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Introduction to river mechanics

It has long been understood that water flows downhill. This maybe the only statement to be remembered until a river dries out and crops wilt. Droughts unfortunately threaten humanity with the constraint that, without water, life cannot be sustained. On the other hand, the devastating consequences of excess water through floods stem from the fact that humanity, crops, and cattle are not well adapted to submerged life. Although nomadic tribes coped with the continuously changing pulses of fluvial systems, sedentary conditions forced humanity to protect against floods and droughts. In arid lands, perennial streams with regulated flow and a year-round supply of water are so much more valuable to humanity and wildlife than are natural sequences of short floods that succeed long droughts in dry ephemeral streams. River engineers are facing the daunting challenge of optimizing the urban and environmental resources pertaining to rivers while minimizing the damages caused by floods and droughts.

Perhaps the origin of river engineering started with Yu (4000 B.C.) who was selected to be emperor of China on the premise of long-lasting dikes for the protection of fertile Chinese plains against floods. For centuries, Chinese emperors were classified into "good dynasties" or "bad dynasties" depending on whether or not they succeeded in their struggle to harness large rivers. At approximately the same time, in Mesopotamia, an extensive irrigation system was developed between the Tigris and the Euphrates Rivers. Flood-control levees were constructed to protect fertile lands from destructive inundations. In these early periods of civilization, humanity's cultural development was dominated by fear of thunder, lightning, rain, floods, storms, cyclones, and earthquakes. The lack of understanding of cause-and-effect relationships to explain natural phenomena such as floods has characterized earlier civilizations. Nonetheless, humanity was compelled to develop hydraulic engineering and tame rivers in order to prevent famine and to survive. Today, several hydraulic structures from past civilizations serve as landmarks of excellence.

Natural philosophy emerged during Greek antiquity. Thales of Miletus (circa 600 B.C.) explored natural laws through philosophical meditation in replacing mythological traditions with logical thoughts and reflections based on observations of nature. Basic principles underlying natural processes were deduced by rational approaches, including reflection and speculation. Hypotheses and assumptions were formulated by natural philosophers. For instance, Thales believed that "water was the origin of all things" and "the earth rested on water." Plato (428–348 B.C.) speculated on matters of physics and metaphysics alike, without interest in possible discrepancies between theory and reality. Democritus of Thrace (465 B.C.) believed everything to be inherently mechanical in nature and admitted nothing fortuitous or providential.

In opposition to Plato's speculative ideas, the philosophy of Aristotle (384–322 B.C.) contemplated nature through facts, and his writings on logic, physics, biology, metaphysics, and ethics promote continuous advances and evolution of knowledge in each field. He recognized two types of action: a motivation, to which the speed of movement is directly proportional, and a resistance, to which motion is inversely proportional. He also believed that the motivation was proportional to the density of the body and that the resistance was proportional to the density of the medium through which it moved. These statements essentially describe the concepts of linear momentum and resistance to motion. Archimedes (287–212 B.C.) was the greatest mathematician of antiquity, with chief interest in geometry, centers of gravity, hydrostatics, a theory of floating bodies, and anticipated foundations for differential and integral calculus.

Another important milestone, achieved by Hippocrates of Cos (460–380? B.C.), is worth mention. He proved the existence of evaporation by weighing a vessel filled with water over a long period of time. The most splendid achievements are twofold: (1) The concept of studying nature through experiments was born; and (2) the concept that quantitative information could be gathered from measurements was developed. It took nearly 2,000 years after Hippocrates before experiments and measurements supplanted speculations and hypotheses. The real treasures of natural philosophy found between 600 and 300 B.C. were highly reputed, but they had few practical effects, and society could hardly benefit from this new knowledge. Humanity had to wait until the Renaissance, circa 1500 A.D., to appreciate the long-lasting values of the Greek civilization.

