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Hillslopes, rivers, plows, and trucks: mass transport on Earth's surface by natural and technological processes

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Earth Surface Processes and Landforms

ABSTRACT: The surface of the earth is being transformed by a new force in the form of technological systems and processes that move significant quantities of mass large distances. Because movement of mass is perhaps the most basic geomorphic process, and because the continuing rise of technology appears to characterize a new epoch in earth evolution (the Anthropocene), it is of interest to compare technological and natural mass transport mechanisms. A purely dynamical 'mass-action' metric, representing the product of mass displaced, distance moved, and mean speed of displacement, is used to compare the transport effectiveness of selected systems. Systems with large mass-action tend to be advective, and systems with small mass-action diffusive. Local environments are conditioned by mass-action through the introduction of transport corridors, such as roads and rivers, which put constraints on mass transport by embedded diffusive systems. Advection also subjects local environments to externally determined time scales, such as the times for delivery of unit mass of water or sediment to a river mouth, and supports the emergence of associated dynamical processes there, for example those of human activity or delta construction, that are too rapid to be sustained by diffusion.

Most of the world's mass-action is generated by the motion of fluids of global or continental extent, as in atmospheric circulation or river flow. Technological mass-action exceeds that of all land-based geomorphic systems except rivers. Technological systems with large mass-action tend to be comprised of discrete, self-powered units (e.g. trucks). Discretization of transported mass reflects the different locomotion strategy required for transport of solids on land, compared with the transport requirements of spatially extensive fluids in nature. The principle of maximum entropy production may provide a framework for understanding the emergence of advective, technological mass-transport systems. Copyright © 2010 John Wiley & Sons, Ltd.

KEYWORDS: mass transport; technoloy; anthropocene; humans; mass-action

Introduction

Mass transport is a fundamental geomorphic process. Perhaps the main use made of mass flux in geomorphological studies is to calculate its divergence – the difference in mass flow into and out of a given volume – which , combined with mass conservation, permits conclusions to be drawn about changes in surface topography. Without displacement of mass, landscape would remain unchanged, and without consideration of mass dynamics, no explanation for the patterns and shapes found on the earth's surface could be found. These points are so obvious that in analyzing earth surface processes we often skip over the phenomenon of mass transport itself and focus instead on specific mass-displacement mechanisms and their consequences. Thus, hillslope evolution is explained in terms of gravity-driven creep of soils (Culling, 1963; Carson and Kirkby, 1972; Fernandes and Dietrich, 1997; Jyotsna and Haff, 1997), fan and delta evolution are analyzed in terms of sediment erosion and deposition mediated by fluid stresses (Paola *et al.*, 1992), the effects of volcanic eruptions are studied through application of aerodynamics to tephra falls (Carey and Sparks, 1986), and so on. It is of course well appreciated among geomorphologists how mass-movement driven by the use of technology is changing the land surface. Hooke (1994, 2000) and Wilkinson (2005) are among a relatively small number of authors who have made a comprehensive, quantitative comparison of the contributions of technological (e.g. agriculture, mining, and construction) and natural processes to the quantity of mass moved per year on the earth's surface. Hooke (1994) showed that if plowing is included, modern humans displace a greater mass of soil and rock per year than all natural geomorphic processes combined. Similarly, Wilkinson (2005) argued that humans are an order of magnitude more effective at moving soil and rock than is the sum of all natural surface processes. Most other studies have considered more specific consequences of technology on mass movement, for example, changes in patterns of sedimentation and runoff due to farming or site construction (Wolman, 1967), destabilization of soils by off-road vehicle activity (Webb and Wilshire, 1983), or alteration of stream patterns by dams (Walter and Merritts, 2008). Most such studies focus on how natural systems respond to anthropic activity, with technology-driven mass movement treated as an impact or perturbation on the "normal" or "natural" function of the earth's surface.

Here, a different approach is taken. Instead of focusing on the consequences of specific impacts of technological mass-movement on nature, basic dynamical characteristics of technological and natural mass transport are compared, and, on the basis of that comparison, we try to gain a new perspective on the role of technology in transporting mass on the earth's surface. One observation is that although elevation change driven by divergence of mass flux is often an important consequence of mass transport, mass flux also plays a potentially significant role in earth surface dynamics even when net changes in elevation are small or absent, for example by the introduction of mass-transport pathways that constrain transport by other systems that also use that surface: the presence of a highway strongly influences mass transport in small streams and transport of biomass along animal pathways. The investigation of new perspectives on earth surface function in a technological world comprises part of what was earlier called neogeomorphology (Haff, 2002; 2003) – the study of the earth's surface that treats the deployment of technology as the continuation of the natural evolution of the earth, and thus as an intrinsic component of earth function rather than an add-on effect. For convenience, the word 'natural' is often used below with its traditional meaning – to distinguish the anthropogenic from the non-anthropogenic – but the basic viewpoint of the paper is that technology is an emergent earth surface phenomenon, and as such is a part of nature. Humans and technology are natural.

The initial motivation for the present study was to investigate how distance of transport affected the comparison of natural versus technological mass transport. Hooke's work (1994) showed that human activities moved more soil per year than all the earth's rivers, but I wondered how the comparison would stack up if the great distances of river transport relative to many human earth-moving activities were factored in. This study was also stimulated by the observation that the earth has likely entered a new epoch in its geologic history – the Anthropocene (Crutzen and Stoermer, 2000) – where the influence of humans and technology increasingly competes with nature in defining planetary behavior. To put the latter point in perspective, imagine an alien observer with no knowledge of earth biology, humans, or technological transport systems like highways, who lands on earth at the beginning of a new geologic period, the Silurian. She would notice the recently emerged vascular land plants, with their characteristic waxy cuticles, stomata, and xylem supporting tissue, all of which were then novel developments. These structures were clearly generated in each case by the plants that bear them, and they play roles that are critical to plant function. If she had a scientific bent, our alien would avoid teleological explanations for the origin of these features, and would not attribute their emergence to the 'intention' of the plants to establish themselves on land. Presumably she would settle on Darwinian evolution as a suitable explanation. If our alien then visited the present epoch, the Anthropocene, she would observe recently emerged human organisms that have spread across the earth's surface, much like land plants did during the Silurian. As in the case of plants, she would see that the global human population is supported by a set of novel characteristics that are essential to its existence, including the ability to construct technological devices and systems. Without technology, the size of the modern human population would soon collapse toward Stone Age values (about 4×10^6 individuals (McEvedy and Jones, 1978)). The proximate origin of technology can be located in human intentional behavior in the same way that the mechanisms of developmental biology represent the proximate origin of essential plant characteristics, but, as in the case of plants, our alien might be inclined to look for broader physical principles to help explain technological emergence. To the extent that such technology leads to major changes in earth surface function, the question of its emergence is of interest to geomorphology.

