What is suspended sediment?

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Suspended sediment is conventionally regarded as that sediment transported by a fluid that it is fine enough for turbulent eddies to outweigh settling of the particles through the fluid. In rivers, this load is generally divided into suspended bed material and finer material introduced into the flow (particularly during storm runoff), termed the wash load (Figure 1). In the field of aeolian sediment transport, suspended sediment is simply classified based on residence time in the atmosphere (Tsoar and Pye, 1987; Figure 2). Any such classifications, however, are secondary to the fundamental understanding of the mechanism by which suspension is achieved. Early work in the fluvial field (for a review see Graf (1971), and for the development of these ideas see Clifford (2008)) attributed suspension to turbulence, and led to the notion of a critical threshold for maintaining sediment in suspension. Specifically, this threshold was applied to the manner of transport of material entrained by the fluid from its bed, but in principle applies equally to the maintenance in suspension of material introduced into the fluid, for example by storm runoff into a river. Based upon qualitative reasoning from photographs (Prandtl, 1952), Bagnold (1966) postulated that sediment is maintained in suspension as a result of an asymmetry between upward and downward velocity components of shear turbulence that gives rise to a residual upward momentum flux. He argued that it is this residual upward momentum flux that resists the tendency of the particle to fall under gravity and supports the mass of suspended sediment. He further argued that, since the movement of suspended sediment is unopposed, it travels with the same velocity as the fluid in which it is suspended.

The critical condition for sediment of a particular size being maintained in suspension by a given fluid flow – expressed as the critical shear velocity – has been the subject of considerable research in the fluvial literature but rather less so in the aeolian literature. The research has led to a variety of values for this critical condition (Figure 3). While for silt-sized grains composed of quartz the differences are very small, for sand-sized grains the differences in critical shear velocity range over an order of magnitude. Despite their numerical differences, however, all of these calculations for the critical conditions share a common characteristic: that they are based upon some ratio between a critical value of the time-averaged shear velocity u_{*c} (m s^{-1}) and a time-averaged downward particle velocity that is assumed to be equal to its settling velocity w_s (m s^{-1}). The reasoning behind this assumption is that the fluid flowing around a bed particle induces a drag that is comparable to the resistance exerted by the fluid on a suspended particle as it settles. The use of u_{*c} rather than the residual upward velocity component of shear turbulence for defining the critical conditions is justified by the fact that the latter varies with the former (Bagnold, 1966). In consequence, these equations predict that so long as the dimensionless critical threshold u_{*c}/w_c exceeds a critical value (k), under steady flow the sediment will remain in suspension. In the field of aeolian sediment transport, Owen (1964) proposed that the ratio of shear velocity to the particle's weight could be used as the upper limit for parabolic saltation trajectories of particles in wind. Bagnold (1966) tested the ratio u_{*c}/w_c for the critical conditions for suspension of particles by wind, and argued that the observed minimum size of dune sand provided support for the argument. Cooke *et al*. (1993) define k as equal to 1 for aeolian suspension. The situation for suspended sediment transport in air is further complicated by the greater range of particle densities that result from the greater degree of particle aggregation in air than water.

Research on both turbulence structures and the interactions between suspended sediment and bedforms in rivers has shown a more complex story. Coherent turbulent flow structures, such as eddy-like, macro-turbulent structures (Roy *et al.*, 2004) and smaller-scale bursting events such as sweeps and ejections (Grass, 1971), reveal a two-way vertical exchange of fluid momentum between the sediment bed and the water surface. The advection and propagation of these turbulent flow structures results in this exchange being intermittent, of short duration and high magnitude (Willmarth and Lu, 1972). Thus the movement of suspended particles is strongly governed by the dynamics of these structures (Clifford *et al.*, 1993; Nezu and Nakagawa, 1993; Ashworth *et al.*, 1996; Niño and García, 1996; Nikora and Goring, 2002; Cuthbertson and Ervine, 2007). Suspended particles are driven both towards and away from the bed by these coherent flow structures, often expressed at the water surface as "kolks" or "boils". These periodic motions can cause order-of-magnitude variations in apparent suspended sediment concentration and are thought to be responsible for much of the vertical mixing in rivers (Lapointe, 1992; Kostaschuck and Church, 1993; Thorne *et al*., 1996; Babakaiff and Hickin, 1996). Turbulence is responsible not only for the travel of suspended particles but also their entrainment and subsequent deposition (e.g. Bai *et al*., 2013). Thus the latter are not simply a function of the ratio between time-averaged shear velocity and settling velocity, as often assumed by earlier work. The further implication is that if turbulence causes suspended sediment to be repeatedly deposited and re-entrained then the sediment spends periods of time on the bed awaiting re-entrainment. Consequently, it has a virtual velocity that is less than the velocity of the transporting medium.

