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ENVIRONMENTAL HYDRAULICS OF OPEN CHANNEL FLOWS

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Preface

Rivers play a major role in shaping the landscapes of our planet (Table P.1, Fig. P.1). Extreme flow rates may vary from zero in drought periods to huge amount of waters in flood periods. For example, the maximum observed flood discharge of the Amazon River at Obidos was about 370 000 m^3/s (Herschy 2002). This figure may be compared with the average annual discharges of the Congo River (41 000 m^3/s at the mouth) and of the Murray-Darling River (0.89 m^3/s at the mouth) (Table P.1). Even arid, desertic regions are influenced by fluvial action when periodic flood waters surge down dry watercourses (Fig. P.1(a)).

Hydraulic engineers have had an important role to contribute although the technical challenges are gigantic, often involving multiphase flows and interactions between fluids and biological life. These engineers were at the forefront of science for centuries. For example, the arts of tapping groundwater developed early in the Antiquity in Armenia and Persia, the Roman aqueducts, and the Grand canal navigation system in China. In the author's opinion, the extreme complexity of hydraulic engineering is closely linked with:

1. *The geometric scale of water systems*: e.g. from $<10\,m^2$ for a soil erosion pattern (e.g. rill) to over $1000\,km^2$ for a river catchment area typically, and ocean surface area over $1 \times 10^6\,km^2$.
2. *The broad range of relevant time scales*: e.g. <1 s for a breaking wave, about 1×10^4 s for tidal processes, about 1×10^8 s for reservoir siltation, and about 1×10^9 s for deep sea currents.

Table P.1 Characteristics of the world's longest rivers

River system (1)	Length (km) (2)	Catchment area (km^2) (3)	Average annual discharge (m^3/s) (4)	Average sediment transport rate (tons/day) (5)
Amazon-Ucayali-Apurimac (South America)	6400	6 000 000	180 000	1 300 000
Congo (Africa)	4700	3 700 000	41 000	–
Yangtze (Asia)	6300	1 808 500	31 000	–
Yenisey-Baikal-Selenga (Asia)	5540	2 580 000	19 800	–
Parana (South America)	4880	2 800 000	17 293	–
Mississippi-Missouri-Red Rock (North America)	5971	3 100 00	17 000	–
Ob-Irtysh (Asia)	5410	2 975 000	12 700	–
Amur-Argun (Asia)	4444	1 855 000	10 900	–
Volga (Europe)	3530	1 380 000	8050	–
Nile (Africa)	6650	3 349 000	3100	–
Huang Ho (Yellow River) (Asia)	5464	752 000	1840	4 400 000
Murray-Darling (Australia)	3370	1 072 905	0.89	–

Average annual discharge: at the river mouth.

(a)

(b)

Fig. P.1 Photographs of natural rivers. (a) Small flood in the Gascoyne River, Carnarvon, WA (Australia) (courtesy of Gascoyne Development Commission and Robert Panasiewicz). The Gascoyne River has catchment area of about 67 770 km^2 and it extends 630 km inland. Average annual rainfall is <250 mm throughout the basin and this is an ephemeral river. There are typically one to two flow periods per year following seasonal rainfall or cyclone activity, but it may fails to flow at all once every 5 or 6 years. (b) Tingalpa Creek, Redlands Qld (Australia) on 21 January 2003 at high tide at about 9 km from the river mouth, looking upstream.

3. *The variability of river flows* from zero (dry river bed during droughts) to gigantic floods.
4. *The complexity of basic fluid mechanics*, with governing equations characterized by non-linearity, natural fluid instabilities, interactions between water, solid, air and biological life and;
5. *Man's (and Life's) total dependence* on water.

