Estimating hydraulic and aerodynamic roughness using illumination and shadow of digital elevation models

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1. Introduction

The estimation of flow resistance in wind and water is complex due to the influence of many factors including boundary characteristics and flow variation. For uniform bounded flow conditions much of the hydraulic resistance may be attributed to grain roughness and flow resistance and is usually estimated with the Colebrook-White equation where the grain diameter is modified by a multiplier to account for the non-uniform nature of gravel-bed roughness (Hey 1979). Despite the widespread use of this approach it is widely recognised to be inaccurate, particularly for open channel flow under natural conditions where other roughness factors also influence the overall flow resistance (Bathurst 1981, Carling and Reader 1982, Richards and Clifford 1991, Clifford et al. 1992). However, flume studies have identified and corroborated the finding that roughness is controlled by object size, shape (height, width and thickness), and spacing (Sayre and Albertson 1963, Nowell and Church 1979). Despite extensive wind tunnel and field work the estimation of aerodynamic roughness length also remains crude (Dong et al. 2002).

The aim here is to develop a recently introduced method for estimating fluid flow roughness (hydraulic and aerodynamic) based on the relationship between fluid drag and the shadow cast by roughness elements at varying illumination angles (Chappell and Heritage, 2007). The significance of the new approach is that it is spatially distributed and has the potential to tackle spatial heterogeneity to deal with scale and roughness type issues. The concept is based on the relationship between fluid flow and illumination angle. It will be tested by establishing the relationship between the area in shadow for given illumination conditions (angle and direction) and the parameters defining hydraulic roughness validated against previous flume and wind tunnel studies. This is made possible by the simulation of virtual surfaces comprising various roughness elements and configurations (fields) using a fine resolution digital elevation model (DEM) matching surfaces reported in previous studies. The new methodology provides improved estimation of hydraulic and aerodynamic roughness and may be integrated into wind and water flow models to enhance their predictive capability.

2. Methods

2.1 Concept

In fluids exhibiting unbounded flow (e.g., air) velocity increases from close to zero at the surface (z_0) to the free-stream velocity at a height where the frictional effect of the surface becomes negligible. The form of the velocity increase is strongly dependent on the size and configuration of the roughness elements at the surface. As the surface roughness increases it acts to retard flow close to the boundary where the shear velocity and the average velocity decline (Figure 1a). In a simple situation where the surface roughness is represented as a vertical obstruction on a flat surface, its drag may be conceived as a vector-based triangle. The vertical component represents the height above the surface with an average flow velocity (V_d). The horizontal component represents the roughness element height (h) relative to the surface (Figure 1b). The angle α ($aTan(V_d/h)$) increases as roughness height (h) increases and/or average velocity height (V_d) declines.

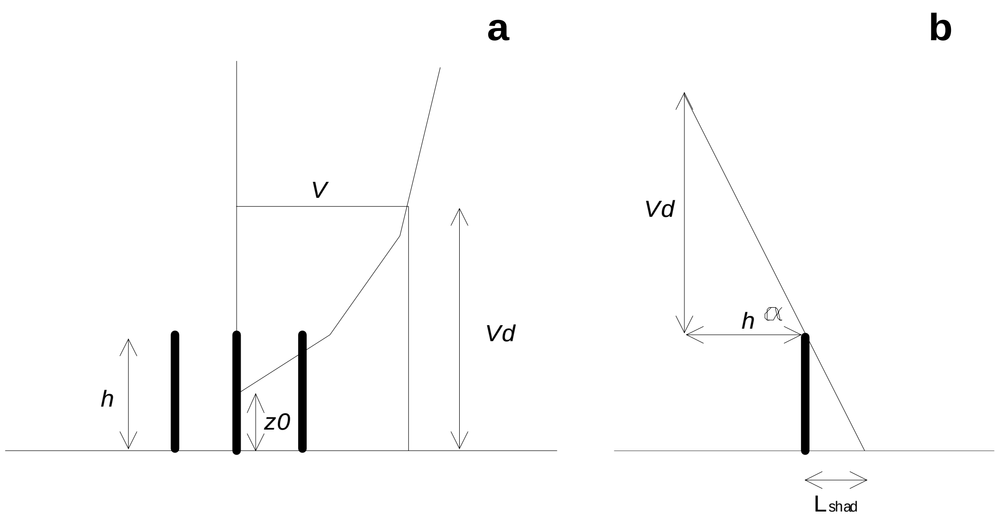

Figure 1. Relationship between shadow, roughness height and average wind velocity for unbounded flow.