Mass-Action

A useful first step in this direction that looks beyond human intention and the specific design of individual technological systems is to consider the fundamental physical variables that characterize all dynamical systems, whether natural or technological. An analysis based purely on physical variables places nature and technology on the same footing, and allows a direct, dynamical comparison of processes between the two classes of systems. A suitable language for describing not just the amount of mass that is moved but the *effectiveness* with which it is moved can be constructed from the variables mass, length, and time (or speed). Here, these quantities are combined to define a metric of mass-movement, which I call the *mass-action*.

Consider an object transported as part of an arbitrary physical system. The object or 'part' transported might be a truck on a highway, a drop of water in a river, a parcel of air in the atmosphere, a human being afoot, a pile of soil being pushed by a bulldozer, and so on. If the object in question has infinitesimal mass, or if it moves zero distance, or if its rate of movement is indefinitely slow, then any reasonable metric of mass-transport should vanish. Thus, I define the mass-action a of an object to be the product of its mass m, times the distance l it moves between changes in direction, times its average speed, v, between such changes, i.e. $a = mlv$. A metric based on mass-action is used below to compare the mass-transport effectiveness of natural and technological systems, to discuss environmental effects of large-scale mass transport, to identify some distinguishing characteristics of technological mass transport on land, and to suggest one approach for understanding the emergence of technological transport as an earth surface process.

Through its dependence on velocity, v, the value of mass-action depends on the reference frame chosen to describe the motion. The reference frame used here is one that is fixed to the surface of the earth. (The mass-action of very slowly moving tectonic plates is estimated from the point of view of an observer attached to one of the plates.) Mass-action has dimensions $mass \times length^2/time$, or $energy \times time$, which are the dimensions of what in physics is called 'action' (Landau and Lifshitz, 1960), hence the name 'mass-action'. The mass-action for a composite system, comprised, for example, of the trains in a railway system or the sediment grains on a hillslope or in a river bed, is computed as the sum of the mass-action of its parts $A = \Sigma mlv$, i.e. a sum over all trains, sediment grains, or other transported elements.

Other metrics of mass transport than mass-action (mlv) or mass displaced per unit time (mt^{-1}) (Hooke, 1994) might include average momentum, i.e. mass moved weighted by average speed of displacement (mv), or a measure proportional to average kinetic energy (mv^2). Weighting displaced mass by powers of the speed alone, without weighting by distance, has the disadvantage of not distinguishing between very short but fast motions, such as thermal motion of molecules, and slower but longer motions associated with bulk displacements. For example, the total kinetic energy at room temperature of the molecules of a body of water at rest is of the same order of magnitude as that of the body moving as a whole at the speed of sound in air – two very different types of motion. Mass-action is the simplest metric of mass movement that includes both speed and distance weighting, allowing it to distinguish such cases.

It may be worth noting that in physics the principle of least action (Hamilton's principle) says that a conservative mechanical system evolves in such a way that its action is a minimum (Landau and Lifshitz, 1960). If we consider only average motion without explicit reference to forcing mechanisms, as if the mass moved freely along its pathlength l, then the action corresponding to this averaged motion would be the time integral of its kinetic energy between the known temporal endpoints of motion. Numerically, the mass-action values reported below represent the minima of this action. Since the principle of least action is the most fundamental statement of the dynamics of any such mechanical system, mass-action as used here is the most fundamental descriptor of average mass motion that can be captured in one number.

It is useful to rewrite the mass-action of a single part or subsystem, such as an automobile or parcel of air, in terms of mass, distance and time $a = ml^2/t$. If the part moves a distance l from one point to another, and then changes direction, like a molecule in a gas when it undergoes a collision, or an automobile when it turns a corner, then t measures the time between starting one leg of the trip, or displacement, and starting the next leg. In gas dynamics t is the collision time, and $v = l/t$ is the actual molecular speed. More generally, if a part remains at rest for a period of time before resuming its motion, then t is taken as the sum of the time of actual motion plus the dead-time elapsed until motion begins again. Then v is the average speed between events that result in changes in direction of motion. If the part momentarily stops moving, but then continues its motion in the same direction, l is taken as the total distance covered until a change of direction does occur, and the average speed is taken as the total unidirectional distance moved divided by the total time t between changes in direction of motion (including any dead-time). The velocity (and hence mass-action) computed below for a composite system of many parts, such as trucks in the highway transportation system, is thus averaged over times long compared with the time interval between changes in direction of motion of a typical constituent part (truck).

A change in direction is the operative criterion for resetting the clock to zero because it distinguishes between two principal modes of transport. Many changes in direction over a period of time imply diffusion-like motion, while no or little change in direction over the same period implies advective-like motion – in one step the mass moves with speed v a distance l. The product lv has the dimensions of kinematic diffusivity (*length*^{2}/*time*). If the mass to be transported moves a vector distance $x > l$ via a mechanism governed by the diffusivity lv, the time τ to move that distance is given by $\tau \sim \frac{x^2}{lv}$, i.e. τ increases as the square of distance. However, if $x < l$ then the particle moves along a straight path, the motion is advective (or ballistic – the single particle analog of advection), and time is proportional to distance, $\tau \sim \frac{x}{v}$. In the discussion below we use the term "diffusive" loosely in reference to systems that support short distance displacements even if those displacements are not strictly random walks. In cases where short-pathlength, diffusion-like motion is superimposed on longer distance transport pathlengths, as when suspended sediment that locally follows the quasi-random motion of turbulent eddies is carried in the downstream direction by the mean river-flow, we choose the longer pathlength with which to compute the mass-action, since it is the more advective process that determines overall system mass transport effectiveness. Other displacement mechanisms may involve back-and-forth or shuttling motion in which there is no net average displacement, as in movement of rolling stock between coal mines and power plants, or of automobiles between home and workplace. As above, these motions are classified as diffusive or advective relative to one another, depending on the values of displacement distances between changes in direction of motion. The significance of mass-shuttling as an earth surface process may rest more on the effects of displacement pathways on the local environment, as discussed below, than on changes in surface topography induced by mass-flux divergence.