DISCUSSION

Armed conflicts around water systems have been plenty. In the Bible, a wind-setup effect allowed Moses and the Hebrews to cross shallow-water lakes and marshes during their exodus. Droughts were artificially introduced: e.g. during the siege of the ancient city of Khara Khoto (Black City) in AD 1372, the Chinese army diverted the Ezen River[1] supplying water to the city.[2] Man-made flooding[3] of an army or a city was carried out by the Assyrians (Babylon, Iraq BC 689), the Spartans (Mantinea, Greece BC 385–384), the Chinese (Huai River, AD 514–515).[4] A related case was the air raids of the dam buster campaign conducted by the British in 1943. Artifical flooding created by dyke destruction played a role in several wars: e.g. the war between the cities of Lagash and Umma (Assyria) around BC 2500 was fought for the control of irrigation systems and dykes.

The 21st Century is facing political instabilities centred around water systems, and freshwater system issues might be the focal point of future armed conflicts. For example, the Tigris and Euphrates River catchments and the Mekong River. The scope of the relevant problems is broad and complex: e.g. water quality, pollution, flooding and drought. An example is the disaster of the Aral Sea with the formation of the permanently-dry isthmus between the northern small Aral Sea and the southern big Aral Sea since 1987 (Waltham and Sholji 2001).

This book was developed to introduce students, professionals and managers to the challenges of open channel flows and environmental hydraulics. After a concise introduction (Part 1), the second section (Part 2) deals with mixing and dispersion of matter in natural river systems. Part 3 presents an introduction to unsteady open channel flows, and the interactions between flowing water and its surroundings are discussed in Part 4.

Mixing and dispersion of contaminants in natural systems are developed in Part 2. Applications include release of organic and nutrient-rich waste water into the ecosystem (e.g. from treated sewage effluent), smothering of seagrass and coral, storm water runoff during flood events, and injection of heated water from an industrial discharge (e.g. at a cooling power plant). For example, during an accidental release of waste occurs in a stream, the water resource scientist needs to predict the arrival time of the contaminant cloud, the peak concentration of solute and the duration of the pollution. Basic theory of molecular diffusion and advection is extended to turbulent advective diffusion in channels.

Gradually varied flow calculations are developed in Part 3. First the basic equations of one-dimensional unsteady open channel flows are presented. That is, the Saint-Venant

[1]Also called Hei He River (Black River) by the Chinese.

[2]Located in the Gobi Desert, Khara Khoto was ruled by the Mongol King Khara Bator (Webster 2002).

[3]By building an upstream dam and destroying it.

[4]It may be added the aborted attempt to blow up Ordunte Dam, during the Spanish Civil War, by the troops of General Franco, and the anticipation of German Dam destruction at the German–Swiss border to stop the crossing of the Rhine River by the Allied Forces in 1945.

equations and the method of characteristics in Chapter 11*. Later simple applications are developed. The propagation of waves, and positive and negative surges is presented in Chapter 12, while the dam break wave problem is discussed in Chapter 13. Simple numerical models are presented and explained in Chapter 14.

There are strong interactions between turbulent water flows and the surrounding environment. Part 4 introduces the basic concepts of the transport of solids (Chapter 16), and of the mixing of air and water at free surfaces (Chapter 17).

At the beginning of the book, the reader will find the table of contents, a list of symbols and a glossary of technical terms and names. After the conclusion, a detailed list of references is presented. The last section presents a correction form. Readers who find an error or mistake are welcome to record the error on the page and to send a copy to the author. Corrections and updates will be posted on the Internet at: http://www.uq.edu.au/~e2hchans/reprints/book7.htm

