15 Patterns of Dirt

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Nor can the geomorphologist rest content, [...] until he knows why sand collects into dunes at all, [...] and how the dunes assume and maintain their own special shapes.

R. A. Bagnold
The Physics of Blown Sand and Desert Dunes

15.1 Introduction

Many natural patterns appear when a simply structured equilibrium state is no longer preferred in comparison to a more complicated restructuring or rearrangement of the system. Our goal is typically a theoretical explanation or rationalization of the physical process, and invariably proceeds by way of mathematics; we formulate equations that describe the physical processes and seek to solve them in the appropriate context. Many standard techniques are available for the purpose to aid our analysis. For example, sometimes, hints about the patterns that will form can be extracted from a study of disturbances of infinitesimal amplitude, and so linear stability theory and decomposition into normal modes are our tools. Often, however, the ultimate, nonlinear mechanism of saturation is critical to selecting or shaping the forming pattern, and this cannot be revealed by linear stability analysis alone. Instead, we must advance into the nonlinear regime where we can use ideas from weakly nonlinear and dynamical system theory complemented by numerical simulation.

In fluid flows, instabilities are common and many kinds of patterns are observed, ranging from convection cells and surface waves to meandering jets and vortices. Such instabilities arise purely from the hydrodynamics of the flow, but by transporting solid particles in suspension, they may further shape the walls or bed containing the fluid. This is one mechanism by which patterns may appear in geomorphology, but much more significant are new effects introduced by the interaction of the flow with the erodible bed over which the fluid runs. By this interaction, many new complex patterns arise.

In their full complexity, erosion and sedimentation result from the dynamical interaction between a turbulent fluid flow and the granular medium composing the bed. But we know only a little about turbulence, much less about granular
media, and not much at all about their interaction. Consequently, the theoretical problems one must formulate to understand geomorphological patterns generated by sediment motion are all, at present, intractable. Instead, drastic simplifications must be tolerated, and in many instances empiricism necessarily replaces first principles. However, even though some of the basic aspects of this field are “built upon sand,” in the last forty years much progress has been made, and our overall understanding of geomorphic patterns has significantly increased.

In this contribution, we briefly discuss some of these results, choosing those that are both simple and close to our hearts. We concentrate mainly on patterns that are found in association with waters running in sloping channels. Similar patterns are generated by the interaction of sea water and coastal sediments (such as sand waves, or tidal bedforms), and by the interaction of air and sand (aeolian bedforms, such as desert ripples and dunes) – and these are described in following chapters.

We embark with an introduction to the phenomenology of natural channel dynamics through a succession of images of bedforms, channel shapes and drainage networks. Our theoretical discussion then begins with a description of sediment transport and it continues with the formulation of the governing equations and an exploration of the linear stability problem for the simple case of a shallow water approximation. We pose briefly to describe an example of a purely fluid dynamical instability – the roll wave. Subsequently, we plunge into the dynamics of flows over an erodible, non-cohesive bottom, and we discuss some of the pattern-forming instabilities of the coupled fluid–dirt system. We hope that these specific examples will be of some use to start the journey into the realm of dirty flows, which continues further and deeper in chapters to follow.

15.2 Bedform Phenomenology

When a turbulent fluid flows down a channel having a non-cohesive bottom, composed by sediment such as sand that can be moved from one place to another, several things can happen. A first important point concerns the bottom stress exerted by the flowing water. If the stress is large enough to lift the bottom material, then the interaction between the flow and the sediment can generate bedforms – patterns of sand on the bottom of the watercourse. These include ripples, dunes and anti-dunes (Fig. 15.1). Second, the water course itself can become disrupted or diverted by the large-scale redistribution of bed material. This creates a pattern in the shape of the watercourse, such as braids and meanders (Figs. 15.2, 15.3). Finally, on the grandest scale, there can be multiple

\[\text{In this discussion we consider only cases where gravity is a stabilizing factor that competes with the sediment mobilization induced by the stress exerted by the fluid. When the channel slope is large, gravity can become a destabilizing factor, and a large portion of the bottom sediment becomes entrained in the fluid. In such a situation, one speaks of a debris flow, a fluid composed of a mixture of water and sediment. One of the following chapters is entirely devoted to debris flows.}\]