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THE ROLE OF ENVIRONMENTAL FLUID MECHANICS IN WATER SYSTEM MANAGEMENT

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Abstract

Water has several unique physical and chemical properties that have influenced Life as it has evolved. Indeed the very concept of Life on the Earth is dependent on water supply. Although the total volume of fresh water on Earth is only a small fraction of that in the oceans, the biological and environmental role of freshwater systems is considerable. Environmental management of water systems (rivers, lakes, seas) is therefore a necessity to sustain economical development despite the technical challenges. Scientific methodology is based primarily upon the application of basic fluid mechanics to complex systems involving two- and possibly three-phase flows : e.g., sediment transport (water-solid), air-sea interactions (air-water). The writer proves the role of environmental fluid mechanics in gaining a sound understanding of water systems and in solving environmental problems. This is illustrated for a complete catchment system. That is, from upstream to downstream, the problem of reservoir sedimentation, stream re-oxygenation with in-stream aeration cascades, the impact of tidal bores on estuarine systems and the contribution of breaking waves to air-sea mass transfer. In each case, the complexity of the problem is shown and new technological advances are described highlighting the essential role of environmental fluid mechanics.

The management of water systems is extremely complex because of a combination of factors including Man's dependence on water, the geometric scale of water systems (up to 1E+7 km^2), the range of relevant time scales (from less than 1-s to over 1 E+9-s), and the complexity of the governing equations (non-linearity).

1. INTRODUCTION

The dependence of Life on water is absolute on Earth. Water is the major constituent of plant and animal cells. Up to 90 percent of the weight of living organisms is water. Nature has an important role in supplying Life and Man with water. In its various form (i.e. liquid, solid and vapour), water occupies about 1.41 E+18 m^3 on our planet, 97.25 per cent of the water volume being in the oceans. The cycle of water on Earth includes evaporation of water, circulation in the atmosphere, precipitation (e.g. rain, snow) and flowing streams at surface level and underground.

Man and Nature have to live together in a sustainable fashion. A number of natural events (e.g. typhoons, tsunamis, storm surges) affect diversely Man while the gradual deterioration of ecological systems caused by human interventions requires remedial actions be initiated. Since Antiquity, Man has attempted to control rivers : i.e., to use and to divert springs, ground water and streams. River regulation is achievable by building dams and weirs across the natural river bed, but such structures affect both the upstream and downstream catchments. The complexity and scale of most environmental problems makes it difficult to get an overview of an issue in all its dimensions (e.g. water quality of a river) unless a concerted management policy strategy exists. In the context of a water body, the role of fluid mechanics scientists is essential to solve the environmental problems.

In this paper, the writer highlights the role of basic fluid mechanics in gaining a sound understanding of water systems and in solving environmental problems. His opinion is illustrated for a complete catchment system. That is, from upstream to downstream, the problem of reservoir sedimentation, the use of in-stream re-aeration cascades, the impact of tidal bores and the contribution of breaking waves to air-sea mass transfer. The paper is based largely upon the writer's experience as a researcher, lecturer and consultant. He wrote four books (CHANSON 1995, 1997, 1999, 2001). He presented several keynote lectures and he gave several short courses on environmental hydraulics. He has been lecturing fluid mechanics and hydraulics to civil and environmental engineering students at both undergraduate and postgraduate levels.

What is environmental fluid mechanics ?

Fluid mechanics is the science dealing with the properties of liquids and gases, and concerned with the response of fluids to forces exerted upon them. It is based upon three fundamental principles : conservation of mass (continuity), momentum and energy. The complexity of fluid mechanics is due in large part to the non linearity of the basic equations: e.g., under certain conditions, fluid flows become unstable and behave in ways that seem chaotic.

Fluid mechanics is a relatively ancient science. It is believed that Hero of Alexandria (1st century AD) understood the continuity and momentum principles ([1]). Daniel BERNOULLI (1700-1782) made a significant contribution to the modern understanding of the energy principle ([2]) and Henri DARCY (1805-1858) promoted the understanding of energy loss ([3]). Although the term fluid mechanics embraces both fluid dynamics and hydrostatics, environmental fluid mechanics relates predominantly to the science of water in motion, and the interactions between the flowing fluid (water) and the surrounding environment. This includes the transport of solids, the dispersion of chemicals, the mixing of air and water at the free-surfaces. Environmental fluid mechanics encompasses two- and three-phase flows, yet includes also interactions with aquatic life (e.g. fish) ([4]).

2. EXTREME RESERVOIR SILTATION

2.1 Presentation

Waters flowing in streams and rivers have the ability to scour channel beds, to carry particles heavier than water and to deposit materials. This phenomenon (i.e. sediment transport) is of great economical importance and numerous failures have resulted from the inability of engineers to predict sediment motion (Fig. 2-1). Traditional (fixed-

[1]Hero was a Greek mathematician working in Alexandria, Egypt. He wrote at least 13 books on mathematics, mechanics and physics. His treatise "*Pneumatica*" described Hero's fountain, siphons, steam-powered engines including the first gas turbine, a water organ, and hydraulic and mechanical water devices. In his book "*Dioptra*", HERO stated rightly the concept of continuity for incompressible flow : the discharge being equal to the area of the cross-section of the flow times the speed of the flow.

[2]D. BERNOULLI was a Swiss mathematician, physicist and botanist who developed the Bernoulli equation in his "*Hydrodynamica, de viribus et motibus fluidorum*" textbook (1st draft in 1733, 1st publication in 1738, Strasbourg).

[3]H.P.G. DARCY was a French civil engineer who performed numerous experiments of flow resistance in pipes and in open channels, and of seepage flow in porous media (DARCY 1856, 1858).

[4]In a broader sense, environmental fluid mechanics includes also meteorology, wind flows, wind-wave interactions, wind-blown soil erosion, and fluid-structure interactions.

boundary) hydraulics cannot predict the morphology changes of natural streams because of the numerous interactions with the catchment, its hydrology and the sediment transport processes. It is now recognised that sediment motion is characterised by strong interactive processes between rainfall intensity and duration, water runoff, soil erosion resistance, topography of the stream and catchment, and stream discharge.

When a dam is built across a river, it acts as a sediment trap. After several years, the reservoir might become filled with sediments and cease to provide water storage. The primary consequence is the reduction of the reservoir capacity and of its economical and strategic impact. Figure 2-2 presents three cases of rapid siltation. Each reservoir failed because the designers did not understand the basic concepts of soil erosion, sediment transport and catchment management. Reservoir sedimentation is a very complex process. The dam, the reservoir and the catchment must be analysed as a complete system which cannot be dissociated, and a total catchment management policy must be considered from the early stages of reservoir design.

Fully-silted reservoirs stand as a source of embarrassment for the scientists and the governments, but also as safety hazards (e.g. CHANSON and JAMES 1999). However each reservoir failure must be recognised as a pedagogic tool to heighten the awareness of students, professionals and local authorities and of the public. Society must learn from its mistakes, not to repeat them again.

Fig. 2-1 - Bridge failure between Kaohsiung and PingTung city on the Kaoping river (Taiwan, 27 Sept 2000) (Courtesy of HUANG L.C., The Liberty Times)

The 1-km long bridge failed because of scour and the collapse of a 100-m long section after 22 years in operation. Scour was caused by floods and excessive (illegal) gravel extraction. Of interest, witnesses described a rumbling sound as the four-lane bridge broke and concrete fell into the river.

Fig. 2-2 - Extreme reservoir siltation

(A) Nishiyawa dam on the Hayakawa river (Japan, 1957) - Looking at the dam wall in background from the fully-silted reservoir (Photograph taken in Nov. 1998) - Dam : H = 39 m, L = 112 m - Reservoir Capacity : 2.38 Mm^3 - Spillway capacity : Q = 575 m^3/s - Reservoir fully-silted by gravel bed-load in less than 20 years and dredged around 1988 (2-m depth)

(B) Saignon dam, La Motte-du-Caire (France, 1961) (Photograph taken in June 1998) - Dam : H = 14.5 m - Reservoir Capacity : 0.14 Mm^3 - Catchment area : 3.5 km^2 - Reservoir fully-silted in 2 years - View from the right bank with the spillway in foreground (right), the fully-silted reservoir and the intake tower in background

(C) Gap weir, Werris Creek NSW (Australia, 1902) (Photograph taken on 13 June 1997) - Dam : H = 6 to 10 m (thin concrete arch dam) - Catchment area : 160 km^2 - Reservoir fully-silted by suspended load in 20 years. Since the dam wall was blasted twice to reduce upstream flooding and to drain the reservoir for rural usage

2.2 Discussion

A major issue in reservoir management is the lack of acknowledgment of sedimentation problems. For example, in Australia, there is conflicting information on whether reservoir siltation has been significant. For many decades, reservoir sedimentation has not been an issue : "the (sediment) yield [...] is relatively low compared to others in the world" (OUTHET 1984, NSW Water Resources Commission); the classical text book *Open Channel Flow* by F.M. HENDERSON, University of Newcastle NSW, made no mention of reservoir siltation in its section "Sediment transport" (HENDERSON 1966). The issue of reservoir siltation in Australia was ignored and rejected until the 1980s (CHANSON and JAMES 1998,1999).