If characteristic length and time parameters can be factored out, then total system mass-action is

$$A = \sum mlv = \sum \frac{ml^2}{t} = M\frac{l^2}{t} \tag{1}$$

where $M = \sum m$ is the total mass of all components transported a distance l during a time t. The quantity $\frac{M}{t}$ is the total mass delivery rate. The mass delivery rate is not necessarily a measure of total mass delivered from one point to another point in a given time, but rather the total rate at which the collective mass of individual components is delivered to potentially many different points from many different initial locations over distances comparable with the characteristic step length. For example, it might represent the total rate of coal distribution from a set of mines by rail transport to widely distributed points of consumption, the rate of water delivery from clouds to the ground via rain drops, or the rate of sediment delivery to the oceans by major rivers. Although in these examples this motion is advective if measured over short enough length scales, it is diffusive when viewed at large enough scales, as discussed in the first part of the preceding paragraph. That is, the mass-action metric treats advection as if it were diffusion with long displacement distances.

If it is possible to estimate the total number N of system components each with known mass, and a characteristic displacement length and time, the mass-action of one component can be multiplied by N to get the total mass-action. Where mass is not transported in countable units that are easily identified, but in a continuous phase, as in the displacement of water and air, or where transport data are compiled in terms of mass flux, then mass-action is most easily estimated in terms of a total mass delivery rate, $R = \frac{M_T}{T}$, referenced to a specified reporting time, for example one year in the case of annually reported data. Here M_T is the total mass transported during the reporting period, T. For oil pipelines, for example, one could estimate R from data on the number of barrels of oil consumed per day. In this example the total mass-action would be $A = Rl^2$, where l is average pipeline length. For a given system, the quantities $\frac{M_T}{T}$ and $\frac{M}{t}$ have the same numerical value but refer to two different time periods for estimating delivery rates.

The relative mass-transport effectiveness of two systems, such as highway freight and rail freight transportation systems, having components i (trucks and trains) with masses, pathlengths, and velocities represented respectively by M_i, L_i, V_i and m_i, l_i, v_i, is the ratio of their mass-actions

$$\mathrm{Ma}_{M,m} = \frac{\sum M_i L_i V_i}{\sum m_i l_i v_i} \tag{2}$$

where $\mathrm{Ma}_{M,m}$ is a dimensionless mass-action number. If $\mathrm{Ma}_{M,m}$ compares transport of equal physical masses ($\sum m = \sum M$) and each system has its own characteristic, or dominant, pathlengths and velocities, then the mass-action number reduces to the ratio of two kinetic diffusivities, $\mathrm{Ma}_{M,m} \rightarrow \frac{LV}{lv}$. In a fluid, where eddies and molecules each transport the *same* physical mass, the mass-action number is equivalent to the Peclet number, Ma → Pe.

In some systems there may be no obvious characteristic length-scale. For example, the displacement distribution of bank notes, used as a proxy for human travel patterns, decays as a power-law (Brockman *et al*., 2006). Long-distance travel by automobile (USDOT, 2007) for vacations, business, or other purposes, can be measured in hundreds or thousands of kilometers, while the effective length scales of urban driving (USDOT, 2005) may extend over only a few kilometers. For some biological organisms, such as honeybees, locomotion is mostly diffusive, but also includes long distance foraging excursions (Levy flights) (Reynolds *et al*., 2007). Using simply the average displacement distance in calculating the mass-action of such systems can be misleading; a few very large displacements can make a greater contribution to the mass-action than a large number of small ones. One strategy, adopted here in cases where there is a wide spread in displacement values and data are available, is to compute separately the mass-actions for different displacement distances, and then either to report the sum or the dominant contribution to system mass-action, as done for example for debris flows, or, for systems such as automobiles, volcanic eruptions, rivers, and birds, to report values separately for different displacement length categories.

Mass-Action of Selected Natural and Technological Systems

Table I lists my estimates of mass delivery rates, pathlengths, mass-actions, and logarithms of mass-action numbers for selected natural and technological systems, and Figure 1 shows selected systems ordered by mass-action number. Mass-action *A* was computed by multiplying the mass delivery rate *R* by the square of the pathlength *l*. Space limitations make it impossible to discuss here each entry in detail, but several examples are given below to illustrate estimation methods. The mass-action number Ma is computed relative to the mass-action arising from (biological) locomotion of the modern human population, which by construction has a mass-action number of 1. Below, the terms 'large-mass-action' (or 'high-mass-action') and 'small-mass-action' (or 'low-mass-action') are used for convenience to indicate the relative mass-action values of two systems, or to indicate, respectively, a mass-action number significantly larger than, or less than, 1.

For most systems in Table I the data available to calculate mass-action are of poor quality; estimates of pathlengths, masses, and time scales can each be uncertain. However, the large spread (nearly 20 orders-of-magnitude) in calculated mass-action values means that an accuracy to within a couple of orders of magnitude for each system is sufficient for the study of overall transport patterns. For example, the global delivery rate for large main-stem rivers was taken as roughly equal to total river discharge, 40,000 $km^3 y^{-1}$, with transport distance to the sea on the order of 1000 *km* (Oki and Kanae, 2006). Choosing either 3000 *km* or 300 *km* instead would increase or decrease estimated mass-action by about a factor of ten. In any case, river-flow mass-action remains orders of magnitude larger than that of other classical geomorphic processes, or of any technological process, and orders of magnitude less than that of major climatic circulation systems.

The natural systems with largest mass-action, found in the upper part of Figure 1, are climate systems, and include atmospheric and oceanic circulation modes, such as the Hadley cells, ocean gyres, and the oceanic conveyor belt. These systems move large amounts of mass over global distances at speeds ranging from tens of centimeters per second to a few meters per second, and up to one hundred meters per second in the case of jet streams. Other systems with very large mass-actions include the world's large rivers, tectonic plates, and the Antarctic ice sheet.