As much as Greeks were interested in pure rational knowledge, Romans were the true pragmatic engineers of antiquity. Marcus Vitruvius Pollio (first century B.C.) and Sextus Julius Frontinus (40–103 A.D.) were concerned with the construction of the aqueducts that supplied water to Rome. There is still debate as to whether water conduits had been calculated, but colossal aqueduct and water-distribution systems were designed on the basis of only experience and rough estimates. It is intriguing that the simple concept of conservation of mass was not understood at the time of the design. Frontinus could measure flow depth, and he keenly observed that a steeper slope results in higher flow velocity. However, he incorrectly considered that the discharge corresponds to the cross section given by the measured canal width and flow depth. He observed that velocity increases the discharge, but he could not recognize the quantitative proportionality between velocity and discharge. Correct understanding of the relationship between discharge Q, cross-sectional area A, and velocity V in terms of $Q = AV$ is due to Hero of Alexandria (first century A.D.).

Almost 1,500 years elapsed until the discharge relationship was correctly rediscovered by Leonardo da Vinci (1452–1519) and Benedetto Castelli (1577–1644?). The Renaissance period marks the rebirth of civilization after the Middle Ages. The development of printing contributed to rapid dissemination of knowledge. Leonardo da Vinci understood the principles of experimental science and advocated the necessity of observation: "I will treat of such a subject. But first of all I shall make a few experiments and then demonstrate why bodies are forced to act in this manner. This is the method that one has to pursue in the investigation of phenomena of nature. It is true that nature begins by reasoning and ends by experience; but, nevertheless, we must take the opposite route: as I have said, we must begin with experiment and try through it to discover the reason."

Flow kinematics became better understood under Benedetto Castelli, who wrote "Sections of the same river discharge equal quantities of water in equal times, even if the sections themselves are unequal. Given two sections of a river, the ratio of the quantity of water which passes the first section to that which passes the second is in proportion to the ratio of the first to the second sections and to that of the first and second velocities. Given two unequal sections by which pass equal quantities of water, the sections are reciprocally proportional to the velocities."

The seventeenth century brought remarkable advances in mechanics and mathematics. Dynamic concepts of inertia and momentum became clear under René Descartes (1596–1650), who wrote "I assume that the movement which is once impressed upon a given body is permanently retained, if it is not removed by some other course; that is, whatever has commenced to move in a vacuum will continue to move indefinitely at the same velocity."

Pressure concepts in fluids at rest were described by Blaise Pascal (1623–1662), who postulated that pressure was transmitted equally in all directions. Christian Huygens (1629–1695) defined the principle of centrifugal force and is sometimes credited with the principle of conservation of energy. Isaac Newton (1642–1727) clearly formulated three laws of motion as a concise synthesis of concepts explicitly formulated by Descartes, Wallis, Huygens, and Wren. His contribution is a concise definition of mass, momentum, inertia, and force.

He also studied fluid resistance between a fluid and a solid to conclude that resistance is proportional to the relative velocity of adjacent zones. Energy concepts and present-day calculus evolved around the contribution of Gottfried Wilhelm von Leibniz (1646–1716). He introduced the concept of a live force that is proportional to the second power of velocity, now known as kinetic energy, and raised a lively debate between kinetic energy and momentum proportional to the first power of velocity.

Hydrodynamics can be attributed to outstanding mathematical developments in the eighteenth century. Daniel Bernoulli (1700–1782) dealt with fluid statics and dynamics. It is nevertheless Leonard Euler (1707–1783) who rigorously derived the Bernoulli equation and the differential forms of the equations of continuity and acceleration in frictionless fluids.

Resistance to flow remained obscure until the nineteenth century when experi ments on flow in small pipes resulted from the studies of Gotthilf Heinrich Ludwig Hagen (1797–1884), Jean-Louis Poiseuille (1799–1869), Julius Weisbach (1806–1871), Henry Phillibert Gaspard Darcy (1803–1858), Wilhelm Rudolf Kutter (1818–1888), Emile Oscar Ganguillet (1818–1894), and Robert Manning (1816–1897). The Navier–Stokes equations for the analysis of viscous fluid motion became possible from the contributions of Jean-Claude Barré de Saint-Venant (1797–1886), Louis Marie Henri Navier (1785–1836), Baron Augustin Louis de Cauchy (1789–1857), Simeon Denis Poisson (1781–1840) and George Gabriel Stokes (1819–1903). Turbulence challenged generations of scientists including Joseph Boussinesq (1842–1929), Osborne Reynolds (1842–1912), Ludwig Prandtl (1875–1953), and Theodor von Kármán (1881–1963), who contributed to unveil part of its inherent complexity.