A proper understanding of reservoir siltation mechanics requires a broad knowledge of all intervening parameters including long-term climatic changes. The world community has focused its attention on the early detection of drought (*El-Niño*), which is termed a "major catastrophe" in Australian television news ([5]). The El-Niño phenomenon is a recurrent climate pattern : it takes place in average every 5 to 7 years. In Australia, there have been a strong correlation between extreme siltation events and La Niña events (CHANSON and JAMES 1998). For example, at the Junction Reefs reservoir (1902 floods after the Great Drought of 1900-1902), the Moore Creek reservoir (flood of February 1908), the Gap weir (floods of 1919), the Melton reservoir (flood of 1941), the Quipolly reservoir (floods of

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[5]because the El-Niño is associated with very long periods (i.e. several years) of droughts in Eastern Australia. Of interest inter-annual climatic events (El-Niño or ENSO) associated with long period of droughts were first established in Australia between 1878 and 1888 by Sir Charles TODD, South Australia Government Observer, and well documented by H.C. RUSSELL, New South Wales Government Observer (GROVE 1995, p. 17).

1942-43). However the El-Niño/La Niña phenomenon is not properly managed by Local, National or International Institutions. No contingency for long-term policy has been made, in Australia or anywhere, to deal with the impact of El-Niño climatic pattern on reservoir management.

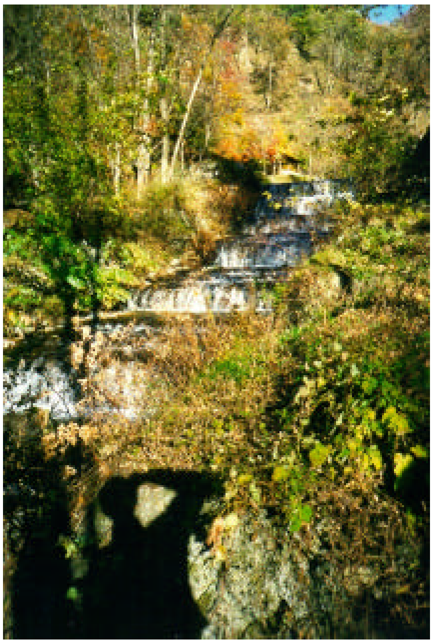

Fig. 2-3 - Ancient Sabo works (1916-18) near Matsumoto, Nagano Prefecture (Japan) (Photograph taken in Nov. 1998) - Artificial stepped channel modelled on 19th century French protection works in the Durance catchment

Future challenges ?

The writer is convinced that progresses in soil conservation and management practices are necessary. Too little is known on soil erosion by rainfall droplets, the impact of forestation on sediment runoff or the effects of rural practices. Yet major soil conservation programs undertaken in France (Grands Travaux de Forestation) and in Japan around 1850-1930 demonstrated outstanding results (e.g. CEMAGREF 1988) (Fig. 2-3).

A major engineering challenge will be the development of efficient desilting devices. For example, most Australian reservoirs have been inadequately equipped with flushing devices : e.g., a single scour outlet (∅ = 0.1 to 0.2 m). Only few dams were equipped with two or more flushing systems : e.g., Illalong Creek dam completed in 1914 and now fully-silted. In comparison the Nabataeans ([6]), Romans and Spaniards equipped their reservoirs with large sediment flushing system. For example, the Roman engineers equipped the Monte-Novo dam (A.D. 300, Portugal) with two outlets of 1.2 and 1.4 m^2 cross-section area each. Modern trend suggests the installation of large but expensive sluices (Fig. 2-4). Such sluice systems are not efficient and operate like the orifice flows of Jean-Charles de BORDA in the 18th century ([7]). Little technological progress has been achieved despite the economical significance of the problem. The writer believes that greater input from fluid mechanics scientists is needed.

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[6]habitants from an ancient kingdom to the East and South-East of Palestine that include the Neguev desert. The Nabataean kingdom lasted from around B.C. 312 to A.D. 106. The Nabataeans built a large number of soil-and-retention dams. Some are still in use today.

[7]Jean-Charles de BORDA (1733-1799) was a French mathematician and military engineer. He achieved the rank of Capitaine de Vaisseau and participated to the U.S. War of Independence with the French Navy. He investigated the flow through orifices and developed the Borda mouthpiece.

Fig. 2-4 - Large desilting sluice at St Martin auf Wollmissberg, Austria (in August 1999)

Left : view of the scour outlet and radial control gate - Right : detail of the radial gate (note sand and debris in foreground)

3. IN STREAM RE-AERATION CASCADES

3.1 Presentation

One of the most important water quality parameters is the dissolved oxygen content (DOC). DOC is a prime indicator of the quality of the water. Deep and slow pools of water upstream of a dam reduce the gas transfer process and the natural re-aeration as compared to an open river. Aeration enhancement by in-stream cascades has been used in polluted and eutrophic streams (Table 3-1). For example, in Chicago, five re-aeration cascades were built recently to re-oxygenate the depleted waters of the Calumet waterway. In operation their aeration efficiency corrected to a temperature of 15 Celsius is nearly 95% (ROBISON 1994). Similarly stepped weirs are designed downstream of large dams to control the quality of water releases (e.g. nitrogen supersaturation effect) (e.g. BOYER 1971). Despite the associated hydropower loss, a two-steps re-aeration cascade was added downstream of the Petit-Saut dam in French Guyana to treat turbined waters which had unacceptable high methane content (GOSSE and GREGOIRE 1997).

Basically in-stream cascades are efficient means of aeration because of the strong turbulent mixing, the large residence time and the substantial air bubble entrainment (Fig. 3-1). Nonetheless little information is available to optimise a cascade design because the multiphase flow hydrodynamics has been poorly understood.

Basic mass transfer equation

Aeration or re-aeration is a mass transfer process between atmosphere and water. The mass transfer rate of a chemical across an interface in a quiescent fluid varies directly as the coefficient of molecular diffusion and the negative gradient of gas concentration (Fick's law). For volatile chemicals (e.g. oxygen, nitrogen) in water, the mass transfer equation becomes :

Fig. 3-1 - In-stream re-aeration cascade : Emerald Creek weir (Australia, 1947) in 1951 (Courtesy of Qld Dept. Natural Resources, Dam Safety) - Weir : H = 5.2 m, L = 79.5 m, 3 steps, timber crib held with timber piles

$$\frac{\partial}{\partial t} C_{gas} = K_L * a * (C_s - C_{gas}) \qquad (3\text{-}1)$$

where C_{gas} is the concentration of the dissolved chemical in liquid, t is the time, a is the specific surface area defined as the air-water interface area per unit volume of air and water, K_L is the liquid film coefficient and C_s is the concentration of dissolved gas in water at equilibrium. The mass transfer coefficient K_L is almost constant regardless of bubble sizes and flow situations, but the air-water interface area is greatly affected by air bubble entrainment (e.g. Fig. 3-1). The presence of entrained air bubbles increases drastically the air-water interface area due to the cumulative bubble surface area. For example, if the mean bubble diameter is 2-mm and the air content is 12%, the specific interface area is 750 m^2 per cubic metre of air and water (almost the size of a basketball court).

Traditionally, environmental engineers used to express the overall efficiency of an aeration cascade in terms of the deficit ratio r or the aeration efficiency E defined as :

$$E = \frac{C_{DS} - C_{US}}{C_s - C_{US}} = 1 - \frac{1}{r} \qquad (3\text{-}2)$$

where C_{US}, the upstream dissolved gas concentration, and C_{DS}, the dissolved gas concentration at the downstream end of the channel, were measured. Neither parameter (r or E) relates to the flow hydrodynamics nor the rate of air entrainment on the weir. Recent progresses in multiphase flow dynamics provide new information on the air-water interfacial properties (e.g. TOOMBES and CHANSON 2000). Some results are described below.

3.2 Air-water interfacial properties on stepped cascades

New experiments were performed in near full-scale stepped cascades (Table 3-2). The distributions of void fraction, bubble counts and air-water specific area were recorded with resistivity probes (inner electrode ∅ = 25 µm to 0.35-mm). Measurements were performed for a wide range of flow conditions (Table 3-2).