Discussion

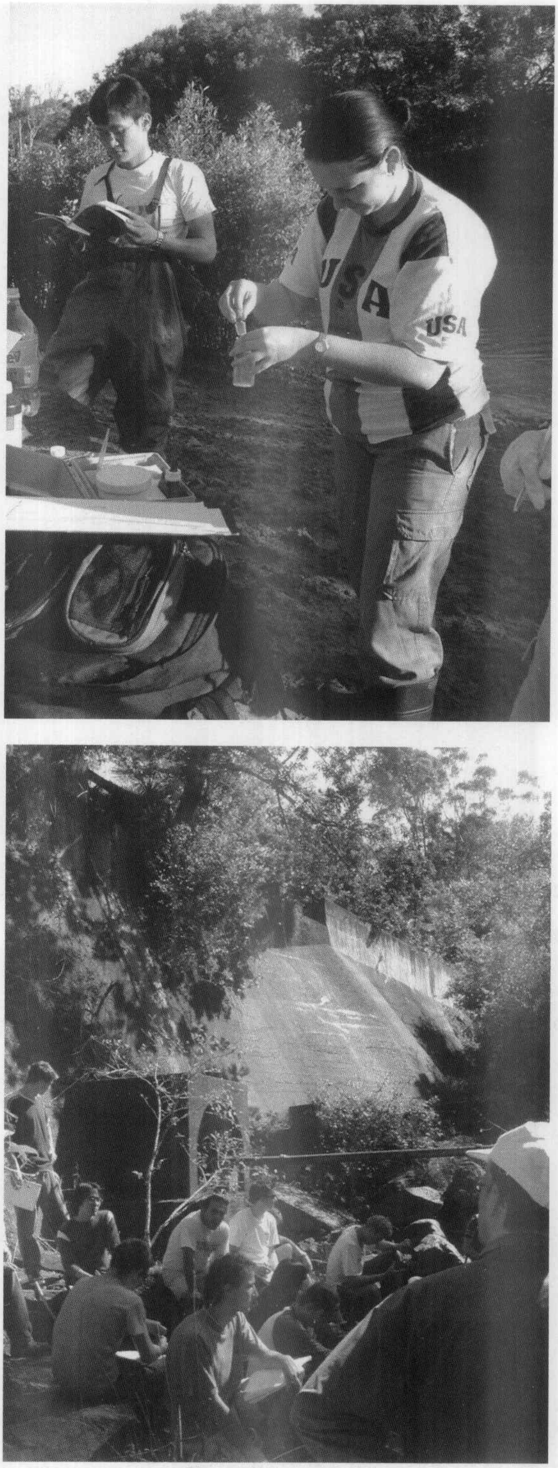
The lecture material is based upon the author's experience at the University of Queensland, and at other universities. It is designed primarily for undergraduate students in civil, environmental and hydraulic engineering. The author has taught Part 1 in Years 2 and 3, and Parts 2 and 3 as parts of advanced undergraduate electives in Year 4. Some material of Part 4 is usually introduced in the advanced hydraulics elective subject, and the course is further developed at postgraduate levels.

The author wants to stress, however, that field studies are a necessary complement to traditional lectures in environmental hydraulics. In the context of undergraduate subjects, design applications in classroom are restricted to simple flow situations and boundary conditions for which the basic equations can be solved analytically or with simple models. Fieldwork activities (Fig. P.2) are essential to illustrate real professional situations, and the complex interactions between all engineering and non-engineering constraints.

The author has organized undergraduate fieldworks in hydraulic engineering for more than 10 years involving more than 1000 undergraduate students. Figure P.2 illustrates recent examples. Figure P.2(a) shows mixing and dispersion class students conducting an ecological assessment of the estuarine zone of a small subtropical creek. For 12 h, students surveyed hydrodynamics, water quality parameters, fish populations, bird behaviours and wildlife sightings at four sites (Chanson *et al.* 2003). They concluded their works with a group report and an oral presentation in front of student peers, lecturers, professionals and local community groups. Figure P.2(b) shows hydraulic design students in front of the fully silted Korrumbyn Creek Dam disused since 1926. The dam and reservoir were accessed after a 45-min bushwalk guided by National Park and Wildlife rangers in the dense sub-tropical rainforest of Mount Warning National Park (NSW). The fieldworks was focused on sediment processes in the catchment. Students surveyed both upper and lower catchments, the fully silted reservoir and discussed its possible use as touristic attraction and potential source of aggregate for the local construction industry. Figure P.2(c) presents the civil design students surveying a flood plain in the heart of Brisbane. Students working in groups surveyed eight sections of the creek including culverts and wide flood plains. Each group conducted hydraulic computations for design and less-than-design flow rates, and prepared newer designs for a larger flood.

