

The regional scale is balanced among the five research designs identified, and the local scale is dominated by upscaling due to the analytical method of physical variables, rather than the theoretical frameworks created by the THED or Multi-scale alternative. Only at the continental scale is a theoretical division present. Three of the four studies utilizing systematic generalization support the THED (Eckholm, 1974; Bowonder, 1982; Myers, 1986), and four of the five studies using scale linking support the Multi-scale alternative theory (Hamilton, 1987; Ives and Messerli, 1989; Singh, 1991; Bandyopadhyay and Gyawali , 1994). This slight division offers some insight into the role of scale and theory in research of the Himalaya–Ganges–Brahmaputra interaction.

Implications for research created by the scale independent model represent the reliance upon a single model for analysis. The model represents an assumption on the homogeneity of the land cover–stream discharge relationship across all scales. Of all the stream discharge/stream sediment articles reviewed for this study, none attempted a hierarchical or nested approach that tried to assess the impact of scale upon the land cover–stream discharge relationship. Thus, by assuming scale independence of this relationship, Ives and Messerli's Multi-scale alternative theory is not being investigated.

CONCLUSIONS

The three patterns and scale independent model identified in this scale comparison support several strategies for future research on the links between the Himalaya–Ganges–Brahmaputra fluvial system and floods in Bangladesh. As a first strategy we suggest targeting "neglected variables." Research topics with physical variables are under-represented at the regional and continental scales. Perhaps further investigation of physical processes at the continental scale or natural resources at the local scale will offer new insight into the link between mountain watershed alteration and lowland floods.

A second strategy for future study is to route scale independent variables, such as stream discharge and sediment load, from local mountain watersheds to the lowlands and deltas. For example, discharge from first-order Himalayan streams can be routed to the Bay of Bengal. Such a scheme may identify the different manifestations of a given process at various spatial scales. This strategy directly attacks the issue of scale by categorizing scale as a variable itself, and has been previously suggested by Ives *et al.* (1987) and Meentemeyer (1989).

The final strategy is to devise studies that discard the general scale independent stream discharge and sediment load model. Due to the predominance of this model in research at all scales, it has played a major role in development of current theory regarding the Himalaya–Ganges–Brahmaputra interaction. By discarding this scale independent model and searching for a new, perhaps scale sensitive, model, new theories, answers, or solutions to the Himalaya–Ganges–Brahmaputra dilemma may be found.

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