Table 3-1 - Re-aeration stepped cascades

Cascade (1)	Ref. (2)	Purpose (3)	Characteristics (4)	Performances Prototype data (5)
Calumet waterway cascades, Chicago USA	[1,5]	Five re-aeration cascades. Designed to re-oxygenate the depleted waters of the Calumet waterway.	Cascades with pooled steps.	E_{15} = 0.95 (3-steps) to 1.0 (4-steps) for q = 0.021 m^2/s
Canyon weir, USA	[2]	Re-aeration weir downstream of a hydropower station. Designed to re-oxygenate turbined waters.	Labyrinth weir (crest length : 118 m). Single drop (h = 1 m). Plunge pool depth : 1.9 m..	E_{15} = 0.50 to 0.65 for Q = 3 to 14 m^3/s
Chatuge weir, USA	[2,3]	Re-aeration weir downstream of Chatuge hydro project on Hiwasse river (USA). Designed to re-oxygenate turbined waters.	Hollow broad-crested weir. Single drop (h = 2.9 m). Plunge pool depth : 1.1 m. Design flow conditions : 1.2 m^2/s.	E_{15} = 0.63 to 0.73 for Q = 14 to 40 m^3/s
Petit-Saut re-aeration cascade, French Guyana	[6]	Re-aeration weir downstream of Petit-Saut dam (French Guyana). Designed to re-oxygenate turbined waters and to remove methane.	Labyrinth weir. Two drops (h = 2 m each). Design flow conditions : 110 m^3/s. Initial methane level > 10 g/m^3	Oxygen supersaturation. E(methane) = 80%
South Houlston weir, USA	[2,4]	Re-aeration weir downstream of a hydropower station. Designed to re-oxygenate turbined waters.	Labyrinth weir (crest length : 640 m). Single drop (h = 2.3 m). Plunge pool depth : 0.91 to 1.37 m.	E_{15} = 0.55 to 0.70 for Q = 14 to 68 m^3/s

Ref.: [1] CARGILL (1994); [2] HAUSER and MORRIS (1995); [3] HAUSER et al. (1992); [4] RIZK and HAUSER (1993); [5] ROBISON (1994);[6] GOSSE and GREGOIRE (1997).

Notes : E_{15} : aeration efficiency in terms of DOC at 15 Celsius.

Table 3-2 - Re-aeration potential of stepped cascades

Ref. (1)	α deg.	h m (2)	W m (3)	d_c/h (4)	Δz_o m (5)	E (6)	Comments (7)
University of Queensland							
Configuration No. 1	3.2	0.143	0.25	0.60 to 0.87	0.143	4.1 to 3.4%	Nappe flow NA3. L = 3.2 m. 1 drop.
Configuration No. 2	3.4	0.143	0.50	0.38 to 0.92	1.43	18 to 19%	Nappe flow NA3. L = 24 m. 10 drops.
Configuration No. 3	3.4	0.07	0.50	0.78 to 1.8	1.43	13 to 22%	Nappe transition and skimming flows. L = 24 m. 10 drops.
Configuration No. 4	21.8	0.10	1.0	0.6 to 1.5	0.9	4.0 to 0.7%	Nappe transition and skimming flows. L = 2.7 m. 9 drops.

Notes : h : step height; W : chute width; d_c : critical flow depth; Δz_o : total drop in invert elevation; E : aeration efficiency at a stepped cascade in terms of DO at standard pressure ($P = P_{std}$) and T = 20 Celsius.

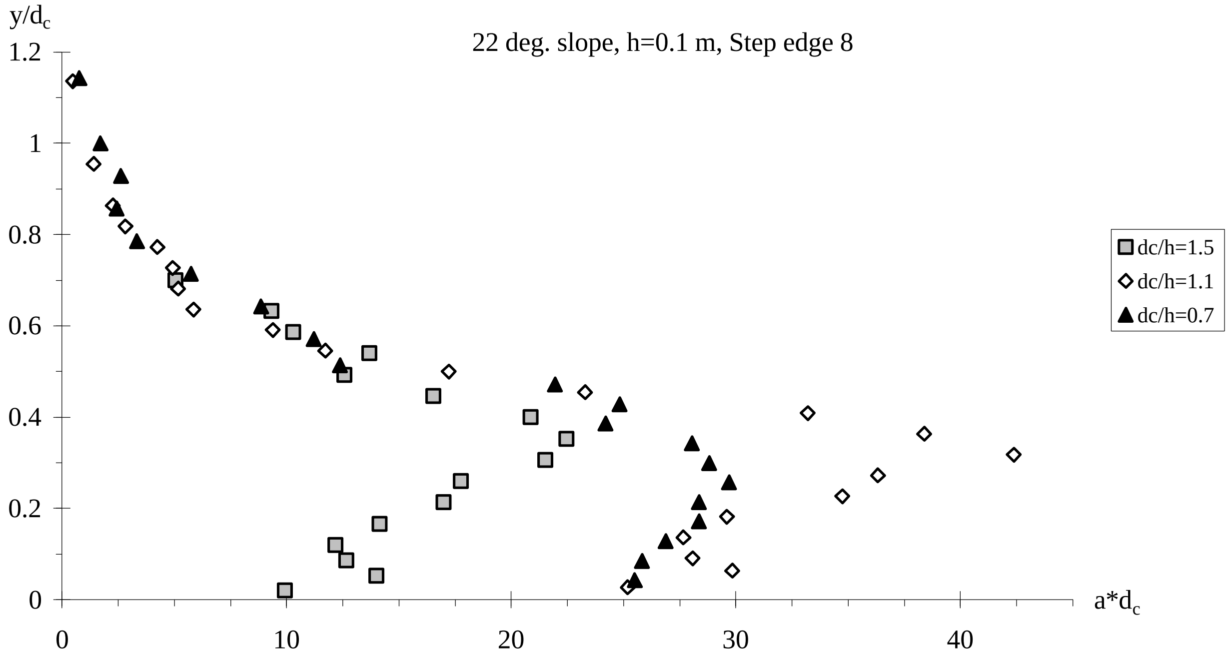
Experimental data show large air-water interfacial areas, with depth-averaged specific interface area ranging from 20 to over 320 m^{-1} typically along each step, and local specific interface area of up to 650 m^{-1} at the largest flow rates (Fig. 3-2). The integration of the mass transfer equation (Eq. (3-1)) was conducted for each experimental configuration (Table 3-2, column 6). Optimum results were achieved with a flat chute. For configurations No. 2 and 3, it yields aeration efficiencies for a single step ranging from 1.5 to 4% (in terms of dissolved oxygen) depending upon the flow rate and step location. The strongest aeration was achieved at the largest flow rate. The results imply overall

cascade aeration efficiencies of 13 to 22% depending upon the flow rate for a total head loss of 1.4-m only. These figures were obtained by integrating the mass transfer equation (Eq. (3-1)) using interface area measurements and they were double-checked by measuring DO upstream and downstream of the structure.
Overall the study demonstrates the potential of aeration cascades at low to medium flows and provides a better understanding of the basic aeration mechanisms (e.g. Fig. 3-1).