Anonymous student feedback demonstrated the very significant role of fieldworks in the teaching of hydraulic engineering (Chanson 2004c). Seventy-eight per cent of students

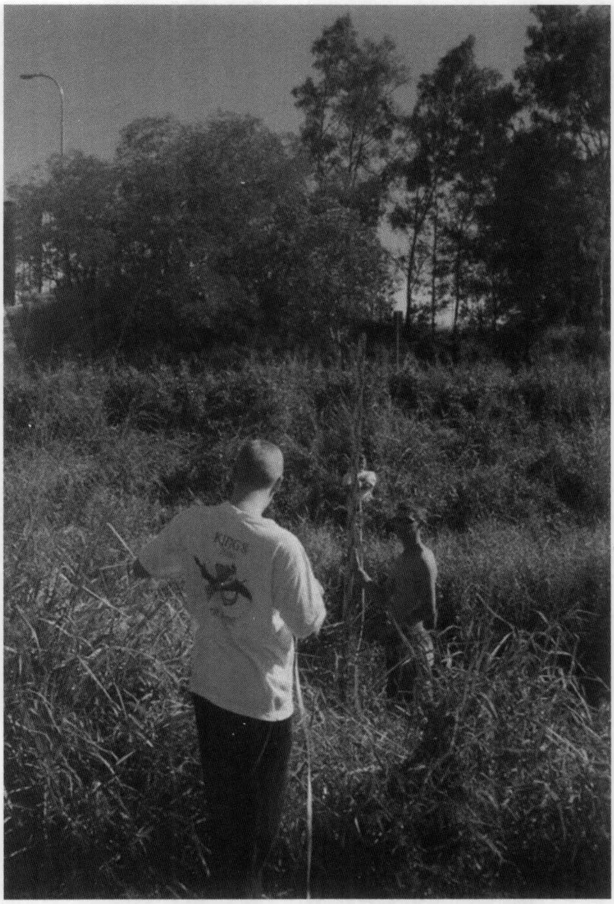
* It is acknowledged that, in Chapter 11, the basic derivation of Saint-Venant equations and method of characteristics presents some similarities with sections of another textbook (Chanson, 2004b).



(a)

(b)

Fig. P.2 Photographs of undergraduate student field trips. (a) Mixing in estuary fieldwork (39 students) at Eprapah Creek on 4 April 2003, students conducting sampling tests in the mangrove (courtesy of Ms H. Joyce). (b) Field study on 4 September 2002 with hydraulic design class (24 students), students in front of the fully silted Korrumbyn Creek Dam in a dense sub-tropical rainforest.



(c)

(d)

Fig. P.2 (*Contd*) (c) Civil design students (73 students) surveying a flood plain in 2002 (courtesy of L. Cheung). (d) Group bonding at the end of 12 h of estuarine field study (4 April 2003) (courtesy of Ms H. Joyce).

believed strongly and very strongly that 'fieldwork is an important component of the subject'. Eighty-four per cent of students agreed strongly and very strongly that 'all things considered, fieldworks and site visits are the vital components of civil and environmental engineering curricula'. Ninety-six per cent of students believed that 'fieldworks play a vital role to comprehend real-word engineering' and 100% of interviewed employers stressed that fieldworks under academic supervision was a basic requirement for civil and environmental engineering graduates. Lecturers and professionals should not be complaisant with university hierarchy and administration clerks to cut costs by eliminating field studies. Although the preparation and organization of fieldworks with large class sizes are a major effort, the outcome is very rewarding for the students and the lecturer. From his own experience, the author has had great pleasure in bringing his students to hydraulics fieldwork for more than a decade and to experience first hand their personal development (Fig. P.2(d)).