In comparison with those of hydraulics, the advances in sediment transport, which is essential to understanding river mechanics, have been extremely slow. Two contributions before the twentieth century are noteworthy: (1) the contributions of Albert Brahm on the relationship between the bedflow velocity and the 1/6 power of the immersed weight of bed material and (2) the concept of tractive force by Paul Francois Dominique du Boys (1847–1924) and his relationship to bed-sediment transport.

Today, in-class discussions can emerge from a simple question such as, Why do rivers form? It is interesting to note the required physical processes that lead to river formation. The concept of a gravitational-force component should first come to mind. The need for erodible material or alluvium emanates from the discussion. The concept of an alluvial river usually is gradually becoming clear. However, all of this does not explain why rivers form. Do we understand the mechanics of formation of alluvial rivers? The effects of flow convergence and divergence allude to the concepts of continuity of water. Aggradation and

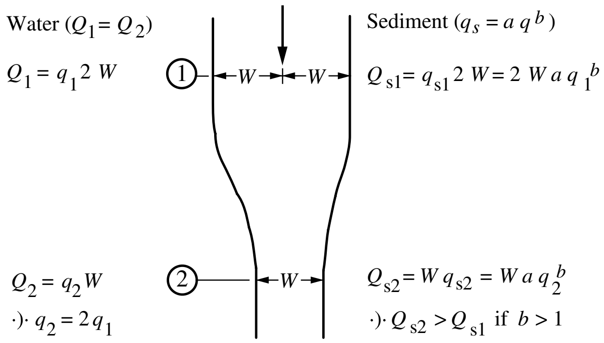

Figure 1.1. Water and sediment balance for converging flow.

degradation results from conservation of sediment. Does converging flow tend to cause aggradation or degradation? We can formulate an intuitive understanding by using a simple sediment rating curve of the type $q_s = aq^b$, where, q_s is the unit sediment discharge and q is the unit discharge; see Fig. 1.1.

The results of converging flow are to cause degradation when $b > 1$ and aggradation when $b < 1$. Is there any reason from our understanding of erosion and sedimentation that supports that $b > 1$? If so, I guess we have answered our question. In a simplified form, rivers form because sediment concentration increases with unit discharge. Flow convergence thus causes scour, and this clearly illustrates that river mechanics stems from an understanding of hydrodynamics and sediment transport.

On Earth, the study of the water and sediment discharge to the oceans from the rivers around the world shows that the annual suspended sediment discharge is 13.5×10^9 metric tons per year. Some important rivers are listed in Table 1.1. Approximately half of the sediment discharge to the oceans originates from rivers in Southeast Asia. In comparison, the total freshwater flow to the oceans from all rivers of the world combines to 1.2×10^6 m^3/s. The average sediment concentration of flows to oceans is $\sim$360 mg/l.

The proposed physical analysis of river mechanics is based on the concept of water and sediment transport down the rivers under the action of gravity from the upland areas to the oceans. The surface area of the land that drains into a particular river delineates the watershed, also termed the drainage basin or catchment. Chapter 2 outlines the physical properties of water and sediment and the governing equations of motion. Chapter 3 reviews the sources and the yields of water and sediment at the watershed scale. Chapter 4 treats the steady-flow conditions in canals and rivers. Chapter 5 delves into the mechanics of unsteady flows in rivers. Chapter 6 describes the downstream hydraulic

Table 1.1. *Water and sediment loads of selected rivers (after Jansen et al., 1979)*