Under conditions of bounded flow (e.g., water) the continuity equation states that flow depth is proportional to the flow velocity, hence the overall depth of flow (d) and the surface roughness (h), act to influence the velocity profile (Knighton 1998). Under bounded conditions it is possible to substitute flow depth for average velocity and the depth and object height components have been linked here to form a single index (h/d) analogous to the relative roughness (Figure 2a). Using the simple situation of a single vertical roughness element, flow depth (d) and roughness height (h) may be represented as the vertical and horizontal components of a triangle. The angle α ($aTan(d/h)$) increases as roughness height (h) increases and/or flow depth (d) declines (Figure 2b).

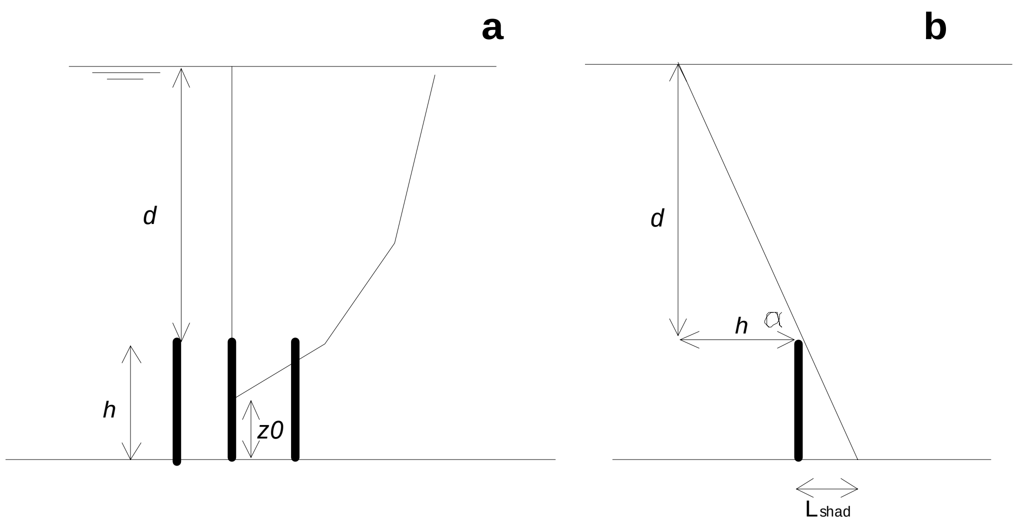

Fig. 2. Relationship between shadow, roughness height and flow depth for bounded flow.

In these cases of bounded and unbounded flow, the angle α may be translated to the surface as the length of the shadow (L_{shad}) to describe the distance between the roughness object and the incident point with the surface along the length of an imaginary ray of light (downray). For an object placed on a flat surface, shadow length (L_{shad}) is a function of the angle of incidence of a light ray on an object described by the tangent of the angle created between the object and the light ray (α) multiplied by the object height (h_{obj}) ($=aTan\ (d/h).h_{obj}$ or $aTan(V_d/h).h_{obj}$)

2.1 Application

A computer programme was written to automate the shadowing procedure across DEM surfaces. It allowed the relationship to be established between shadow area and the parameters defining surface roughness (object shape, size and spacing). Surfaces (400x400 units) comprising discrete roughness elements (fields) were simulated using a fine resolution digital elevation model (DEM). Flow depth and velocity effects were investigated using incremental shadow angles ranging from 5° (large flow) to 85° (small flow) across a uniform surface of square blocks. Height, width and spacing effects were investigated using square blocks of 10, 20 and 30 units arranged on the surface in a regular diagonal pattern with inter-block spacings of 1, 2, 5, 10, 15 and 20 units. Block height was set at 0.5, 1, 1.5, 2 and 5 times the unit width. The angle of incidence was varied across surfaces from 5^o to 85^o. The effect of element shape on shadowing characteristics was also investigated using computer-generated surfaces of regular diagonally spaced hemispheres exhibiting identical size and spacing characteristics to the blocks (Figure 3). The angle of incidence was varied across surfaces from 5^o to 85^o. Shadow area was calculated for comparison with the block results.