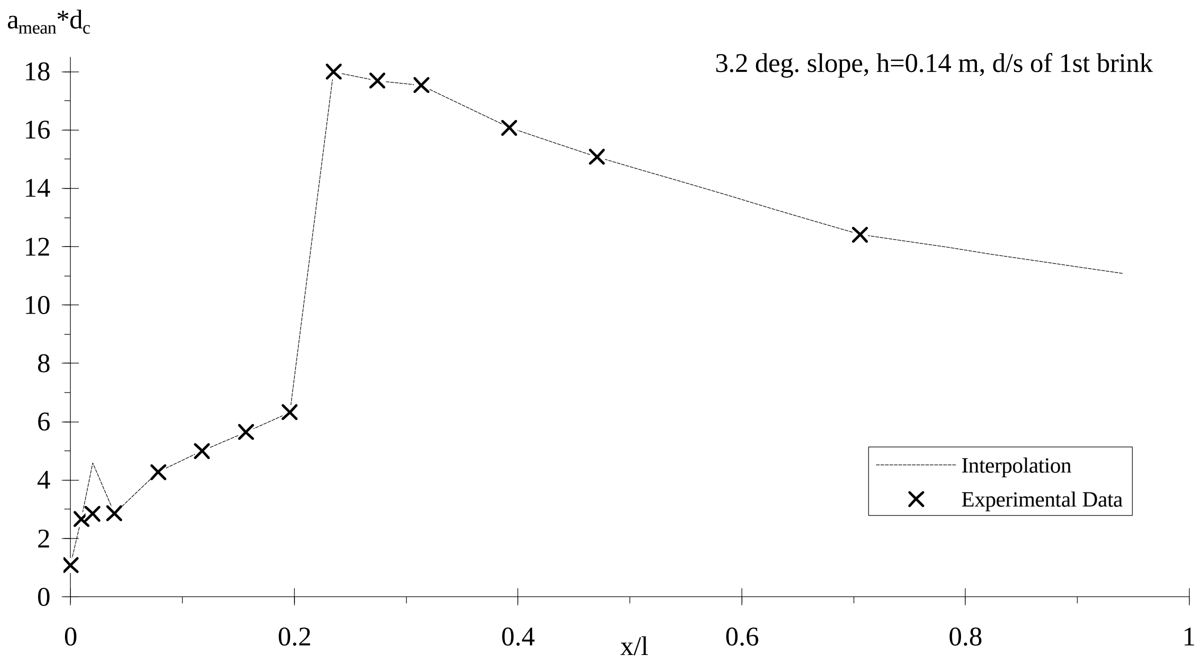
3.3 Discussion

A detailed multiphase flow analysis provides a new understanding of the aeration mechanisms. The results highlight that the aeration performances are strongly affected by the type of flow regime which in turn is a function of the step geometry (height, length, shape) and flow rate (CHANSON 1995,2001).
At low flow rates (nappe flow regime), the aeration efficiency is primarily a function of the discharge q and total drop height Δz_o. The oxygen transfer increases with increasing drop in elevation for a given discharge. Also the mass transfer increases with decreasing discharges for a given drop in elevation and channel slope. At high flow rates (skimming flow regime), the aeration efficiency is nearly zero as long as no free-surface aeration occurs. When free-surface aeration take place, the oxygen transfer increases sharply with the dimensionless drop in elevation $\Delta z_o/d_c$. The largest aeration efficiencies are obtained with the smallest discharges. The analysis shows also that the channel slope and dimensionless step height h/d_c have little effects on the aeration efficiency of skimming flows.

Fig. 3-2 - Distributions of air-water specific interface area
(A) Measured air-water interface area in skimming and transition flows - Configuration No. 4, 22-degree chute, step edge 8



(B) Depth average mean specific interface area along one step (nappe flow) - Configuration No. 1, 3.2-degree chute, q = 0.105 m^2/s



In summary, air-water gas transfer is maximum for small discharges with skimming flows; and it is maximum for relatively large discharges in nappe flow situations. This apparent contrast is explained by the different mechanisms of air entrainment and air-water gas transfer between the two flow regimes.

In the writer's opinion, the example demonstrates the role in multiphase flow dynamics to gain a better knowledge of complex flow situations. The results will provide new guidelines for optimum cascade design when environmental considerations lead to maximise mass transfer for a small environment-friendly structure.

4. ENVIRONMENTAL IMPACT OF TIDAL BORES ON ESTUARINE SYSTEMS

4.1 Presentation

A bore is a positive surge of tidal origin which may form with large tidal ranges in a converging channel forming a funnel shape. The front of the surge absorbs random disturbances on both sides and this makes the wave stable and self-perpetuating (CHANSON 1999). With appropriate boundary conditions, a tidal bore may travel long distances upstream: e.g., the tidal bore on the Pungue river (Mozambique) is still about 0.7 m high about 50 km upstream of the mouth and it may reach 80 km inland. Famous bores include the Hangzhou (or Hangchow) bore on the Qiantang river, the Amazon bore called *pororoca*, the tidal bore on the Seine river (*mascaret*) and the Hoogly (or Hooghly) bore on the Gange. Smaller tidal bores occur on the Severn river near Gloucester, England, on the Dordogne river, France, in the Bay of Fundy (at Petitcodiac and Truro), on the Styx and Daly rivers (Australia), and at Batang Lupar (Malaysia) (Fig. 4-1).

A tidal bore affects shipping industries. For example, the *mascaret* of the Seine river had had a sinister reputation. More than 220 ships were lost between 1789 and 1840 in the Quilleboeuf-Villequier section (MALANDAIN 1988). The height of the *mascaret* bore could reach up to 7.3 m and the bore front travelled at a celerity of about 2 to 10 m/s.

Even in modern times, the Hoogly and Hangzhou bores are hazards for small ships and boats. Tidal bores affect also estuarine eco-systems. The effect on sediment transport was studied at Petitcodiac and Shubenacadie rivers, on the Sée and Sélune rivers and on the Hangzhou bay (TESSIER and TERWINDT 1994, CHEN et al. 1990). The impact on the ecology is acknowledged in the Amazon where piranhas eat matter in suspension after the passage of the bore, at Turnagain Arm where bald eagles fish behind the bore, in the Severn river (sturgeons in the past, elvers) and in the Bay of Fundy (striped bass spawning).

4.2 Basic flow characteristics

Despite their impact on estuarine processes, little is known on the flow field, mixing and sediment motion beneath tidal bores. Some salient characteristics are revealed in photographs of field occurrences : e.g., most tidal bores develop as undular surges (Fig. 4-1). In absence of detailed field measurement, a quasi-steady flow analogy may be applied to investigate an undular tidal bore with the physical model of an undular jump (CHANSON 2001b).

Detailed experiments were performed at the University of Queensland in a 0.5-m wide horizontal flume. For each experiment, the supercritical inflow was partially-developed : i.e., $\delta/d_1 \sim 0.4$ where δ is the boundary layer thickness and d_1 is the upstream water depth. The upper fluid layer was nearly an ideal flow characterised by low turbulence level typical of field situations ([8]). Careful measurements of free-surface profiles, velocity, pressure and bottom shear stress were conducted beneath the undular flow.

Fig. 4-1 - Undular tidal bore of the Dordogne river on 27 Sept. 2000 at 5:00 pm (Photographs by the author)

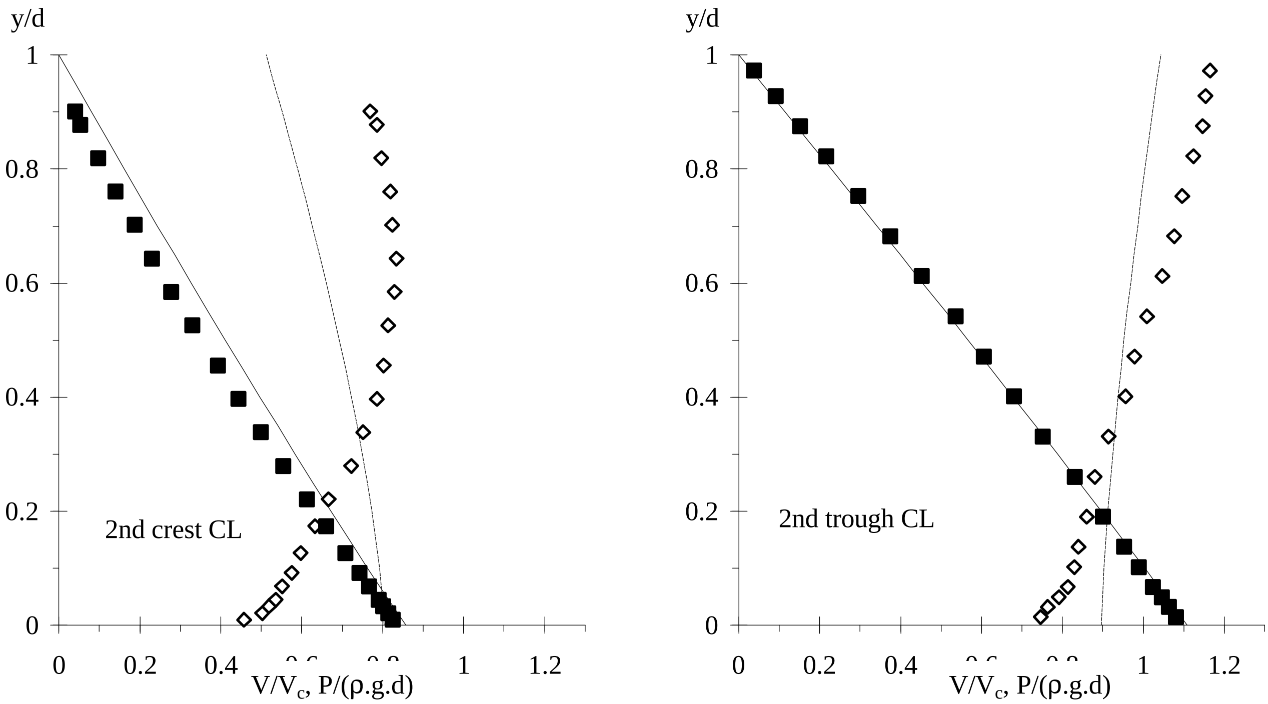
(A) Looking downstream at the incoming undular bore

[8]Visually the river flow before bore arrival is quiet, and the free-surface is smooth and glossy (e.g. Fig. 4-1B). In the model, the inflow turbulence level was minimised with a relatively small boundary layer thickness.

