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A cost path and network analysis methodology to calculate distances along a complex river network in the Peruvian Amazon

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ABSTRACT

Distance is a key variable in explicating environmental, social, and economic conditions and in defining spatial and temporal patterns. Prior research has primarily focused on using simple to complex algorithms for calculating distances along road networks. In contrast, few algorithms are available for distance calculations along fluvial networks which are often more erratic, divergent and transient than road networks. Fluvial transportation is relied upon worldwide, particularly in developing regions, where communities use river networks for transportation, access to natural resources and for trade and commerce. This paper presents a methodology developed for mapping complex fluvial networks for travel distance analysis. The methodology was applied in four major river basins in western Amazonia over some 35,000 km of river length and incorporating 919 communities as origins/destinations. A cost path and network analysis methodology was created using vector and raster datasets in a Geographic Information System (GIS) to assess interactions among communities and the distances traveled by river to reach district capitals, major urban centres and marketplaces. An accuracy assessment using distance values calculated from a previous study using a different methodological approach in the region as well as Google Earth Pro, found a high degree of concordance for distance calculations. Our methodology creates a very flexible approach for complex river systems that can be use to calculate river distances in an adaptive and efficient manner and that can be use in other regions of the world where rural communities must rely on rivers for transportation.

1. Introduction

Beyond geographic location (e.g., latitude and longitude), distance is potentially one of the most important variables for understanding spatial and temporal patterns and interactions in both natural and social environments. For instance, distance is commonly used to assess accessibility (Salonen, Toivonen, Cohalan, & Coomes, 2012), interactions between entities in a network (Rouquette et al., 2013) and to evaluate natural (Hyatt et al., 2003) and social (Rossi, Byrne, & Pickering, 2015) phenomena. Distance measurements range in complexity from simple measures such as Euclidean and Manhattan distances to more complex ones based on networks (Apparicio, Abdelmajid, Riva, & Shearmur, 2008). Networks aiming to represent transportation routes or flow require elements such as origin, destination, paths, barriers and direction. Once the network is defined, computer algorithms can be implemented to determine, for example, the shortest path between two points in the network (Djokic & Maidment, 1993) or calculate distances between several locations. Estimating distances in land areas using network-based elements has become more common with the development of Geographic Information Systems (GIS) tools (e.g., ArcGIS Network Analysis, QGIS) (Djokic & Maidment, 1993), detailed digital road networks for some regions of the World, and the constant evolution of GPS technologies and WebGIS platforms (Zook & Graham, 2007). In comparison, fluvial routes and river networks are often less well mapped; still, these networks are fundamental for transportation, exchange and resource exploitation in many developing regions (Dugan, Dey, & Sugunan, 2006; Salonen et al., 2012).

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The Peruvian Amazon is highly fluvial in nature, more ‘riverscape’ than landscape (Toivonen, Mäki, & Kalliola, 2007). The complex river network of the region is greatly influenced by seasonal changes which in turn directly impact transportation dynamics (Tenkanen, Salonen, Lattu, & Toivonen, 2015). Rural peoples in the Peruvian Amazon depend heavily on the river network for commerce, social communication and sustenance (Hiraoka, 1989; Lathrap, 1973) and typically describe distances along the river network by the number of meanders to assess travel time (Abizaid, 2005). Settlement is concentrated almost entirely along the major rivers and tributaries, with Iquitos and Pucallpa being the primary markets and urban centres. Secondary markets are found in the district capitals, small riverside towns with several thousand inhabitants, and a myriad of dispersed native and folk villages dot the river banks and bluffs. Villagers practice a mix of agriculture, fishing, hunting and forest product extraction for subsistence and cash income (Chibnik, 1994). As villages are small – typically with 30–50 households – residents must rely on urban centres and towns to sell their produce and purchase supplies. Strong spatial zonation exists according to distance (time) to market, with perishable products sent from nearby areas and progressively less perishable items sent at distance (Salonen et al., 2012). Transport represents a significant cost to producers and market access conditions influence not only incomes earned but the value of assets held by households in more remote communities. In absence of local markets, households exchange key inputs such as seeds and labour, and again, distances from other settlements influence the opportunities and capabilities of rural households (Abizaid et al. In preparation). Indeed, remoteness – to market and other communities – has been suggested to be a key determinant of geographical poverty traps (Bird, McKay, & Shinyekwa, 2010; Jalan & Ravallion, 2002) and a significant impediment to poverty reduction policies (Barbier & Hochard, 2014).