For the large-mass-action systems above, mass transport is associated with the flow of fluids, i.e. air, water, magma, or the deformation of ice, materials for which no minimum force is required for flow to occur. Motion is driven by ambient forces due to solar heating, gravity, or mantle convection, resulting in large quantities of mass advecting over distances of continental to global scale, thus generating large mass-action. The largest-mass-action systems in nature that transport solids, besides tectonic plates, are comprised mostly of particulates – for example, eolian dust, river sediment, submarine landslides, and subaerial landslides and debris flows. In all of these systems except that of subaerial landslides, which has the smallest mass-action of the group, motion is mediated by fluids that directly provide the motive force, or that provide a mechanism that reduces effective friction to values less than rock–rock dry friction. Estimation of global frequency–size distributions for mass-wasting events is especially uncertain. For debris flows, the age of the large (>4 km^3) Osceola event of 5000BP (Iverson *et al*., 1998) suggests that events with similar or slightly smaller volumes probably occur at least several times per thousand years. The mass-action for debris flows was calculated assuming one 1 km^3 flow per century, with runout on the order of 100 *km*, a distance characteristic of very large debris flows (Legros, 2002). If frequency or volume estimates of long runout or other mass-wasting events were off by an order of magnitude, the corresponding mass-action numbers in Table I would shift up or down by only about one unit, with only slight changes to the overall distribution of mass-actions.

Other natural systems or processes having large mass-actions include coastal currents (littoral cells), precipitation, first-order streams, tides, and large volcanic eruptions. Precipitation moves more mass per year than main stem rivers, but has much smaller mass-action because of its relatively small transport length, on the order of a few kilometers. For the same reason, first-order streams, which move about half the mass per year of large rivers, but only over distances of about a kilometer, have much smaller mass-action than the large rivers into which they ultimately drain. The diurnal oscillation of the oceanic tidal bulge moves large volumes of water, but only over distances on the order of a meter, resulting in smaller mass-action than for any other major water transport system considered here. Like streams of different order, volcanic eruptions of different Volcanic Explosivity Index (VEI) (Newhall and Self, 1982) generate a wide range of mass-actions. As a consequence of longer displacement distances and greater average mass-delivery rates, rare ultraplinian eruptions collectively generate more mass-action than the sum of more frequent but smaller Plinian and Strombolian events.

Many natural systems in Figure 1with relatively small mass-action, such as hillslopes (creep) or biological populations, are

Table I. Mass-action numbers for selected systems. R is the mass delivery rate, l is pathlength, $A = Rl^2$ is mass-action, and log (Ma) is the base-ten logarithm of the mass-action number defined relative to the mass-action of modern humans, Ma = $A/A_{modern\ humans}$

Natural systems	R (kg · s^{-1})	l (m)	A (kg · m^{2}s^{-1})	log(Ma)
Jet stream	2·4E+11	6·0E+06	8·6E+24	13·7
Ocean gyres	1·2E+12	2·0E+06	4·8E+24	13·5
Ocean conveyor belt	1·2E+11	5·0E+06	3·0E+24	13·3
Hadley cells	2·6E+11	3·3E+06	2·8E+24	13·3
Large rivers (water)	1·3E+09	1·0E+06	1·3E+21	9·9
Continents (drift)	4·4E+06	5·0E+06	1·1E+20	8·8
Seafloor spreading	1·6E+06	5·0E+06	4·1E+19	8·4
Antarctic ice sheet	2·2E+07	1·1E+06	2·7E+19	8·2
River sediment	5·0E+05	1·0E+06	5·0E+17	6·5
Eolian dust	7·8E+03	5·0E+06	2·0E+17	6·1
Precipitation	1·6E+07	2·0E+03	6·4E+13	2·6
Whales	1·9E+03	5·0E+06	4·7E+16	5·5
Fish (marine, migrating)	1·0E+03	1·0E+06	1·0E+15	3·8
First-order streams	6·3E+08	1·0E+03	6·3E+14	3·6
Submarine slides	3·8E+04	1·1E+05	4·6E+14	3·5
Volcanoes (all, ~VEI 7)	4·0E+04	1·0E+05	4·0E+14	3·4
Coastal currents	2·7E+04	1·0E+05	2·7E+14	3·2
Caribou (migrating)	3·1E+01	6·4E+05	1·3E+13	1·9
Birds (migrating)	4·8E–01	5·0E+06	1·2E+13	1·9
Tides	8·2E+12	1·0E+00	8·2E+12	1·7
Debris flows/lahars	6·3E+02	1·0E+05	6·3E+12	1·6
Volcanoes (Plinian, VEI 4)	1·6E+04	1·0E+04	1·6E+12	1·0
Subaerial landslides	1·8E+04	7·0E+03	8·7E+11	0·7
Volcanoes (Strombolian, VEI 2)	9·1E+03	1·0E+03	9·1E+09	–1·2
Humans (Stone Age)	2·3E+05	1·0E+02	2·3E+09	–1·8
Birds (feeding)	1·7E+05	1·0E+02	1·7E+09	–2·0
Tigers	1·3E+01	7·0E+03	6·3E+08	–2·4
Hillslope creep	1·9E+04	1·0E+02	1·9E+08	–2·9
Ants	1·1E+06	1·0E+01	1·1E+08	–3·1
Vegetation (transpiration)	9·1E+05	1·0E+01	9·1E+07	–3·2
Worms (castings)	5·3E+06	2·0E–01	2·1E+05	–5·9
Technological Systems				
Maritime shipping (open ocean)	8·0E+04	5·0E+06	2·0E+18	7·1
Rail (freight)	5·4E+04	1·3E+06	9·1E+16	6·5
Trucks (freight, for hire)	1·1E+05	8·4E+05	7·8E+16	6·4
Pipelines	3·1E+04	8·1E+05	2·0E+16	5·8
Automobile (>2000miles)	2·8E+03	2·5E+06	1·8E+16	5·8
Automobile (1000–1999miles)	6·7E+03	1·1E+06	8·1E+15	5·4
Maritime shipping (coastal)	1·6E+05	5·0E+05	4·0E+16	5·4
Automobile (500–999miles)	2·2E+04	5·5E+05	6·6E+15	5·3
Automobile (300–499miles)	3·3E+04	3·1E+05	3·1E+15	5·0
Automobile (urban, <50miles)	3·4E+07	9·0E+03	2·8E+15	4·9
Airplanes (passengers)	1·0E+03	1·4E+06	2·0E+15	4·8
Irrigation	8·8E+07	1·0E+04	8·8E+15	4·7
Automobile (200–299miles)	4·1E+04	2·0E+05	1·6E+15	4·7
Automobile (50–200miles)	1·1E+05	1·1E+05	1·4E+15	4·7
Trucks (freight, private)	1·2E+05	1·0E+05	1·2E+15	4·6
Airplanes (freight)	1·1E+02	3·1E+06	1·0E+15	4·5
Humans (modern)	1·5E+09	1·0E+01	1·5E+11	0·0
Earth moving (road construction)	9·4E+04	3·0E+01	8·5E+07	–2·6
Earth moving (house construction)	2·5E+04	3·0E+01	2·3E+07	–3·1
Earth moving (plowing)	4·7E+07	1·0E+00	4·7E+07	–3·5