(B) Looking upstream at the murky waters after the bore passage (foreground) and the glossy free-surface in background

Fig. 4-2 - Dimensionless pressure and velocity distributions : comparison with inviscid Boussinesq theory (MONTES and CHANSON 1998) - Exp. No. 2 centreline data - Legend : Black square = P/ρ*g*d; White diamond = V/V_c

(A) Second wave crest (B) Second wave trough



Visual observations and detailed measurements showed a two-dimensional undular flow. Figure 4-2 presents typical dimensionless pressure and velocity distributions. The data are compared with an inviscid solution of the Boussinesq equation (MONTES and CHANSON 1998). Beneath the undulations, the pressure distributions are not hydrostatic.

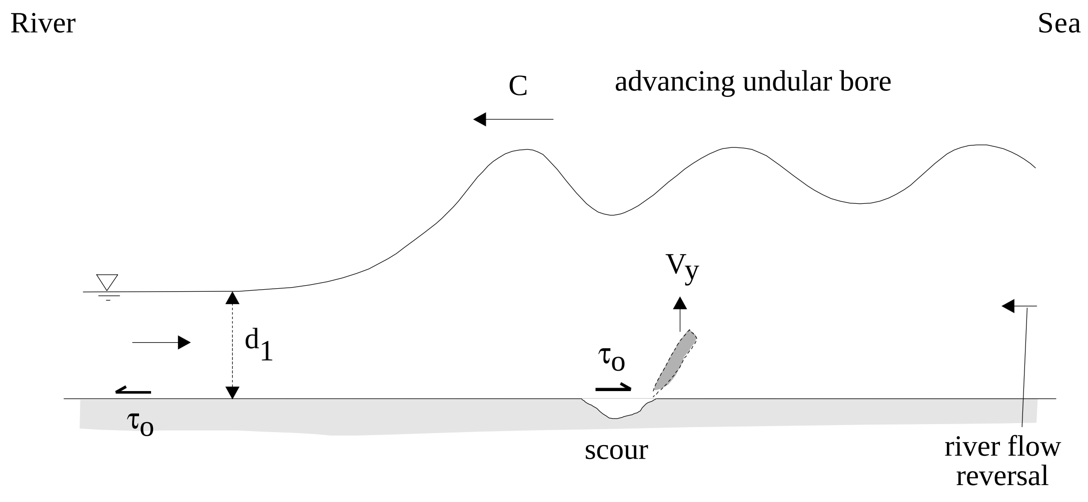
The pressure gradients are larger than hydrostatic when the free-surface is curved upwards (i.e. concave) and less than hydrostatic when convex as predicted by irrotational flow motion theory, although greater deviations from hydrostatic pressure distributions are experimentally observed (Fig. 4-2). The velocity data show rapid redistributions between the troughs and crests. Bottom boundary shear stress data show maximum boundary shear stresses below wave troughs and minimum values below the crests. Large longitudinal variations of shear stress are observed : e.g., the boundary shear stress below the second trough is about twice of that observed at the second and third wave crest.

Applications to tidal bores

Considering an undular bore progressing upstream, the river bed is subjected to a rapid flow reversal at the wave front associated with bottom shear stress reversal and maximum (negative) boundary shear stress beneath the troughs. This pattern suggests some scour beneath wave troughs while sediment matter is carried upwards by vertical flow motion occurring between a trough and the following wave crest (Fig. 4-3). Experimental data and ideal flow calculations show strong vertical (upward) velocity components between trough and crest. Further scour and sediment dispersion continue beneath the following undulations. Fine sediments (silt, clay) are put into suspension and transported upstream with the bore. Ultimately they are deposited in intertidal zones.

The writer observed the tidal bore of the Dordogne river at St Pardon (France) about 103 km upstream of Pointe de Grave on 27 September 2000 (coefficient: 103). At that location, the river is about 350 m wide and there is no sharp bend for about 3 to 4 km. In September 2000, the bore exhibited about 8 to 12 well-formed undulations (height ~ 1 m, length ~ 8 m, Fr_1 ~ 1.3) followed by chaotic waves (Fig. 4-1). Two dominant features of the bore were the murkiness of the water after the passage of the bore, suggesting significant sediment scour and mixing, and the chaotic wave motion lasting for some time, making difficult for surfers to come back on shore even 20 minutes after the bore passage. Although the latter effect was not documented, researchers observed similar chaotic wave motion propagating as far as x/d_c ~ 2,000 downstream of undular jumps in laboratory and in man-made canals (DARCY and BAZIN 1865, CHANSON and MONTES 1995).

Fig. 4-3 - Sketch of sediment bed scour and dispersion at an undular tidal bore



4.3 Comments

Despite some limitation of the quasi-steady flow analogy, such a basic fluid mechanics approach provides a new understanding of the impact of tidal bores. Undular bores have a great potential to scour the channel bed and to carry upstream matters into suspension (although they do not have the spectacular appearance of breaking bores). They will affect the river topography and the eco-system. In turn the existence of the tidal bore is influenced by the bed geometry and by man-made interventions. River training and dam construction inhibit bore development : e.g., the Seine and Colorado river bores disappeared after extensive river training; the Petitcodiac and Couesnon river bores vanished after the construction of upstream barrage ([9]).But, in one case, Petitcodiac (Can.), bore conditions were improved after adjustments to the spring gate management plan were made.

5. AIR-SEA MASS TRANSFER : CONTRIBUTION OF BREAKING WAVES

5.1 Breaking waves in deep-waters

Air-sea mass transfer at the ocean surface is an important process for the exchange of nitrogen, oxygen and carbon dioxide between the atmosphere and the ocean. The dissolution of carbon dioxide in the sea, the supersaturation of oxygen in the ocean and the oxygen release to the atmosphere contribute to the balance between these gases in the atmosphere (SARMIENTO 1984,1992). During storm events or for large wind speeds (> 10 m/s), wave breaking with extensive air bubble entrainment occurs and contributes significantly to the air-sea mass transfer process. Large numbers of bubbles are entrained by breaking waves and by the re-attachment of wind blown drops. It was suggested that the presence of entrained air bubbles at depths might explain why the world's oceans are on average 3% supersaturated with dissolved oxygen while this level of supersaturation can rise to 8% after a storm (ALEKSEYEV and KOKORIN 1984, STRAMSKA et al. 1990).

Table 5-1 - Comparison between field observations and predictions based upon plunging jet flow experiments (CHANSON and CUMMINGS 1994)

Parameter (1)	Predictions CHANSON and CUMMINGS (1994) (2)	Field observations (3)	Comments (4)
Maximum bubble size	0.3 to 0.4 mm	0.13 mm (from 1.5-m depth) 0.3 mm (from 0.7-m depth)	Margaret's Bay, Nova Scotia (JOHNSON and COOKE 1979). Wave heights : 1.8 m and 2 m.
	0.25 to 0.3 mm	0.35 mm (from 1.5 m depth)	Deep sea (KOLOVAYEV 1976). Wind speeds: 11 to 13 m/s.
Bubble penetration depth	--	20 m	Storm in North Atlantic (KANWISHER 1963).
	0.4 to 8.1 m	8 m	Deep sea (KOLOVAYEV 1976). Wind speeds: 11 to 13 m/s.
Oxygen flux	--	3.75 E-6 to 1.85 E-5 mole/s.m^2	Mid Atlantic Bight (WALLACE and WIRICK 1992). Wind speeds: 4.3 to 18.8 m/s. Temperatures : 7.7 to 12.5 Celsius.
	--	1.5E-5 mole/s.m^2	Georgia Straight (FARMER et al. 1993). Wind speeds up to 15 m/s. Temperature : 9 Celsius.
	1.1 E-5 mole/s.m^2	--	Caused by plunging breakers with 10 m/s wind speed at 10 Celsius.

[9]to limit sea water flooding at high tides.

Fig. 5-1 - Plunging breaking wave

Plunging breaking waves play a major role in air-sea mass transfer and an analogy was developed between plunging breakers and plunging jet flows (CHANSON and CUMMINGS 1994) (Fig. 5-1). Using the experience of air bubble entrainment at plunging jets in civil, chemical and mechanical engineering applications, estimations of air entrainment rates, bubble sizes, bubble penetration depths and mass transfer rates were found to match observations of air bubbles in the ocean and their behaviour during storms (Table 5-1). The study demonstrated the substantial contribution of air entrainment at plunging breaking waves in deep-sea mass transfer, and it provided a better knowledge of the drastic increase of dissolved gas contents in ocean deep waters after storm events.

Discussion

The overturning of breaking waves is an unsteady and three-dimensional process. CHANSON and CUMMINGS' (1994) calculations were based upon steady two-dimensional plunging jet flows. Although the unsteadiness and three-dimensional aspects of wave breaking do not affect maximum bubble size nor bubble penetration depth computations, it is acknowledged that the rate of air bubble entrainment cannot be estimated accurately from classical plunging jet correlations. Further progresses in mass transfer processes in deep waters will require new ideas associated with field investigations.