In this paper we present a methodology to determine travel distances between communities using fluvial transport in the Peruvian Amazon. A cost path and network analysis methodology was created using vector and raster datasets to assess connections among communities and the distances people have to travel from their communities to reach district capitals and major urban centres and to access marketplaces and state services. Whereas an earlier study from the region calculated distances from a predetermined area to a single destination using a grid-based model (e.g. distance to Iquitos) (Salonen et al., 2012), our study allows for substitution of origin and destination communities (i.e. nodes) and adjustments to the river network as it naturally evolves (i.e. links). In an Origin-Destination Cost Matrix, distance values with the shortest impedances were calculated from every node to every other node in an iterative manner (Djokic & Maidment, 1993). In this analysis, impedance was defined as length whereby the resulting distance values reflect the shortest length of travel by river. Any location represented by a point may serve as an origin or destination, thus distances can be calculated between communities, markets, protected areas (e.g. national parks), schools, oil reserves or territories of indigenous peoples in voluntary isolation. This methodology creates a very flexible system for complex river systems that can provide distance measurements in an adaptive and efficient manner. With a standardized measurement such as kilometres, distances can be compared precisely. In determining communities' interactions and proximity along the river system, the network analysis methodology, when coupled with information on communities' travel preferences and behaviours (e.g. transportation modes), is useful in identifying isolated areas, limits to accessibility and the general fluvial transportation patterns of local communities. Although our work focused on the Peruvian Amazon, our methodology can be applied to other river networks, especially with the current development of freely accessible global databases (Lehner, Verdin, & Jarvis, 2008; Yamazaki, Trigg, & Ikeshima, 2015) and their continuous refinement for more local areas.

2. Methods

2.1. Study area

Our study encompasses a vast area (117,680 km^2) located in the administrative regions of Loreto and Ucayali in the Peruvian Amazon (Fig. 1). The area is divided into four main river basins (Amazon, Napo, Pastaza and Ucayali) that are further partitioned into sub-basins defined by the Peruvian Amazon Rural Livelihoods and Poverty (PARLAP) project (Table 1). This area presents a highly complex and extensive river network, which forms the basis of fluvial transportation for most of its inhabitants (Kvist & Nebel, 2001; Salonen et al., 2012). The river network extent covers a highly diverse set of ecosystems (Dumont, Lamotte, & Kahn, 1990; Josse et al., 2007), land use and land cover features (Oliveira et al., 2007) and indigenous and non-indigenous groups (Kvist & Nebel, 2001). A major component of this region is the floodplains (periodically inundated areas) where important economic activities such as agriculture, fishing, forestry and others take place (Hiraoka, 1989; Moreau & Coomes, 2006; Nebel, 2001). For this study, the river network extends for approximately 35,000 km, with 27,800 km in the region of Loreto and 7,200 km in the region of Ucayali.

A point layer indicating the geographic location of the communities in both regions was created from coordinates collected in the field using GPS by a team contributing to the PARLAP project (919 communities). In addition, a few communities were added and revised using the Peruvian *Instituto Nacional de Estadística e Informática* database (INEI, 2015). ArcGIS 10.2.2 (ESRI, 2011) was used to calculate the distance values for communities for both approaches included in the methodology.

2.2. River network creation

In order to create the river network for the Loreto and Ucayali regions, a base 1: 100,000 river layer (polylines) was used. To convert the river layer into an actual river network, each section was digitized into single river lines. While portions of the input river layer were represented by a single line, much of the layer outlined the banks of the rivers. Thus, a line running through the middle of the river was needed to simulate the transportation paths. The analysis is premised on the assumption that boats used by Peruvian communities, which vary in size and type (Salonen et al., 2012), would be able to travel through all river segments, including narrow areas of the river network ($\geq$5 m). However, it should be noted that accessibility depends on factors such as the type of boat and seasonality (i.e. flood or low water season) as fluctuations in the water levels (De Jesús & Kohler, 2004; Tenkanen et al., 2015) can limit access. This methodology calculates the lower bound of distance values thus those that are not affected by additional limitations of seasonality and equipment. Furthermore, all possible paths, for instance those around islands, were incorporated in the simplified river line to allow for a more accurate calculation of the shortest routes in which communities would travel to reach their destinations. Depending on the location of communities and their destinations, the shortest paths may differ when traveling around the numerous islands of this fluvial system (Salo et al., 1986).

For particularly wide segments of the river or areas that might be designated as lakes, extra lines were manually digitized to reach