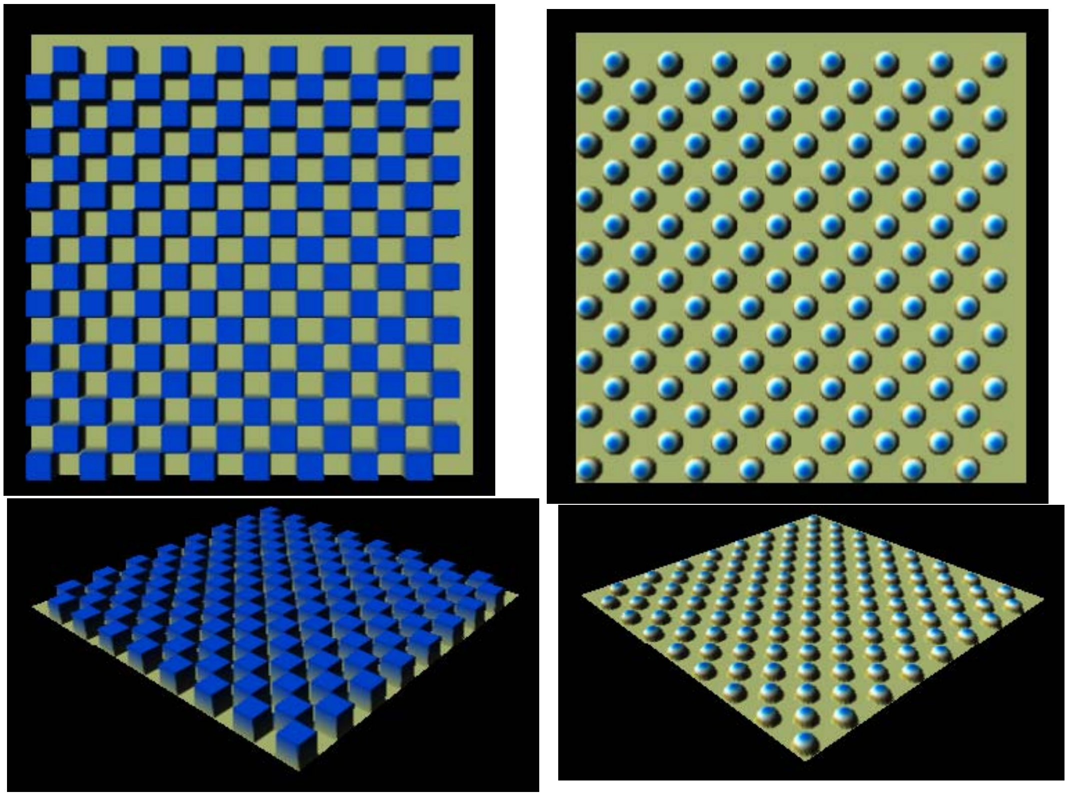

Figure 3. Example simulated block and hemisphere surfaces used in the shadowing process.

The affect of roughness element shape on the form of the shadow area-incidence angle relationship was investigated. A surface comprising equally spaced 20-unit diameter blocks was shadowed and compared with that of similarly spaced 20-unit hemispheres vertically elongated to a height of 20 units (Figure 3).

The ability of the new approach to estimate hydraulic and aerodynamic roughness was also investigated by simulating artificial flume and wind tunnel surfaces and comparing shadow values with measured roughness values. Flume data was used from Sayre and Albertson (1963), Vittal et al. (1976) and Nowell and Church (1979). All three studies provided detailed descriptions of their flume arrangement, measures of hydraulic roughness and uniform spatial roughness for differing roughness elements; sheet baffles (Sayre and Albertson 1963), Triangular ‘dune forms’ (Vittal et al. 1976) and square ‘lego’ blocks (Nowell and Church 1979). Shadow areas were simulated using the computer-generated surfaces of the flume configurations. The relationship between shadow and aerodynamic roughness was investigated using wind tunnel data from Dong et al. (2002) who present the results of a study to determine the effect of nearly hemispherical gravel elements of varying size and spacing on local aerodynamic roughness as defined by the roughness length (z_0). They provided a description of their wind tunnel arrangement and aerodynamic roughness length for a variety of gravel hemispheres arranged uniformly.

3. Conclusions

Fluid flow represents the dominant geomorphological agent acting to alter the land surface through erosion and deposition. Aerodynamic / hydraulic (fluid flow) roughness has a direct affect on fluid motion by retarding flow close to the surface and influencing the velocity profile and hence shear stress acting on the surface. Consequently, roughness characterisation has assumed importance in many fields (e.g., meteorology, open channel hydraulics, acoustics and wind erosion). Despite its widespread demand, the accurate estimation of fluid flow roughness remains problematic in practice as evident in the empirical approaches employed in the literature.

The alternative model presented here innovatively represented fluid drag as the shadowed area of a rough surface characterised by a fine resolution digital elevation model illuminated at an angle dependent upon the local roughness height, flow depth or average flow velocity. The approach developed existing work on shadow and object shape, size and spacing. The model proved to be sensitive to shape and spacing parameters and offered new insights into the relative effect of these variables. Shadow area computed for a variety of flume and wind tunnel configurations corresponded remarkably well to published roughness index values for their respective surfaces. Conceptually, the methodology presented here has the advantage of providing a single roughness measure for spatially complex surfaces across differing types and scales of roughness elements. It also has the potential to account for large temporal variations that exist with turbulent phenomena. The model has considerable potential to improve the estimation of fluid flow roughness over complicated heterogeneous surfaces across multiple spatial scales because of its use of increasingly availability of digital elevation data.

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