5.2 Air bubble entrainment at breaking waves near the coastline

Air bubble entrainment by breaking waves is also a significant factor in the surf zone under high wave conditions (Fig. 5-2). However the influence of entrained air on the wave field near the surf zone has not been well investigated except for some research on energy dissipation by wave breaking. It was recently proposed that air entrainment due to plunging breakers may be a energy transfer mechanism generating free long-period waves and that it contributes to some mass transfer (CHANSON et al. 2000). However, since the air bubble entrainment process is improperly scaled by a Froude similitude, most laboratory experiments tend to underestimate its effects (WOOD 1991, CHANSON 1997).

A near-full-scale modelling of plunging breakers in the surf zone was conducted by CHANSON et al. (1999,2000). The plunging jet of the breaker was modelled by an unsteady water jet (0.75-m by 0.07-m) discharging into a wave flume with initial water depths ranging from 0.2 to 0.5 m. For some experiments, air entrainment was suppressed (by a factor of 2 to 3) to investigate specifically the effects of air entrainment at breaking. The idealised breaker model provided new qualitative and quantitative informations.

Fig. 5-2 - Breaking waves on a shore line : the white waters highlight air bubble entrainment at wave breaking
Main Beach on 7 Aug. 1999, Gold Coast, Australia

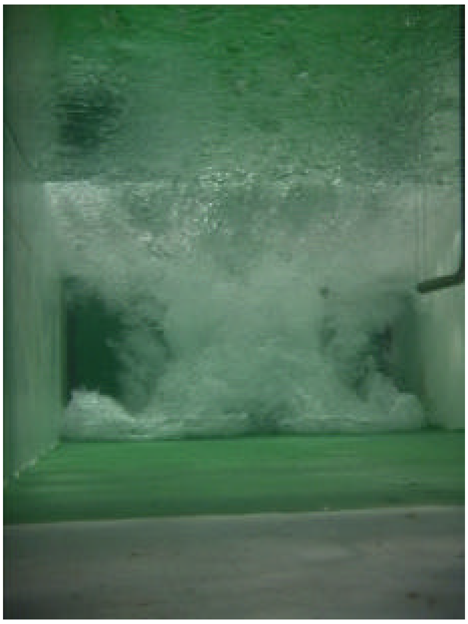
The initial instants of jet impact were characterised by strong splashing of short duration (i.e. less than 0.4 s) and the generation of a downward underwater bubble plume (Fig. 5-3). High void fraction (i.e. greater than 98%) was observed in the splashing, and some droplets could travel up to 2.5-m from the impact point and reach heights in excess of 0.4 m above the initial free-surface level. A similar splashing process was observed, in field and laboratory, during the initial stage of the plunging breaking wave (e.g. PERLIN et al. 1996). Below the free-surface, the initial bubble entrainment formed a densely populated bubble plume travelling downwards. The underwater bubbly plume flowed downwards until it reached the bottom and then propagated parallel to the bed with clear-water above as the plume front expanded with some rising bubbles (Fig. 5-3B). This mechanism was of short duration (< 1 sec.) and the plume was seen to reach horizontal distance x/d up to 3, where d is the initial water depth. These initial instants were followed by the development of a "boiling" flow next to the plunge point. The "white water" region was extremely turbulent with a lot of entrained air bubbles; it has the same appearance as a hydraulic jump roller and occupies a large area (x/d up to 7). Average void fractions of nearly 12% are observed next to the nappe impact and 4 to 6% air contents were recorded at 1-m downstream of the nappe impact for the duration of the breaker. Most entrained bubbles had a millimetric sizes. The boiling flow pattern lasted typically 50% longer than the plunging jet. Visually most entrained air bubbles disappeared after about 3 to 4 times the breaker duration, although fine bubbles were still seen several minutes after the experiment end.

The wave data analysis suggested further that air entrainment affected the wave field, in particular the more energetic waves. Higher water levels were observed in the early stages, followed by lower water levels. The initial water level rise was caused by the entrained bubbles while the subsequent drop in water level was induced by a strong circulation associated with the upwelling current due to bubble rise, the time scale of which was almost linear to the water depth (i.e. the rise time of the bubbles).

Fig. 5-3 - Full-scale modelling of a plunging breaker at Toyohashi University of Technology

(A) Overview of nappe impact
initial water depth : 0.40 m

(B) Underwater bubble plume, looking at the jet impact
0.33 sec. after nappe impact (0.30-m initial water depth)



Discussion

In this case study, physical modelling was conducted because the breaking process cannot be modelled analytically nor numerically in a simple manner. In laboratory, the flow parameters can be controlled but the selection of the model scale is critical to minimise scale effects. For example, in the field, a 0.2-m high breaking wave will be characterised by some air entrainment while a 1:4 scale model of the same wave will not.

Wave breaking near the coastline is often associated with significant sediment transport and the resulting flow becomes a three-phase flow: gas (air), liquid (water) and solid (sediment). The challenges ahead of fluid dynamics experts will be to comprehend the interactions between the three phases.

6. SUMMARY AND RECOMMENDATIONS

Environmental management deals from problems and ecological impact to remedial actions and concerted strategies. Issues regarded by many as the most urgent include a rational scientific approach, the transfer of know-how and technology across disciplines and countries, and the planning and decision making process. Although the total volume of fresh water on Earth is only a small fraction of that in the oceans, the biological and environmental role of freshwater systems is considerable. Man's water supply for drinking water, irrigation and hydropower derives nearly exclusively from freshwater streams.

The complexity of environmental problems linking air, soil and water pollution causes considerable difficulties for environmental planning and management. The scientific approach is based upon the application of fluid mechanics principles. Scientist have an important role to contribute, even if the technical challenges involving multiphase flows and interactions between fluids and biological life are gigantic. In the writer's opinion, the extreme complexity of water system management is closely linked with :

- Man's (and Life's) total dependence on water,
- the geometric scale of water systems : e.g., from less than 10 m^2 for a soil erosion pattern (e.g. rill) to over 1,000 km^2 for a river catchment area typically, and ocean surface area over 1 E+6 km^2,
- the broad range of relevant time scales : e.g., < 1 second for a breaking wave, ~ 1 E+4 s for tidal processes, ~ 1 E+8 s for reservoir siltation, ~ 1 E+9 s for deep sea currents,
- the variability of river flows from zero (dry river bed during droughts) to gigantic floods, and
- the complexity of basic fluid mechanics, with governing equations characterised by non-linearity, natural fluid instabilities, interactions between water, solid, air and biological life.

It is hoped that this keynote lecture has demonstrated the complexity of the issues, because this has direct implications on research, education and world policies.

Political role(s) of water systems

The writer believes that environmental management of water systems is closely linked with political stability, and that the sustainable development of Earth water systems is the key of long-term peace and stability. The 21st century is facing high risks of armed conflicts centred around water systems, and the writer is convinced that freshwater system issues will be the focal point of future armed conflicts. For example, present unrest in the West Bank (Palestine, 2000-01) is linked with the control of groundwater reserves. This situation is not new but the risks are far greater in the 21st century.

Fig. 6-1 - Japanese forces opposing a Mongol fleet during the 13th century

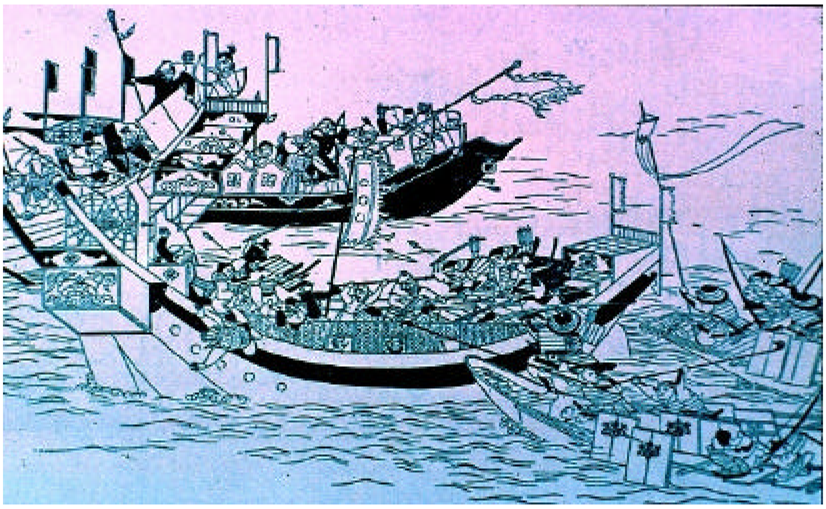
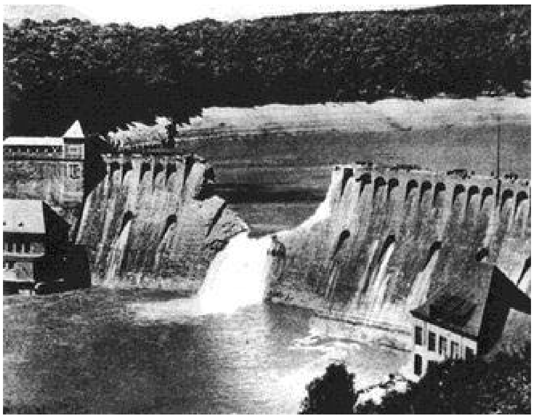


Fig. 6-2 - Möhne dam shortly after the R.A.F. raid on 16-17 May 1943 - Almost 1,300 people died in the floods following the dam buster campaign, mostly inmates of a Prisoner of War (POW) camp just below the dam.