Internet resources

General resources

Gallery of photographs	http://www.uq.edu.au/~e2hchans/photo.html
Reprints of research papers	http://www.uq.edu.au/~e2hchans/reprints.html
Internet technical resources	http://www.uq.edu.au/~e2hchans/url_menu.html
NASA Earth observatory	http://earthobservatory.nasa.gov/
NASA rain, wind and air-sea gas exchange research	http://bliven2.wff.nasa.gov/index.htm
USACE inlets online	http://www.oceanscience.net/inletsonline/
Estuaries in South Africa	http://www.upe.ac.za/cerm/
Whirlpools	http://www.uq.edu.au/~e2hchans/whirlpl.html

Mixing and dispersion in rivers

Rivers seen from space	http://www.athenapub.com/rivers1.htm
Aerial photographs of rivers	ftp://geology.wisc.edu/pub/air

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About the author

Hubert Chanson is a Reader in Environmental Fluid Mechanics and Water Engineering at the University of Queensland since 1990. He was born in 1961 in Paris, France. He lives in Brisbane, Australia, with his wife Ya-Hui (Karen) Chou and their children Bernard and Nicole. He received a degree of 'Ingénieur Hydraulicien' from the Hydraulic Engineering School of Grenoble, France (ENSHMG) in 1983 and a postgraduate degree of 'Ingénieur Génie Atomique' from the Nuclear Engineering Institute of Saclay (INSTN) in 1984. He worked for the industry in France as an R&D Engineer at the Atomic Energy Commission from 1984 to 1986, and as a computer professional in fluid mechanics for Thomson-CSF between 1989 and 1990. From 1986 to 1988, he studied at the University of Canterbury (New Zealand) as part of a PhD project. He was awarded a Doctor of Engineering from the University of Queensland in 1999 for outstanding research achievements in gas–liquid bubbly flows. In 2003, the International Association for Hydraulic engineering and Research (IAHR) presented him the 13th Arthur Ippen Award for outstanding achievements in hydraulic engineering. This award is regarded as the highest achievement in hydraulic research.

His research interests cover design of hydraulic structures, experimental investigations of two-phase flows, coastal hydrodynamics, water quality modelling, environmental management and natural resources. He authored several books: *Hydraulic Design of Stepped Cascades, Channels, Weirs and Spillways* (Pergamon, 1995), *Air Bubble Entrainment in Free-Surface Turbulent Shear Flows* (Academic Press, 1997), *The Hydraulics of Open Channel Flows: An Introduction* (Butterworth-Heinemann, 1999) and *The Hydraulics of Stepped Chutes and Spillways* (Balkema, 2001). He co-authored another book *Fluid Mechanics for Ecologists* (IPC Press, 2002). His textbook *The Hydraulics of Open Channel Flows: An Introduction* has already been translated into Chinese (Hydrology Bureau of Yellow River Conservancy Committee) and Spanish (McGraw Hill Interamericana), and the second edition was recently released (Elsevier, 2004). His publication record includes over 200 international refereed papers and his work was cited over 1000 times since 1990. Hubert Chanson has been active also as consultant for both governmental agencies and private organizations.

Hubert Chanson has been awarded six fellowships from the Australian Academy of Science. In 1995 he was a Visiting Associate Professor at National Cheng Kung University (Taiwan, ROC) and he was a Visiting Research Fellow at Toyohashi University of Technology (Japan) in 1999 and 2001. In 2004, he was a Visiting Research Fellow at the Laboratoire Central des Ponts et Chaussées (France), at Université de Bretagne Occidentale (France) and at McGill University (Canada).