comprised of particulate components like pebbles, soil particles, or organisms, that are either solid or have limited deformability, and that move in contact with the earth's surface. Here frictional resistance can be large, and, in addition, surface obstacles generate a kind of form-resistance that limits displacement distance. Thus soil particles on rough hillslopes collectively generate little mass-action as they undergo slow downslope drift energized by environmental noise such as rainsplash (Furbish *et al.*, 2009) or bioturbation. Animals are self-powered, and on land move (mostly) by employing rotary motion (i.e. pendulum action of legs during walking), which turns the high-friction coefficient between organism and ground into a locomotive advantage by providing traction. However, form-resistance remains, often requiring changes in direction of motion, as when a rodent detours around a bush, so that biological systems operating on land tend to have limited pathlengths and small values of mass-action. The largest values of mass-action for land-based animals are gener-

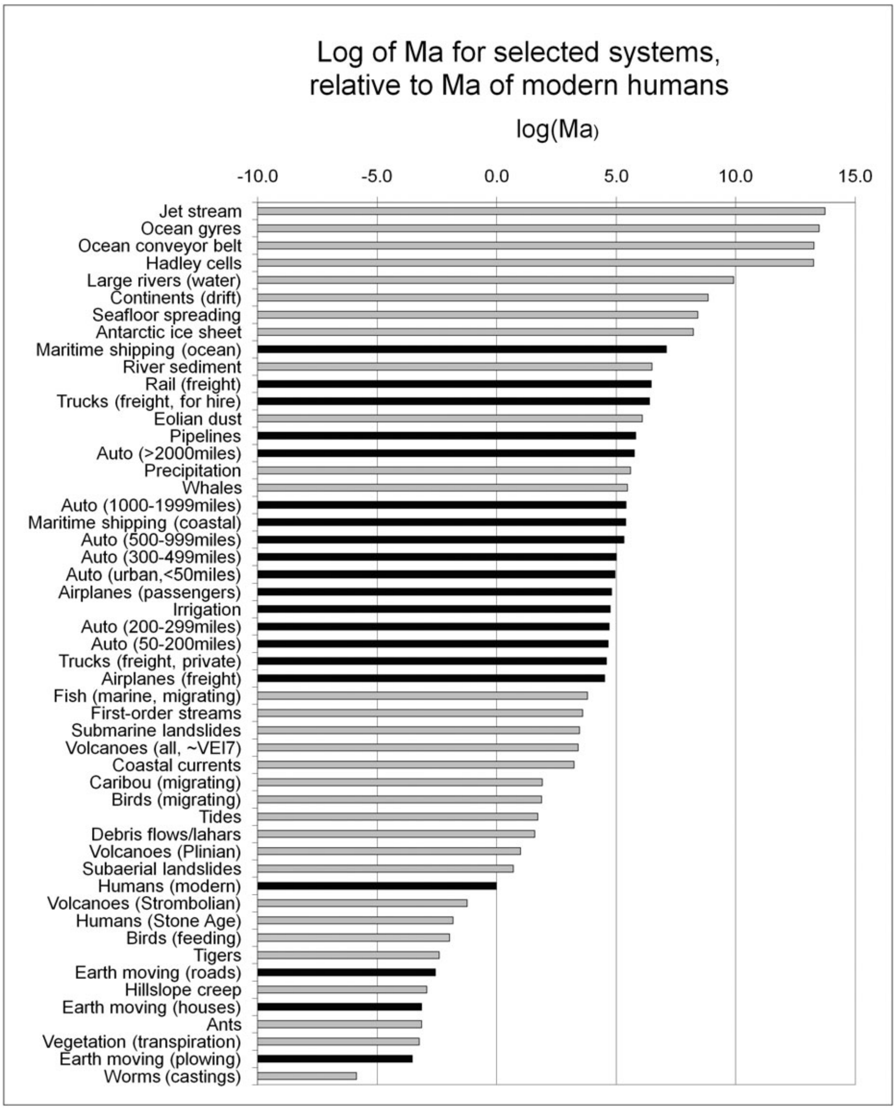

Figure 1. Logarithm of mass-action number Ma, computed relative to mass-action of modern humans, for systems listed in Table I. Light bars represent natural systems and dark bars represent technological systems.

ated by migrating herd species with access to large expanses of relatively unstructured terrain, as exemplified by arctic barren-ground caribou (Kelsall, 1968).

Modern humans, with an assumed individual body mass of 50 *kg*, generate more mass-action than most other non-migrating land species by virtue of their large population, equal by mass to about one sixth that of all land mammals (Bowen, 1966), and their relatively long displacement distances, nominally taken here as 10 *m*, distributed over a total (algebraic) daily displacement of 4 *km*. If humans were to average longer pathlengths, for example 100 *m*, or if their daily pattern of motion included one 500 *m* displacement per day, amongst smaller 10 *m* displacements, then the human mass-action estimate would increase up to an order of magnitude over the tabulated value, with a corresponding decrease in the logarithm of other mass-action numbers of about one unit, but little change in relative mass-action rankings.

Although the data are very uncertain, some long-distance migrating bird, fish, and marine mammal populations probably generate significantly more mass-action than modern humans because of long pathlengths and high displacement speeds enabled by passage through an obstacle-free air or water environment. Most non-migrating animals generate much smaller mass-action than modern humans. Stone Age humans and, for example, tigers, with pathlengths comparable with or longer than that of the modern human population, rank low because of the small size of their populations. Some populations of small animals, such as worms, move large amounts of mass per year, but their relatively small displacement distance and slow speeds place them in the lower part of Figure 1. The total biomass and in some cases displacement distances of ants both approach those of modern humans, but their comparatively low average speed results in small mass-action. The motion of migrating birds, fish, and whales is not normally of significance in geomorphology, but their inclusion here as advecting systems underlines the importance of the material environment, i.e. air or water versus land, for determining mass transport effectiveness. By contrast, transport confined to the land surface, a key natural geomorphic process, is mostly diffusive, and generates small mass-action, except where mass can piggy back on long-distance motion of a host fluid, as in the case of river sediment.