This body of research indicates that suspended sediment neither travels with the same velocity as the flow in which it is suspended (Breugem, 2012), nor is it likely to remain in suspension in perpetuity, even under conditions of steady flow or in unsteady flow the where dimensionless critical value of *k* is permanently exceeded. Rather, like bedload (e.g. Hassan *et al*., 1991; Ferguson and Wathern, 1998), it travels in a series of hops, and is repeatedly deposited on the bed where it remains until it is re-entrained. Is there, therefore, a qualitative difference between suspended and saltating sediment, or is it just a quantitative difference in the size of the jump length and the frequency of re-entrainment? Van Rijn (1984) would appear to argue in favour of the latter definition inasmuch as he defined suspended sediment as that which does not touch the bottom for a streamwise distance of least one hundred particle diameters. Graf (1998: 384) begins the section on suspended-load transport with "transport of sediments in suspension is the mode of transport where the solid particles displace themselves by making large jumps, but remain (occasionally) in contact with the bed load and also with the bed". Van Rijn's definition has been frequently used since it was first introduced but as Niño *et al.* (2003: 250) note "… the definition of the precise threshold level has only statistical significance. Actually, there is a transition range of increasing values of the shear stress in which the frequency of the entrainment events, and the number of particles entrained by those events, increases from a negligible value to a large value". Graf's (1998) depiction of the path of suspended bed material (Figure 1) shows remarkable similarity to that of saltation in the aeolian literature in which there is also a recognition that the boundary between saltation and suspension is far from clear (Nickling and McKenna Neuman, 2009), and the term "modified saltation" has been used to denote the trajectories of saltating particles that are affected by turbulence (Tsoar and Pye, 1987, Figure 2). We would argue, therefore, that there is no inherent physical difference between so-called suspended sediment and bedload or saltating load, and that, in reality, all sediment transport lies along a continuum of hop lengths and virtual velocities. It is our contention that the distinction of suspension as a separate class of sediment transport is both arbitrary and an unhelpful anthropocentric artefact; and to an extent is one that has come about because of measurement techniques

If such a position is accepted then our current knowledge of virtual velocities and hop lengths is limited to the coarse end of this continuum. There has been substantial research into the virtual velocity (Hassan *et al.*, 1992; Ferguson and Wathen 1998; Haschenburger and Church 1998; Ferguson *et al.*, 2002) and hop length (Drake *et al.*, 1988; Habersack 2002; Heays *et al.*,2010; Lajeunesse *et al.*, 2010; Roseberry *et al.*, 2012) of bedload in rivers. Similarly, research on hop lengths (e.g. Nalpanis et al., 1993; Cheng et al., 2006; Zhang et al., 2007) and velocities (e.g. Rasmussen and Sørensen 2005; Kang et al., 2008a,b) of saltating particles in air is well established. However, because neither concept has been thought relevant to so-called suspended sediment, details of how fast suspended sediment moves in relation to the velocity of flow, either as virtual velocity including the periods of rest on the bed or as actual velocity during movement, is lacking. If we recognize that sediment transport is a continuum and applies to any fluid medium rather than split into different “processes” based on arbitrary thresholds and fluids, then recognizing the continuity will enable development of an holistic approach sediment transport, and thus sediment-transport models that are likely to be viable across a wider range of conditions than hitherto.

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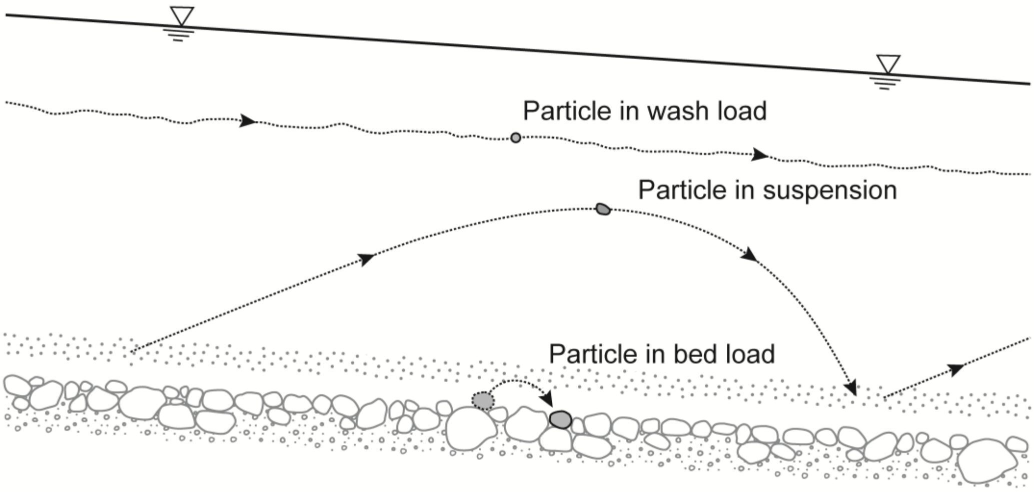

Figure 1 Modes of hydraulic sediment transport (adapted from Graf, 1998)