Oceans played a role in History. For example, the English Channel (*Manche*) stopped the armies of Napoleon Bonaparte and A. Hitler in 1803-05 and 1940 respectively, even if it did not prevent Britain invasion by Julius Caesar (BC 55-54) and the Normands (AD 1066), nor the Allied Forces landing in Normandie in June 1944. In Asia, the Sea of Japan saw the destruction of a Mongol-Korean fleet invading Japan on 1281 ("*divine wind*") (Fig. 6-1).

Armed conflicts around freshwater systems have been plenty. In the Bible, a wind-setup effect allowed Moses and the Hebrews to cross shallow water lakes and marshes (Sea of Reeds) during their exodus and the returning waters crushed the pursuing Egyptian army (Exodus 13-15) ([10]). Man-made flooding ([11]) of an army or a city was carried out by the Assyrians (Babylon, Iraq BC 689), the Spartans (Mantinea, Greece BC 385-84), the Chinese (Huai river, AD 514-15), the Russian army (Dnieprostroy dam, 1941) ([12]) (RÉ 1946, DRESSLER 1952, SMITH 1971, SCHNITTER 1994). A related case is the air raid on the Möhne dam conducted by the British, in 1943, during the dam buster campaign (Fig. 6-2). Dyke destruction and associated flooding played a role in several wars. For example, the Dutch broke dykes near Amsterdam to stop the French army in 1672.

Recently some attention was focused on river management of the Tigris and Euphrates rivers and the potential conflicts between Turkey, Iraq and Syria. However lesser known water conflicts are likely to generate armed conflicts. The scope of the relevant issues is broad and complex : e.g., water pollution, water supply, flooding, drought.

Fluid mechanics research and support

The relationship between Man and the environment is one of interdependence. Water plays a major role in human perception of the environment because it an indispensable element. Past and present efforts to protect the environment have been to a large extent characterised by single-issue approaches. The writer has attempted to highlight the complexity of the scientific issues. The technical challenges are formidable and sustained research efforts are essential. The present paper has demonstrated that complicated water problems (e.g. tidal bores, cascading waters) may be solved in a scientific manner with positive outcomes for environmental planners. However scientific progresses have been hampered by a poor understanding of water system issues and by a lack of concerted financial support from a generation of so-called "environmental planners" and politicians. It is essential that environmental managers,

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[10]The Sea of Reeds ("papyrus") is often mistaken for the Red Sea.

[11]by building an upstream dam and destroying it.

[12]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.

industries and governments understand the scientific difficulties and that they support technical progresses. Although this lecture emphasised the technical difficulties, it has also demonstrated that genuine progresses are achievable.

Higher education

The education of scientists and engineers is another major issue. Basic fluid mechanics is typically introduced in engineering and applied mathematics degrees. Some advanced subjects might be offered in postgraduate courses. However environmental fluid mechanics involves the interactions between water, soil, air and aquatic life. Such topics are not taught in undergraduate curricula nor at postgraduate levels in most universities. The writer has lectured air-water flows at postgraduate levels since 1992 (CHANSON 1997) and he introduced some basic ideas at undergraduate level (e.g. CHANSON 1999, pp. 149-253, 330, 355-364). However he believes that many researchers, professionals, government administrators and politicians do not fully appreciate the complexity of environmental fluid mechanics nor the needs for further education of quality.

It is the writers' belief that environmental management of water systems SHALL NOT SUCCEED without further Research and Higher Education initiatives (i.e. funding) in Basic and Environmental Fluid Mechanics.

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NOTATION

a	air-water specific interface area (m^{-1}), defined as the interfacial area per unit of air and water;
a_{mean}	depth-average specific interface area (m^{-1});
C	air concentration (or void fraction);
C_{gas}	dissolved gas concentration (kg/m^3);
C_s	saturation concentration (kg/m^3);
D_H	hydraulic diameter (m);
d	flow depth (m) measured normal to invert or normal to pseudo-bottom (skimming flow);
d_1	upstream flow depth (m);
d_c	critical flow depth (m);
E	aeration efficiency
Fr	Froude number;
Fr_1	upstream Froude number;
g	gravity acceleration (m/s^2);
H	dam height (m);
h	step height (m);
K_L	liquid film coefficient (m/s);

L length (m);

l step length (m);

P pressure (Pa);

Pstd standard pressure (Pa) : Pstd = 1 atm = 1.01325 E+5 Pa;

Q water discharge (m^3/s);

q water discharge per unit width (m^2/s);

r deficit ratio;

T temperature (K);

t time (s);

V velocity (m/s);

V_c critical flow velocity (m/s);

W channel width (m);

x longitudinal distance (m);

y distance (m) normal to the bed;

α channel slope;

Δz_o total drop in invert elevation (m);

δ boundary layer thickness (m);

ρ water density (kg/m^3);

REFERENCES

ALEKSEYEV, V.V., and KOKORIN, A.O. (1984). "The Effect of Bubbles formed by Breaking Wind Waves on Air-Sea Gas Transfer." *Izvestiya* (in Russian) (Translated in *Atmospheric Ocean Physics*, Vol. . 20, No. 7, pp. 554-559).

BOYER, P.B. (1971). "Gas Supersaturation Problem in the Columbia River." *Proc. Intl Symp. on Man-Made Lakes*, American Geophysical Union, Knoxville TN, USA, pp. 701-705.

CARGILL, G.D. (1994). "Water Quality in the Windy City." *Water Environ. & Technol.*, Vol. 6, No. 9, pp. 52-56.

CEMAGREF (1988). "L'Etude de l'Erosion des Marnes : les Bassins Versants Expérimentaux de Draix. Etude et Mesure de l'Erosion." ('The Study of Marne Erosion : the Experimental Catchments of Draix. Study and Measurement of Erosion.') *Présentation et Synthèse*, CEMAGREF, Aix-en-Provence, 2nd version, May, 38 pages (in French).

CHANSON, H. (1995). "Hydraulic Design of Stepped Cascades, Channels, Weirs and Spillways." *Pergamon*, Oxford, UK, Jan., 292 pages.

CHANSON, H. (1997). "Air Bubble Entrainment in Free-Surface Turbulent Shear Flows." *Academic Press*, London, UK, 401 pages.

CHANSON, H. (1999). "The Hydraulics of Open Channel Flows : An Introduction." *Butterworth-Heinemann*, London, UK, 512 pages.

CHANSON, H. (2001). "The Hydraulics of Stepped Chutes and Spillways." *Balkema Publ.*, Rotterdam, The Netherlands.

CHANSON, H. (2001b). "Flow Field in a Tidal Bore : a Physical Model." *Proc. 29th IAHR Congress*, Beijing, China, Theme E3.

CHANSON, H., AOKI, S., and MARUYAMA, M. (2000). "Unsteady Air Bubble Entrainment at a Plunging Breaker : a Full-scale Modelling" *Proc. Euromech Colloquium, No. 416*, Geona, Italy, September 20-22, Interactions of Strong Turbulence with Free Surfaces, Book of abstracts, pp. 47-48.

CHANSON, H., AOKI, S., and MARUYAMA, M. (1999). "Air Bubble Entrainment at Plunging Breakers and its Effect on Long Period Waves: an Experimental study." *Coastal/Ocean Engineering Report*, No. COE99-1, Dept. of Architecture and Civil Eng., Toyohashi University of Technology, Japan, July, 41 pages.

CHANSON, H., and CUMMINGS, P.D. (1994). "Effects of Plunging Breakers on the Gas Contents in the Oceans." *Marine Technology Society Journal*, Vol. 28, No. 3, pp. 22-32.

CHANSON, H., and JAMES, P. (1998). "Rapid Reservoir Sedimentation of Four Historic Thin Arch Dams in Australia." *Jl of Performance of Constructed Facilities*, ASCE, Vol. 12, No. 2, May, pp. 85-92. Errata : Vol. 12, No. 3, p.169.

CHANSON, H., and JAMES, D.P. (1999). "Siltation of Australian Reservoirs : some Observations and Dam Safety Implications." *Proc. 28th IAHR Congress*, Graz, Austria, Session B5, 6 pages (CD-ROM).