For technological systems, the largest value of mass-action in Figure 1 is associated with the motion of ships, which take advantage, like birds and fish, of a fluid transport environment. Maritime shipping and eolian transport of dust are unique geomorphic processes, in that they represent the only two modes that rapidly transport large quantities of solids between continents.

The highest-mass-action technological systems that operate on land are those based on trucks, autos, pipelines, and trains, Figure 1. Most of the data used here to calculate transportation system mass-action comes from national transportation statistics reports (USDOT, 2007) for the USA, scaled to global values by the ratio of world to US GDP (about 5 in 2007). Most of the estimates in this section refer only to mass moved *by* the motive technology, and not to the (usually lesser) mass of the transporting machinery itself. Automobiles are an exception, where mass-action computed refers to motion of the automobile and not its passengers. Table I shows that about twice as much mass is moved each year by for-hire trucks as by rail, but rail transport distances tend to be slightly longer, so that each transport mode generates about the same mass-action. Pipelines deliver somewhat less mass per year than do trains, over slightly shorter distances, and consequently generate less mass-action. The highest automobile mass-action values are for long-distance driving and the lowest for shorter excursions. Urban driving is an exception to this trend, with very high mass delivery rates off-setting to some extent relatively short driving distances. Irrigation, estimated by assuming diversion of about 10% of the world's river flow, has a mass-action comparable with that of automobiles.

Near the bottom of Figure 1 are three technological systems that transport large quantities of mass over short distances. Pathlengths of a few tens of meters for construction of roads and buildings and on the order of a meter for plowing ensure that these systems are diffusive and have low mass-action. Although geographically widely dispersed, the direct effect of mass transport by these small-mass-action systems remains local.

Requirements for Technological Transport of Solids on Land

Discretization or compartmentalization of mass is a physical requirement for the movement of solids across earth's surface. This is true both for technological systems (e.g. trucks and trains) and natural systems (e.g. animals, creep, debris flows). For sufficiently massive bodies, transport in the presence of large solid–solid friction and significant form-resistance would require application of forces exceeding material strength, resulting in fracture or disaggregation of the mass, i.e. discretization. Moreover, ambient power densities at the earth's surface are in most cases too small to transport any but the smallest particulates more than a short distance. Thus a necessary condition for the existence of large-mass-action, land-based technological systems is compartmentalization of mass-units that are self-powered or have access to dedicated high-power-density sources along their transport paths (e.g. continuous extraction of power from an electric grid).

The requirement of internal power source and compartmentalized transport units has several corollaries. One is that, as in the case of animals, molecular friction becomes an advantage for locomotion by a self-powered discrete system if its components can perform rotary motion, e.g. through use of wheels. A second corollary, following from compartmentalization, is the possibility of transporting mass in many, essentially arbitrary, forms (e.g. food or other commodities, hardware, clothing, armaments, dolls). This property supports coupling between available transportable mass in one location and potential usage or consumption of that mass in a different location. That is, packaging of mass of high economic value enables a 'demand potential' (somewhat like the chemical potential in thermodynamics) that drives large-scale mass transport. A third corollary of mass-discretization and internal power sources is the possibility of separate addressing and timing of each mass-unit, as well as multidirectional (including upslope) transport, thus permitting high geographic and temporal resolution in sourcing and delivery. This property reinforces the coupling between transport source and destination. Finally, system mass-action depends, through pathlength, on the average spacing and amplitude of surface roughness elements. In consequence of the natural roughness of earth's surface, most compartmentalized land-based systems would be limited to diffusive movement and small mass-action, if it were not for the existence of transport corridor *infrastructure*.

Infrastructure in the form of auxiliary components that decrease surface roughness is a concept that can be generalized from its normal technological usage to apply to natural transport systems as well. Such infrastructure is a physical necessity for the existence of high-mass-action land-based systems. Highways and river channels are examples of technological and natural infrastructure, respectively. Systems that lack such infrastructure, such as pebbles creeping down a hillslope or beetles foraging on the forest floor, tend to move along pathways controlled by existing surface irregularities and thus have small mass-actions. Even in small-mass-action systems, however, infrastructure of limited extent often appears spontaneously, as in game trails or in slide chutes on hillslopes. The common occurrence of transport infrastructure, even if only weakly developed, suggests that the emergence of advection in mass-transporting systems is a fundamental process originating at a deeper level than the dynamics of any single system. This point is discussed more fully in the next section.

Advection and Diffusion

Systems with long transport pathlengths, both natural and technological, tend to generate large values of mass-action, whereas shorter-pathlength systems usually generate smaller values, Figure 2. Although the correlation of mass-action with pathlength is suggested by its quadratic dependence on displacement distance, such a relation is not a strict requirement

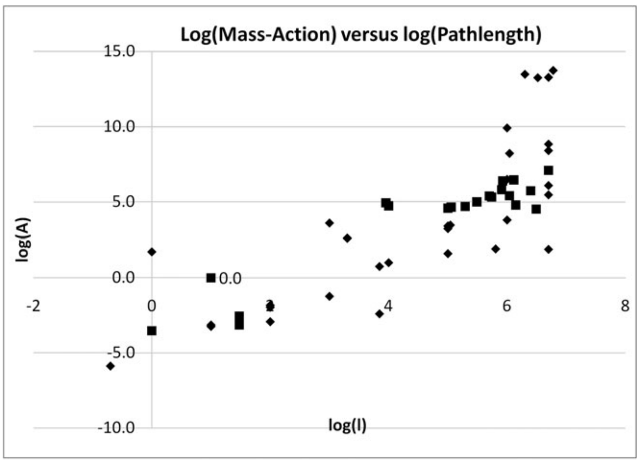

Figure 2. Logarithm of mass-action A (kgm^2s^{-1}) of systems listed in Table I versus logarithm of pathlength $l(m)$. Diamonds represent natural systems and squares represent technological systems.

of transport physics. Delivery of mass over long pathlengths at a sufficiently slow rate could in principle generate small mass-action. The natural long-pathlength systems with the smallest mass-actions are those whose transport environment offers little form-resistance, as in the case of animal populations that migrate through air or sea, or of caribou that pass across relatively smooth and featureless arctic terrain. Similarly, for technological systems, airborne transport generates relatively small mass-action despite long pathlengths. On land, however, long pathlengths for technological systems are associated with large mass-action.

