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Connectivity Concepts

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1.1 The Development of ‘Connectivity Science’

The notion of connectivity can be dated back to Euler’s modelling of the bridges of Königsberg in 1736. However, the use of the term connectivity itself is a later development. Publications using the term can be traced back at least to the 1930s (e.g., Whyburn, 1931). Initially a topic within mathematics, the field grew to encompass a wide range of disciplines. The concept appeared in several disciplines in the 1950s and 1960s but did not enter geomorphology until the 1980s. By 2020, a search on Web of Science under the topic ‘connectivity’ yielded over 237,000 publications encompassing a wide range of disciplines (Figure 1.1) of which engineering neurosciences and computer sciences had the most publications (around 70,000 each), but geomorphology had only 1,102. As early as the 1950s, ideas on connectivity were crossing into new disciplines across unlikely discipline boundaries. For example, Prihar (1956) working in the field of telecommunications cited the work of Luce and Perry (1949) from the study of social groups. Notwithstanding this evidence of cross-fertilisation in the initiation of connectivity concepts, once connectivity is established in a discipline, subsequent studies proceed largely independently of developments in other disciplines within which the concept has been applied (Turnbull et al., 2018). For example, Kool et al. (2013) in a review of connectivity concepts in population dynamics that specifically claims to ‘highlight potential linkages with other fields of research’ (p. 165) cites 167 sources but, other than methodological studies, only 7 from outside the broad area of ecology. Consequently, many of the ideas that have developed in connectivity science within a particular discipline have failed to have the widest impact. Even so, it is fair to say that in many of the disciplines in which the concept of connectivity has been applied, it has led to profound insights into the behaviour of the system being studied and has had significant applications in management of some of these systems (see, e.g., Hulme, 2009; Cerdeira et al., 2010; Iori & Mantegna, 2018; Poepl et al., 2020).

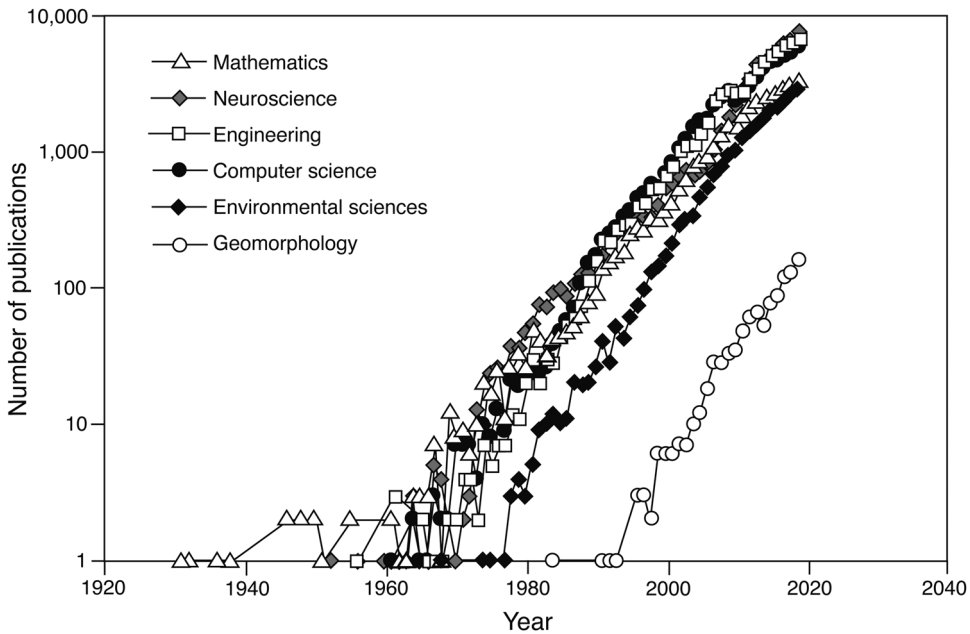


Figure 1.1 The growth of connectivity studies in selected disciplines.

Why has connectivity had such a profound impact on so many disciplines? Fundamentally, all disciplines study phenomena, and those phenomena are typically part of a system of such phenomena, be they galaxies or social groups. In order to understand phenomena, two things are necessary. First, the phenomena must be classified. Without classification, every object is unique. Their study is limited to a description of each object. Put simply, at this level, each discipline might be summarised by the statement ‘Things are thus.’ Classification moves the discipline forward such that one might say, ‘These things are thus, but those things are not thus.’ The process of classification is not straightforward. Knowing which attributes of objects A and B enable them to be characterised as ‘thus’ and of objects C and D that make them ‘not thus’ has been the subject of much dispute. We may all recognise a chair when we see one, but defining one is far from easy. As Wells (1908, p. 16) put it, ‘I would undertake to defeat any definition of chair or chairishness that you gave me.’ One difficulty of classification lies in deciding the extent to which the relationships among the phenomena should be included in their classification and, indeed, whether those relationships can be known a priori in any case or are secondary properties to be inferred from morphological similarities. Classification often dominates early phases of a discipline. For example, the voyages of discovery in the sixteenth century led to the discovery of new species and a strong desire to name these new species and to relate them, through classification, to known species. As a discipline evolves, however, relationships among

groups and individuals become a greater focus of study. As Mabbutt (1968, p. 27) commented, ‘With progressive development it is the links rather than the breaks ... with which we become increasingly concerned.’ Connectivity is, in effect, a means to study these links separately from issues surrounding classification. The growth of connectivity science might also be seen as both complementary to and a consequence of the growth of an interest in systems stemming from the seminal work by von Bertalanffy (1950) on general systems theory. Von Bertalanffy defined a system (p. 143) as ‘a complex of interacting elements’. Connectivity science focuses on the interactions of the elements of a system. The field has gained further significance with the identification of complex systems, the characteristics of which cannot be easily determined and which display such features as emergence and non-linear behaviour. Connectivity science has played a significant role in understanding the processes behind such features (Comin et al., 2020). For example, in the field of climate science, the analysis of teleconnections has thrown light on understanding the stability of the climate system (Tsonis et al., 2008).