Hubert Chanson was the Invited Keynote Lecturer at the *1998 ASME Fluids Engineering Symposium on Flow Aeration* (Washington DC), first *International Conference of the International Federation for Environmental Management System IFEMS '01* (Tsurugi, Japan 2001), *6th International Conference on Civil Engineering ICCE '03* (Isfahan, Iran 2003), *30th IAHR Biennial Congress* (Thessaloniki, Greece 2003) and *International Conference on*

Hydraulics of Dams and River Structures HDRS '04 (Tehran 2004). He gave invited lectures at the *Workshop on Flow Characteristics around Hydraulic Structures* (Nihon University, Japan 1998), International Workshop on Hydraulics of Stepped Spillways (ETH-Zürich, Switzerland 2000) and *29th IAHR Biennial Congress* (Beijing, China 2001). He lectured several short courses in Australia and overseas (e.g. France, Japan, Taiwan).

His Internet home page is http://www.uq.edu.au/~e2hchans. He developed a gallery of photographs web site http://www.uq.edu.au/~e2hchans/photo.html, that received more than 100 000 hits since inception, and a series of world-known technical Internet resources.[1] Reprints of his research papers may be downloaded from: http://www.uq.edu.au/~e2hchans/reprints.html.

[1]http://www.uq.edu.au/~e2hchans/url_menu.html

To Nicole, Ya-Hui

and Bernard

Glossary

Abutment Part of the valley side against which the dam is constructed. Artificial abutments are sometimes constructed to take the thrust of an arch where there is no suitable natural abutment.

Académie des Sciences de Paris The Académie des Sciences, Paris, is a scientific society, part of the Institut de France formed in 1795 during the French Revolution. The academy of sciences succeeded the Académie Royale des Sciences, founded in 1666 by Jean-Baptiste Colbert.

Acid A sour compound that is capable, in solution, of reacting with a base to form a salt and has a pH <7.

Acidity Having marked acid properties, more broadly having a pH < 7.

Accretion Increase of channel bed elevation resulting from the accumulation of sediment deposits.

Adiabatic Thermodynamic transformation occurring without loss nor gain of heat.

Advection Movement of a mass of fluid which causes change in temperature or in other physical or chemical properties of fluid.

Aeration device (or *aerator*) Device used to introduce artificially air within a liquid. Spillway aeration devices are designed to introduce air into high-velocity flows. Such aerators include basically a deflector and air is supplied beneath the deflected waters. Downstream of the aerator, the entrained air can reduce or prevent cavitation erosion.

Afflux Rise of water level above normal level (i.e. natural flood level) on the upstream side of a culvert or of an obstruction in a channel.

Aggradation Raise in channel bed elevation caused by deposition of sediment material. Another term is accretion.

Air Mixture of gases comprising the atmosphere of the Earth. The principal constituents are nitrogen (78.08%) and oxygen (20.95%). The remaining gases in the atmosphere include argon, carbon dioxide, water vapour, hydrogen, ozone, methane, carbon monoxide, helium, krypton, …

Air concentration Concentration of un-dissolved air defined as the volume of air per unit volume of air and water. It is also called the void fraction.

Air entrainment Entrapment and entrainment of un-dissolved air into a water flow. It is also called the air bubble entrainment and self-aeration.

Alembert (d') Jean le Rond d'Alembert (1717–1783) was a French mathematician and philosopher. He was a friend of Leonhard Euler and Daniel Bernoulli. In 1752 he published his famous d'Alembert's paradox for an ideal-fluid flow past a cylinder (Alembert 1752).

Algual bloom Dense aquatic population of microscopic organisms and alguae produced by an abundance of nutrient salts in surface water, coupled with adequate sunlight for photosynthesis. The bloom depletes that water oxygen content, poison aquatic animals and waterfowl irritate the skin and respiratory tract of humans.

Alkalinity Having marked basic properties (as a hydroxide or carbonate of an alkali metal); more broadly having a pH >7.

Alternate depth In open channel flow, for a given flow rate and channel geometry, the relationship between the specific energy and flow depth indicates that, for a given specific energy, there is no real solution (i.e. no possible flow), one solution (i.e. critical flow) or two solutions for the flow depth. In the latter case, the two flow depths are called alternate depths. One corresponds to a subcritical flow and the second to a supercritical flow.