River	Station	Catchment area (10^6 km^2)	Discharge: Water $m^3 s^{-1}$	Discharge: Water mm yr^{-1}	Discharge: Sediment 10^6 tons yr^{-1}	Discharge: Sediment μm yr^{-1}	Sediment as ppm of discharge[a] (mg 1^{-1})
Amazon	Mouth	7.0	100,000	450	900	90	290
Mississippi	Mouth	3.9	18,000	150	300	55	530
Congo	Mouth	3.7	44,000	370	70	15	50
La Plata/Parana	Mouth	3.0	19,000	200	90	20	150
Ob	Delta	3.0	12,000	130	16	4	40
Nile	Mouth	2.9	3,000	30	80	15	630
Yenisei	Mouth	2.6	17,000	210	11	3	20
Lena	Mouth	2.4	16,000	210	12	4	25
Amur	Mouth	2.1	11,000	160	52	15	150
Yangtse Kiang	Mouth	1.8	22,000	390	500	200	1,400
Wolga	Mouth	1.5	8,400	180	25	10	100
Missouri	Mouth	1.4	2,000	50	200	100	3,200
Zambesi	Mouth	1.3	16,000	390	100	50	200
St. Lawrence	Mouth	1.3	14,000	340	10	6	20
Niger	Mouth	1.1	5,700	160	40	25	220
Murray-Darling	Mouth	1.1	400	10	30	20	2,500
Ganges	Delta	1.0	14,000	440	1,500	1,000	3,600

Indus	Mouth	0.96	6,400	210	400	300	2,000
Orinoco	Mouth	0.95	25,000	830	90	65	110
Orange River	Mouth	0.83	2,900	110	150	130	1,600
Danube	Mouth	0.82	6,400	250	67	60	330
Mekong	Mouth	0.80	15,000	590	80	70	170
Hwang Ho	Mouth	0.77	4,000	160	1,900	1,750	15,000
Brahmaputra	Bahadurabad	0.64	19,000	940	730	800	1,200
Dnieper	Mouth	0.46	1,600	110	1.2	2	25
Irrawaddi	Mouth	0.41	13,000	1,000	300	500	750
Rhine	Delta	0.36	2,200	190	0.72	1	10
Magdelena (Colombia)	Calamar	0.28	7,000	790	220	550	1,000
Vistula (Poland)	Mouth	0.19	1,000	160	1.5	5	50
Kura (USSR)	Mouth	0.18	580	100	37	150	2,000
Chao Phya (Thailand)	Mouth	0.16	960	190	11	50	350
Oder (Germany/Poland)	Mouth	0.11	530	150	0.13	1	10
Rhone (France)	Mouth	0.096	1,700	560	10	75	200
Po (Italy)	Mouth	0.070	1,500	670	15	150	300
Ishikari (Japan)	Mouth	0.016	230	450	6	270	850
Tiber (Italy)	Mouth	0.013	420	1,000	1.8	100	140
Tone (Japan)	Mouth	0.012	480	1,250	3	180	200
Waipapa (New Zealand)	Kanakanala	0.0016	46	900	11	5,000	7,500

[a] ppm: parts in 10^6

geometry and equilibrium in alluvial rivers. Chapter 7 discusses the concepts of river dynamics and response to perturbations from equilibrium conditions. Chapter 8 particularly deals with river stability and presents methods to stabilize river banks. Chapter 9 presents several river engineering techniques from flood control to bridge crossings and waterways. Chapter 10 focuses on physical modeling techniques, with a particular analysis on the underlying theoretical concepts. Chapter 11 introduces the reader to numerical methods used to solve river engineering problems. Finally, Chapter 12 summarizes theory and applications of river engineering problems associated with waves and tides, usually observed in river estuaries.

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Physical properties and equations

As a natural science, the variability of river processes must be examined through the measurement of physical parameters. This chapter first describes dimensions and units (Section 2.1), physical properties of water (Section 2.2), and sediment (Section 2.3). The equations governing the motion of water and sediment from upland areas to oceans include kinematics of flow (Section 2.4), the equation of continuity (Section 2.5), the equation of motion (Section 2.6), and the concept of hydraulic and energy grade lines (Section 2.7). In this chapter and in the rest of the book, a solid diamond (♦) denotes equations and problems of particular significance. Problems with a double diamond (♦♦) are considered most important.