1.2 Definitions and Terminology

Connectivity may be defined as a structured set of relationships between spatially and/or temporally distinct entities (Kool et al., 2013) or as a degree to which a system facilitates [or impedes] the movement of matter and energy through itself (CONNECTEUR). The former definition focuses on the structure of a system and the latter on the functioning of it. The two definitions may thus be seen as complementary rather than alternatives. They give rise to the separate concepts of structural and functional connectivity. The former may be defined as the configuration or arrangement of the system elements, whereas the latter describes dynamical processes operating within a structurally connected system (Turnbull et al., 2018). Although the terms structural connectivity and functional connectivity are well embedded in many disciplines, variants do exist. Bracken et al. (2013) prefer the term process-based connectivity over functional connectivity for studies of hydrological connectivity, arguing that the term functional has many uses/interpretations in hydrology already, and Wohl et al. (2019) advocates system configuration instead of structural connectivity. Notwithstanding these arguments, we will adhere in this book to the terms structural and functional connectivity because of their widespread acceptance across many disciplines.

A fundamental difference between structural and functional connectivity lies in the fact that, whereas the former can be relatively easily measured, and a variety of tools exist to do so (see Chapters 9 and 10), the latter tends to be inferred from system behaviour, so that measurement is somewhat indirect. Inferring functional connectivity from system behaviour raises two important issues.

The first is equifinality. Different functional relationships may lead to the same behaviour. Thus, there may not be a one-to-one link between system behaviour and a set of functional relationships between elements of a system. Equifinality is particularly a problem in cases where measurements of system behaviour are restricted. In the field of hydrology, it is common to measure system behaviour as a run-off hydrograph at the outlet of a catchment or base of a hillslope. But as Grayson and Moore (1992) demonstrated, many forms of system behaviour can lead to similar hydrographs. Secondly, is the issue of the consistency of system behaviour and the timescales over which consistency of behaviour, and hence a specific functional connectivity, may exist. System behaviour may be inconsistent for one of two reasons. Either the system itself is changing over time, so that its response to two identical external stimuli occurring at different times is not the same, or its behaviour may vary, both qualitatively and quantitatively, in response to differing external stimuli. Consequently, convenient as it may be, to separate structural and functional connectivity of a system, in reality, the two are interdependent. Most obviously, functional connectivity depends on structural connectivity. Dynamical processes are governed by system architecture. For example, a road network structure determines traffic flows. However, unlike road networks, many systems change their architecture in response to events. That is to say that system architecture, or structural connectivity, changes itself in response to the functioning of the system. Commonly used parts of the system may become better developed, whereas those seldom used become moribund. The system may 'learn' to adjust its behaviour in response to events, or it may be evolving under the influence of some other external drivers. Most obviously, the brain's neural network adapts in response to learning, leading to changes in system architecture and, hence, the relationship between structural and functional connectivity. Conversely, in a system with fixed architecture (such as a road network, in the short term), functional behaviour may adapt to maximise the use of the system's connections. Drivers take longer routes because traffic density on them results in shorter travel times.

1.3 Why Does Connectivity Matter?

There are probably two answers to the question why anything matters. First, there is the human desire for understanding. The discussion in Section 1.2 indicates how connectivity science aids understanding of systems. Second, there is a more utilitarian viewpoint. Does connectivity science tell us anything that is of practical value? Again, examples given in Section 1.1 demonstrate that this is the case. It can, therefore, be concluded that investigating connectivity has both theoretical and practical benefits.

1.4 The Challenges of Connectivity Science

Notwithstanding the compelling arguments in favour of studying connectivity, the ability to apply the ideas of connectivity science in any discipline requires a number of challenges to be addressed. In this section, we will investigate these challenges and some of the attempts to solve them.

The first challenge arises from the definition of a system as a complex of interacting elements. Before interactions can be studied, elements themselves have to be identified. This identification may be far from straightforward. It will depend on the scale(s), both temporal and spatial, at which interactions can be meaningfully measured. The definition of such scales may be conceptual or driven by the practicalities of techniques of measurement. In addition, though it might be self-evident that these elements would be physical entities, they need not be. For example, in social network science, elements may be ideas and behaviours, as well as individuals or social groups.

The second challenge is the nature of the interaction that needs to be measured for connectivity science to be meaningfully applied. Interactions may be directional (A affects B, but B does not affect A), non-directional (A and B are mutually interactive), qualitative (an interaction exists or it does not) or quantitative (the strengths of interactions are measured on some scale). Non-directional, qualitative interactions are more amenable to a wider range of analytical techniques than quantitative directional ones, but the benefits of applying such techniques may be outweighed by the loss of vital information about the interactions being investigated.

The third challenge is to be able to address the relationships between structural and functional connectivity and also to address the issues associated with the evolution of the system. This challenge is associated with the first insofar as these relationships are likely to be dependent on the scales of measurement.

All of the issues discussed in this chapter affect the application of connectivity concepts to geomorphology as much as they do to any discipline. The particular characteristics of these issues that may be specific to the discipline of geomorphology are the focus of Chapter 2.

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