For specific cases one can hypothesize why a terrestrial advective system might not be able to support a small mass-delivery-rate. For example, maintenance of transcontinental highways makes economic sense only if traffic is sufficiently heavy to justify the cost. Similarly, long river channels can be maintained only if there is a sufficient flow of water, and hence a large enough mass-action, to guarantee that water reaches the river mouth in spite of the tendency of hillslope creep and landslides to fill in the channel. A more general explanation of the correlation of pathlength and mass-action might be made in terms of competition for real estate. If a system moves mass long distances, with the mass being displaced quickly and without significant interruption by external events, thus enabling the generation of large mass-action, then its advective pathways must be dedicated to handling that mass flux. If this were not the case, then space occupied by nominally advective pathways, like highways, would be available for use by other transport systems that could introduce foreign mass elements, for example rocks in the process of moving down a hillslope, that interfere with transport by the primary system.

An environmental consequence of land-based high-mass-action systems is thus the presence of extended transport corridors that are generally unavailable for routine use by other systems that share the same environment. These dedicated pathways restrict the ways in which embedded (sharing the same environment) diffusive systems may transport mass. A major effect of rivers on human and land animal movement is the impediment that active stream channels present to organismal locomotion, which is constrained for the most part to interfluves. The same is true for high-mass-action technological systems such as highways. The barrier effect caused by roads and other linear human constructs is significant and well-known in ecology (Forman and Alexander, 1998). In general, transport of mass across a shared two-dimensional surface like the surface of the earth defines a hierarchy of transport barriers among systems whose mass-actions differ substantially from one another. High-mass-action corridors bound the domain of activity of embedded smaller-mass-action systems, which in turn create corridor boundaries for even smaller-mass-action systems; rivers bound human motion, and human foot traffic in turn discourages the passage of ants across a sidewalk or path. The converse of this effect is that mass-transport activity of small-mass-action systems tends to have only a limited ability to directly affect advection by larger-mass-action systems whose environment they share: water flow down rivers and the flow of traffic on highways are not directly affected much by human motion on foot, nor is human foot traffic on established pathways easily slowed or diverted by cross-traffic of lower-mass-action organisms.

Advection can also influence local environments by introducing externally generated short time-scales. Advective systems import and export mass sourced at great distances over times much shorter than could be effected if transport were carried out via diffusion processes alone. By introducing an external short time-scale into the environment of small-mass-action systems, an advective system provides support for local (diffusive) dynamics coupled to that time scale and to the corresponding mass flux, i.e. advection supplies the mass, or quantities advected with the mass, to the local system as a resource, at rates controlled by the advective time scale. Because mass delivery rates of advective systems are usually large, advective coupling is likely to be important to the overall function of embedded systems. For example, at the largest scale, atmospheric circulation distributes air, together with associated moisture and heat, at rates that are fast enough to maintain environments suitable for the function of life, i.e. for supporting the existence of diffusive processes such as human ambulation. In the absence of large-scale circulation in the natural climate system, the time-scales over which continents would desiccate or the higher latitudes would freeze would be very short compared with the lifetime of any member of the human population, which would soon disappear. Similarly, river flows originating at distances not accessible on requisite time scales by biological diffusive transport mechanisms support water consumption requirements of human and other populations. These same flows also advect sediment supplied by distant hillslopes to the river mouth, providing the resources otherwise unavailable for local diffusive growth of deltas (Kenyon and Turcotte, 1985).

In technological systems, similar dependencies of embedded diffusive dynamics on advective transport arise. Large quantities of food, fuel, and other goods are transported on (individual) human time scales by truck, train, plane, ship, and pipeline over great distances to the diffusional environs of cities, when purely human dynamics would be far too slow to support the same level of mass transport. Of course such technological systems were 'designed for' delivery of goods for human use, so it is no surprise that technological advective and human diffusive time-scales are comparable and that the two systems are strongly coupled. But from a dynamical point of view, we can look at the human response to that flux as the particular expression of a system influenced by a large external mass flux. If humans did not exist, but somehow highway and rail transport systems continued to function and deliver their products, then we would expect to see the emergence of diffusive non-human systems whose dynamics was synched to the existing advective transport, perhaps in the form of ecological systems comprised of cockroaches, rats, and their predators built around the large scale delivery of otherwise unused food products to central ('urban') locations.

In classical geomorphology, mass transport is often viewed as a means to an end, elevation changes resulting from the divergence of mass-flux being responsible for the form of the geomorphological landscape. However, transport itself, at each instant of time, is a physical reality on earth's surface which has real-time effects on systems that share that surface, and which may be at least as important for the function of those systems as extant landforms left over from the action of past transport processes. If the river cut the valley in times past, only the valley, not the river flow that cut it, has any immediate effect on modern systems. The modern river on the other hand, has large, on-going, effects on co-existing systems that share its environment, both through the physical presence of its transport corridor and as well as the coupling it provides to mass resources arising at great distances. The same is true for highways and other high-mass-action technological transport systems, which may generate little elevation change, but whose dynamics strongly conditions local environments.