Analytical model System of mathematical equations which are the algebraic solutions of the fundamental equations.

Apelt C.J. Apelt is an Emeritus Professor in Civil Engineering at the University of Queensland (Australia).

Apron The area at the downstream end of a weir to protect against erosion and scouring by water.

Aqueduct A conduit for conveying a large quantity of flowing waters. The conduit may include canals, siphons, pipelines.

Arch dam Dam in plan dependent on arch action for its strength.

Arched dam Gravity dam which is curved in plan. Alternatives include 'curved-gravity dam' and 'arch-gravity dam'.

Archimedes Greek mathematician and physicist. He lived between BC 290–280 and BC 212 (or 211). He spent most of his life in Syracuse (Sicily, Italy) where he played a major role in the defence of the city against the Romans. His treaty 'On Floating Bodies' is the first-known work on hydrostatics, in which he outlined the concept of buoyancy.

Aristotle Greek philosopher and scientist (BC 384–322), student of Plato. His work 'Meteorologica' is considered as the first comprehensive treatise on atmospheric and hydrological processes.

Armouring Progressive coarsening of the bed material resulting from the erosion of fine particles. The remaining coarse material layer forms an armour, protecting further bed erosion.

Assyria Land to the North of Babylon comprising, in its greatest extent, a territory between the Euphrates and the mountain slopes East of the Tigris. The Assyrian Kingdom lasted from about BC 2300 to BC 606.

Atomic number The atomic number (of an atom) is defined as the number of units of positive charge in the nucleus. It determines the chemical properties of an atom.

Atomic weight Ratio of the average mass of a chemical element's atoms to some standard. Since 1961 the standard unit of atomic mass has been 1/12 the mass of an atom of the isotope carbon-12.

Avogadro number Number of elementary entities (i.e. molecules) in 1 mol of a substance: $6.0221367 \times 10^{23}\,\text{mol}^{-1}$. Named after the Italian physicist Amedeo Avogadro.

Backwater In a tranquil flow motion (i.e. subcritical flow) the longitudinal flow profile is controlled by the downstream flow conditions: e.g. an obstacle, a structure, a change of cross-section. Any downstream control structure (e.g. bridge piers, weir) induces a backwater effect. More generally the term backwater calculations or backwater profile refers to the calculation of the longitudinal flow profile. The term is commonly used for both supercritical and subcritical flow motion.

Backwater calculation Calculation of the free-surface profile in open channels. The first successful calculations were developed by the Frenchman J.B. Bélanger who used a finite difference step method for integrating the equations (Bélanger 1828).

Bagnold Ralph Alger Bagnold (1896–1990) was a British geologist and a leading expert on the physics of sediment transport by wind and water. During World War II, he founded the Long Range Desert Group and organized long-distance raids behind enemy lines across the Libyan Desert.

Bakhmeteff Boris Alexandrovitch Bakhmeteff (1880–1951) was a Russian hydraulician. In 1912, he developed the concept of specific energy and energy diagram for open channel flows.

Barrage French word for dam or weir, commonly used to described large dam structure in English.

Barré de Saint-Venant Adhémar Jean Claude Barré de Saint-Venant (1797–1886), French engineer of the 'Corps des Ponts-et-Chaussées', developed the equation of motion of a fluid particle in terms of the shear and normal forces exerted on it (Barré de Saint-Venant 1871a, b).

Barrel For a culvert, central section where the cross-section is minimum. Another term is the throat.

Bathymetry Measurement of water depth at various places in water (e.g. river, ocean).

Bazin Henri Emile Bazin was a French hydraulician (1829–1917) and engineer, member of the French 'Corps des Ponts-et-Chaussées' and later of the Académie des Sciences de Paris. He worked as an Assistant of Henri P.G. Darcy at the beginning of his career.

Bed form Channel bed irregularity that is related to the flow conditions. Characteristic bed forms include ripples, dunes and antidunes.

Bed load Sediment material transported by rolling, sliding and saltation motion along the bed.