2.1 Dimensions and units

Physical properties are usually expressed in terms of the following fundamental dimensions: mass (M), length (L), time (T), and temperature (T°). Throughout the text, the unit of mass is preferred to the corresponding unit of force. The fundamental dimensions are measurable parameters that can be quantified in fundamental units.

In the SI system of units, the fundamental units of mass, length, time, and temperature are the kilogram (kg), the meter (m), the second (s), and degrees Kelvin (°K). Alternatively, the Celsius scale (°C) is commonly preferred because it refers to the freezing point of water at 0°C and the boiling point at 100°C.

A Newton (N) is defined as the force required for accelerating 1 kg at 1 m/s^2. Knowing that the acceleration that is due to gravity at the Earth's surface, g, is 9.81 m/s^2, we obtain the weight of a kilogram from Newton's second law: $F = \text{mass} \times g = 1\ \text{kg} \times 9.81\ \text{m/s}^2 = 9.81$ N. The unit of work (or energy) is the joule (J), which equals the product of 1 N $\times$ 1 m. The unit of power is a watt (W), which is 1 J/s. Prefixes are used in the SI system to indicate multiples or fractions of units by powers of 10:

μ (micro) $= 10^{-6}$, k (kilo) $= 10^3$,
m (milli) $= 10^{-3}$, M (mega) $= 10^6$,
c (centi) $= 10^{-2}$, G (giga) $= 10^9$.

For example, sand particles are coarser than 62.5 micrometers, or μm; gravels are coarser than 2 millimeters, abbreviated 2 mm, and one megawatt (MW) equals one million watts (1,000,000 or 10^6 W).

In the English system of units, the time unit is a second, the fundamental units of length and mass are, respectively, the foot (ft), equal to 30.48 cm, and the slug, equal to 14.59 kg. The force required for accelerating a mass of one slug at 1 ft/s^2 is a pound force (lb). Throughout this text, a pound refers to a force, not a mass. The temperature, in degrees Celsius, $T_C{}^\circ$, is converted to the temperature in degrees Fahrenheit, $T_F{}^\circ$, by $T_F{}^\circ = 32.2\,^\circ\mathrm{F} + 1.8\, T_C{}^\circ$.

Variables are classified as geometric, kinematic, dynamic, and dimensionless variables, as shown in Table 2.1. Geometric variables involve length dimensions only and describe the geometry of a system through length, area, and volume. Kinematic variables describe the motion of fluid and solid particles, and these variables can be depicted by only two fundamental dimensions, namely L and T. Dynamic variables involve mass terms in the fundamental dimensions. Force, pressure, shear stress, work, energy, power, mass density, specific weight, and dynamic viscosity are common examples of dynamic variables. Several conversion factors are listed in Table 2.2.

2.2 Properties of water

The physical properties of a nearly incompressible fluid such as water are sketched in Fig. 2.1.

Mass density of water, ρ. The mass of water per unit volume is referred to as the mass density ρ. The maximum mass density of water at 4 °C is 1,000 kg/m^3 and varies slightly with temperature, as shown in Table 2.3. In comparison, the mass density of sea water is 1,025 kg/m^3 and, at sea level, the mass density of air is 1.29 kg/m^3 at 0 °C. The conversion factor is 1 slug/ft^3 = 515.4 kg/m^3.

Specific weight of water, γ. The gravitational force per unit volume of fluid, or simply the fluid weight per unit volume, defines the specific weight γ. At 10 °C, water has a specific weight, $\gamma = 9{,}810$ N/m^3 or 62.4 lb/ft^3 (1 lb/ft^3 = 157.09 N/m^3). Specific weight varies slightly with temperature, as given in Table 2.3. Mathematically, the specific weight γ equals the product of the mass