Technological Transport as an Earth Surface Phenomenon

Darwinian evolution provides a framework for understanding the emergence of mass transport strategies used by biological organisms. The tools of geology and allied sciences are sufficiently powerful to supply an explanation for both the origin and function of physical natural transport systems and associated landforms, e.g. rivers and hillslopes. The emergence of high-mass-action technological systems into a once all-natural world, on the other hand, is usually explained in terms of human purpose alone, with relatively little attention devoted to elucidation of physical principles that may shape how those purposes are realized. Thus humans plan, design, build, and maintain roads, trucks, ships, planes, pipelines and other elements of technological transport systems for purposes such as gaining access to locally unavailable materials that are necessary for our well-being, like food and fuel, or are simply desirable, like flat screen TVs. The satisfaction of these needs is usually taken as the cause of the existence of the world's extensive transport technology. This is true as far as it goes, but an explanation of the origin of technological transport systems solely in terms of human purpose and design removes from any system to which it is applied much of the potential explanatory power of science, in the same way that the assumption of teleology removes from biology the explanatory power of evolution. Humans design and maintain certain technological systems, but it does not follow that the dynamics of large-scale technologies, such as the global transportation system, whose complexity exceeds what is knowable by any single human, is a function solely of human foresight, planning, or management. Even quintessentially human systems such as social networks (Borgatti *et al*., 2009) are not wholly designed or controlled, or even recognized, by the people whose presence defines them. The short-chain of mutual acquaintances needed to connect two randomly chosen individuals ('six degrees of separation') (Watts and Strogatz, 1998) emerges with no conscious human design, planning, or intention.

Like societies, large-scale technologies can be expected to develop dynamics that transcends human purpose, imposing rules and constraints on the behavior of humans and other elements of earth surface systems that share their environment. An example is the growth of land transportation systems. The US interstate highway system was planned, designed, and built in part to provide fast and effective military transportation routes across the USA (Lewis, 1997). However, once the system was built, population centers near interstates began to grow, and new centers of population came into being at freeway interchanges or along smaller nearby connecting roads. Each increment of population growth brought with it economic opportunities for development, resulting in the addition of numerous smaller roadways, which in turn could support more consumers and producers of goods, requiring more access routes, and so on. If the skeleton interstate system was designed, the associated agglomeration of roadways and infrastructure, whose physical presence and other consequential effects condition the lives of everyone living within the society, was not planned or designed in any organic sense. This large, highly integrated system grew with no overall control or central planning. One could argue that at some point in its development, highway transportation technology began to channel human behavior. If humans are not entirely in control of technology, as the above example suggests, then the evolution and dynamics of the technological world, including technological mass transport, presumably require an explanation that goes beyond an appeal to human intention alone.

One way to look at the emergence of high-mass-action transport modes is suggested by the central role played by advection in these systems. In a world of uneven distribution of resources, gathering or collecting is a physical requirement of everyday life, and thus represents an essential propensity in every human, whatever the stage of technological evolution of the society. In the absence of transport technology, these needs can be satisfied only via human diffusion, i.e. via low-mass-action systems based on gathering or on trade between a small number of localized individuals. However, a physical consequence of trade is an increase of entropy, generated for example by the transformation of low-entropy products such as food or oil into high entropy waste products. There is some evidence that under broad conditions complex dynamical systems tend to adopt a transport configuration that generates entropy at the maximum rate possible (Dewar, 2003). If a sufficiently complex system is in principle capable of transporting mass and associated heat or chemical energy from regions of high concentration to low concentration (e.g. heat from high to low temperature regions, food or fuel from regions of abundance to regions of scarcity), then, of all the possible transport modes that might accomplish this, the principle of maximum entropy production implies that the ones that will be favored are those that generate entropy as rapidly as possible, subject to existing constraints on the system. In mechanical systems these transport modes are typically advective, because advection can disperse mass and energy much more rapidly than diffusion. Avalanches in a sand pile (Dewar, 2003) and horizontal energy flows in the earth's atmosphere and oceans (Paltridge, 2005) have been discussed as processes exhibiting maximum entropy production.

If maximum entropy production is a valid principle to apply to technological mass transport across the earth's surface, then advective transport modes would be expected to appear in the presence of large-enough spatial gradients in the distribution of low-entropy resources, such as food, fuels, and ores, to whatever extent the constraints of geography, law, economics, and the availability of tools such as road construction machinery make possible. A thermodynamic analogy would be the replacement of diffusion by flow in the presence of high enough temperature differences across a Rayleigh-Benard convection cell. Arguments based on maximum entropy production may or may not ultimately be able to explain the emergence of advective pathways in technological mass transport systems; they are offered here by way of example to encourage a physical approach to understanding a phenomenon that might otherwise seem to be a consequence of human intention alone.

Summary

Historically, geomorphology has been the science that studies the mechanisms and consequences of surface mass transport and more generally attempts to bring order and consistency to our understanding of earth surface processes. As an inclusive and integrative science its scope is sufficiently broad to encompass principles derived from biology, chemistry, physics, hydrology, and pedology, as well as geology. One might also include technology on this list. While many geomorphological studies of the impact of technological processes exist, general dynamical principles that might be useful in understanding technological mass-transport as a physical, geomorphic phenomenon rather than solely as an expression of human will, have not been developed. The heterogeneity characteristic of earth surface transport systems, from trucks to plows to rivers to worms, requires that a general framework for treating the behavior of such systems reflect the most basic elements of mass transporting systems. We have explored the use of a particular dynamical measure involving mass, distance, and speed – mass-action. This approach leads to consideration of (i) the correlation of advection with large-mass-action, (ii) the tendency by large-mass-action systems to impose transport constraints on embedded smaller-mass-action systems, (iii) the appearance of short time-scales that couple distant localities to local dynamics, (iv) the physical necessity of infrastructure, discretization, and self-powered mass-units for high-mass-action land transport, and (v) the fact that compartmentalization and internal power sources enable spatially and temporally accurate transport of any kind of mass, with the consequence of enabling demand as a potential driving force.

Ultimately one wants to know why the surface processes arising from technological mass transport exist in the first place. Whereas human design and purpose are proximate causes, from a larger perspective the earth may simply be once again in the process of reorganizing itself, as it has many times before in its history. This time it is the 'anthropic force' of humans and their technology that is joining the forces of wind, water, tectonics and other natural transport agencies as a basic motor of mass movement. The principle of maximum entropy production might provide a physical framework for understanding some of the reasons for the emergence of these new technological mass-moving systems. If a physically based explanation can be found, among its implications might be that the social demand for transported technological mass (building materials for homes, fuel, electronic components for cell phones, etc.) – what we normally consider to be the 'real' use of the technology as opposed to its incidental transport – can also be understood from the earth's point of view as simply a mechanism that aids rapid production of entropy. Technological mass transport would then be a geologic force that incidentally provided desirable products for humans, not a human force that incidentally affected earth's surface. Whatever the results of such an analysis, it is clear that the rise of technology, and especially technology-based mass transport, represents a new dimension in earth surface dynamics.

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