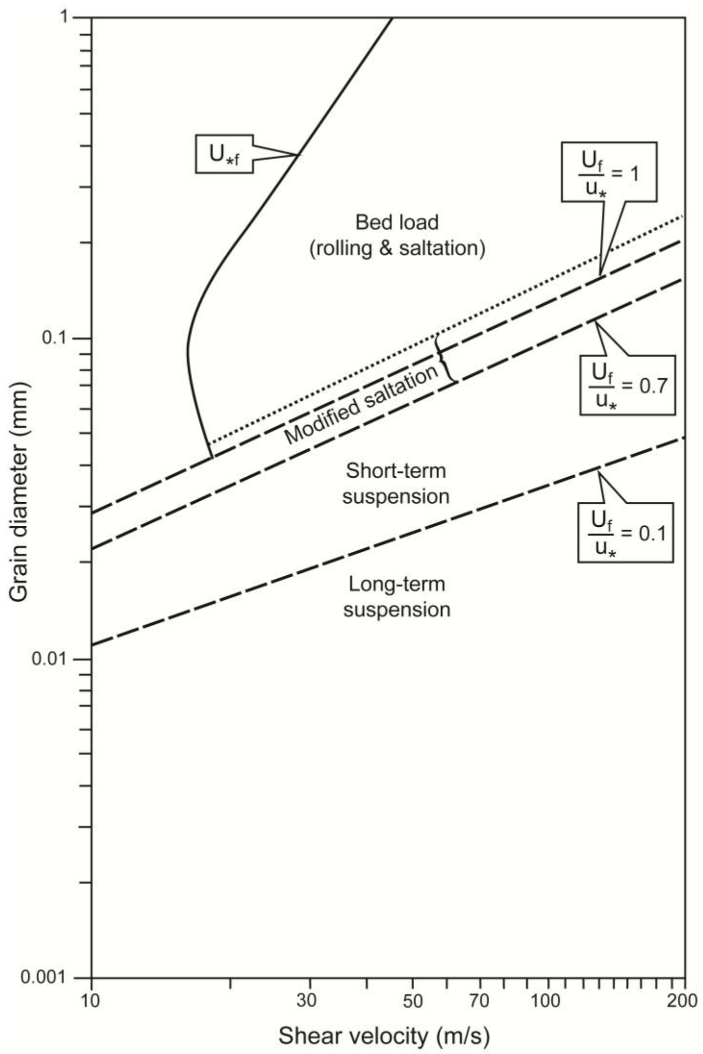

Figure 2 Modes of sediment transport in air (adapted from Tsoar and Pye, 1987)

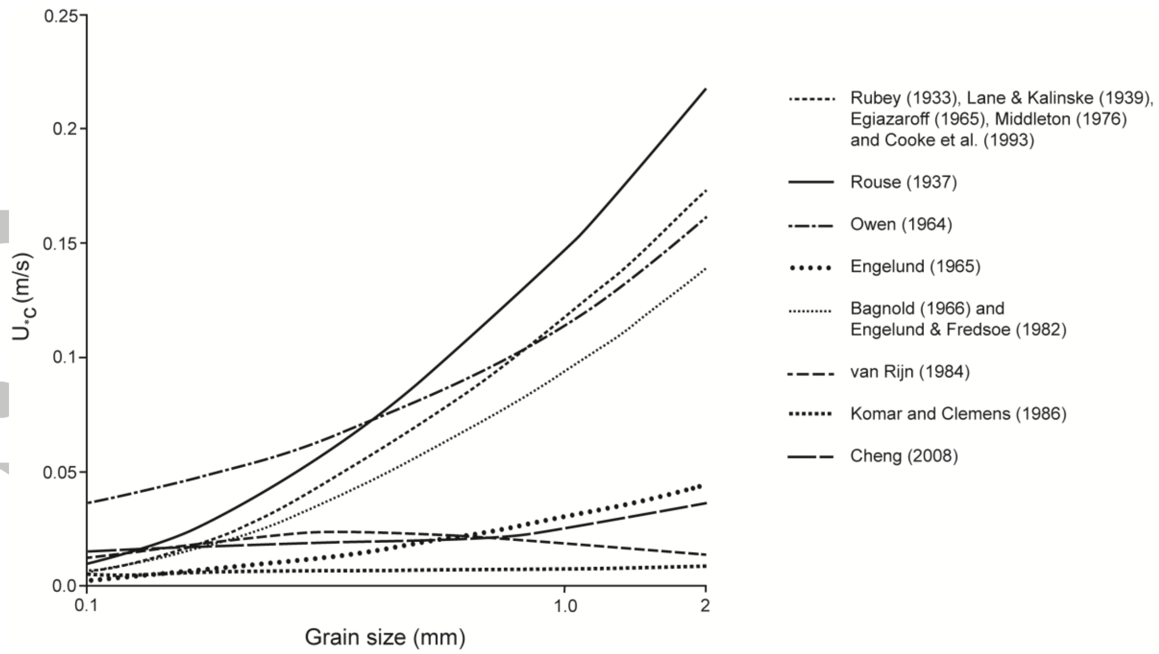

Figure 3 Estimates of the critical shear velocity for suspended sediment motion for grains of varying size.