CHANSON, H., and MONTES, J.S. (1995). "Characteristics of Undular Hydraulic Jumps. Experimental Apparatus and Flow Patterns." *Jl of Hyd. Engrg.*, ASCE, Vol. 121, No. 2, pp. 129.

CHEN, J., LIU, C., ZHANG, C., and WALKER, H.J. (1990). "Geomorphological Development and Sedimentation in Qiantang Estuary and Hangzhou Bay." *Jl of Coastal Res.*, Vol. 6, No. 3, pp. 559.

DARCY, H.P.G. (1856). "Les Fontaines Publiques de la Ville de Dijon." ('The Public Fountains of the City of Dijon.') *Victor Dalmont*, Paris, France, 647 pages (in French).

DARCY, H.P.G. (1858). "Recherches Expérimentales relatives aux Mouvements de l'Eau dans les Tuyaux." ('Experimental Research on the Motion of Water in Pipes.') *Mémoires Présentés à l'Académie des Sciences de l'Institut de France*, Vol. 14, p. 141 (in French).

DARCY, H.P.G., and BAZIN, H. (1865). "Recherches Hydrauliques." *Imprimerie Impériales*, Paris, France, Parties 1ère et 2ème.

DRESSLER, R.F. (1952). "Hydraulic Resistance Effect upon the Dam-Break Functions." *Jl of Research, Natl. Bureau of Standards*, Vol. 49, No. 3, pp. 217-225.

FARMER, D.M., McNEIL, C.L., and JOHNSON, B.D. (1993). "Evidence of the Importance of Bubbles in Increasing Air-Sea Gas Flux." *Nature*, Vol. 361, pp. 620-623.

GOSSE, P., and GREGOIRE, A. (1997). "Dispositif de Réoxygénation Artificielle du Sinnamary à l'Aval du Barrage de Petit-Saut (Guyane)." ('Artificial Re-Oxygenation of the Sinnamary, Downstream of Petit-Saut Dam (French Guyana).') *Hydroécol. Appl.*, Tome 9, No. 1-2, pp. 23-56 (in French).

GROVE, R.H. (1995). "The East India Company, the Australians and the El-Niño : Colonial Scientists and Analysis of the Mechanisms of Global Climatic Change and Teleconnections between 1770 and 1930". *Working Paper No. 182*, Working Papers in Economic History, Australian Nat. Univ., Canberra, Australia, March.

HAUSER, G.E., and MORRIS, D.I. (1995). "High-Performance Aerating Weirs for Dissolved Oxygen Improvement." *Proc. Intl Conf. on Hydropower*, Waterpower'95, ASCE, San Francisco, July, Vol. 2, pp. 1695-1705.

HAUSER, G.E., SHANE, R.M., NIZNIK, J.A., and BROCK, W.G. (1992). "Innovative Reregulation Weirs." *Civil Engineering*, ASCE, Vol. 62, No. 5, pp. 64-66.

HENDERSON, F.M. (1966). "Open Channel Flow." *MacMillan Company*, New York, USA.

JOHNSON, B.D., and COOKE, R.C. (1979). "Bubble Populations and Spectra in Coastal Waters : a Photographic Approach." *Jl of Geophysical Res.*, Vol. 84, No. C7, pp. 3761-3766.

KANWISHER, J. (1963). "On the Exchange of Gases between the Atmosphere and the Sea." *Deep-Sea Research*, Vol. 10, pp. 195-207.

KOLOVAYEV, P.A. (1976). "Investigation of the Concentration and Statistical Size Distribution of Wind-Producing Bubbles in the Near-Surface Ocean Layer." *Oceanology,* Vol. 15, pp. 659-661.

MALANDAIN, J.J. (1988). "La Seine au Temps du Mascaret." *Le Chasse-Marée*, No. 34, pp. 30-45.

MONTES, J.S., and CHANSON, H. (1998). "Characteristics of Undular Hydraulic Jumps. Results and Calculations." *Jl of Hyd. Engrg.*, ASCE, Vol. 124, No. 2, pp. 192-205.

PERLIN, M., HE, J., and BERNAL, L.P. (1996). "An Experimental Study of Deep Water Plunging Breakers." *Physics of Fluids*, Vol. 8, No. 9, pp. 2365-2374.

RÉ, R. (1946). "Etude du Lacher Instantané d'une Retenue d'Eau dans un Canal par la Méthode Graphique." ('Study of the Sudden Water Release from a Reservoir in a Channel by a Graphical Method.') *Jl La Houille Blanche*, Vol. 1, No. 3, May, pp. 181-187 & 5 plates (in French).

RIZK, T.A., and HAUSER, G.E. (1993). "Chatuge Aerating Infuser Physical Model Study." *Report No. WR28-1-17-101*, Tennessee Valley Authority, Norris TN, USA, June.

ROBISON, R. (1994). "Chicago's Waterfalls." *Civil Engineering*, ASCE, Vol. 64, No. 7, pp. 36-39.

SARMIENTO, J.L., and TOGGWEILER, J.R. (1984). "A New Model for the Role of the Oceans in Determining Atmospheric P_{CO_2}." *Nature*,.Vol. 308, April 12, pp. 621-624.

SARMIENTO, J.L., ORR, J.C., and SIEGENTHALER, U. (1992). "A Perturbation Simulation of CO_2 Uptake in a Ocean General Circulation Model." *Jl of Geophys. Res. (Oceans)*, Vol. 97, No. C3, pp. 3621-3645.

SCHNITTER, N.J. (1994). "A History of Dams : the Useful Pyramids." *Balkema Publ.*, Rotterdam, The Netherlands.

SMITH, N. (1971). "A History of Dams." *The Chaucer Press*, Peter Davies, London, UK.

STRAMSKA, M., MARKS, R., and MONAHAN, E.C. (1990). "Bubble Mediated Aerosol Production as a Consequence of Wave Breaking in Supersaturated (Hyperoxic) Seawater." *Jl of Geophys. Res.*, Vol. 95, No. C10, pp. 18281-18288.

TESSIER, B., and TERWINDT, J.H.J. (1994). "An Example of Soft-Sediment Deformations in an intertidal Environment - The Effect of a Tidal Bore". *Comptes-Rendus de l'Académie des Sciences*, Série II, Vol. 319, No. 2, Part 2, pp. 217-233.

TOOMBES, L., and CHANSON, H. (2000). "Air-Water Flow and Gas Transfer at Aeration Cascades: a Comparative Study of Smooth and Stepped Chutes." *Intl Workshop on Hydraulics of Stepped Spillways*, Zürich, Switzerland, H.E. MINOR & W.H. HAGER Editors, Balkema Publ., pp. 77-84.

WALLACE, D.W.R., and WIRICK, C.D. (1992). "Large Air-Sea Gas Fluxes associated with Breaking Waves." *Nature*, Vol. .356, 23 Apr., pp. 694-696.

WOOD, I.R. (1991). "Air Entrainment in Free-Surface Flows." *IAHR Hydraulic Structures Design Manual No. 4*, Hydraulic Design Considerations, Balkema Publ., Rotterdam, The Netherlands, 149 pages.

INTERNET RESOURCES

Reservoir sedimentation	
Extreme reservoir siltation in Australia	{http://www.uq.edu.au/~e2hchans/res_silt.html}
In-stream re-aeration cascades	
Hydraulic design of stepped cascades	{http://www.uq.edu.au/~e2hchans/dpri/topic_2.html}
Free-surface aeration	{http://www.uq.edu.au/~e2hchans/self_aer.html}
Chicago Calumet waterway plant	{http://www.mwrdgc.dst.il.us/plants/sepa.htm}
Tidal bores	
Explanations on tidal bores	{http://www.uq.edu.au/~e2hchans/e2320.html#Surge and bores}
Photographs of tidal bores	{http://www.uq.edu.au/~e2hchans/photo.html#Tidal bores, mascaret, pororoca}
Mascaret (tidal bore) of the Seine river	{http://www.uq.edu.au/~e2hchans/mascaret.html}
Severn bore	{http://boreridersclub.tripod.com/Club.html} Bore Riders Club
Hangchow bore	{http://www.chinapages.com/zhejiang/zjtour.htm}
Pororoca (Amazon river)	{http://vmpsun.sdsu.edu/pororocaphotos.html}
Mascaret on the Dordogne river	{http://mascaret.gironde.waika9.com/WINDOWS/Personal/bore.html}
Cook inlet	{http://girdwood.net/tacl/fjord.htm}
Bay of Fundy	{http://www.umoncton.ca/mediasverts/riverkeeper.html}
Air-sea mass transfer	
NASA rain, wind and air-sea gas exchange research	{http://bliven2.wff.nasa.gov/index.htm}
Northern hemisphere sensitivity to sea surface temperature change	{http://www.giss.nasa.gov/research/paleo/sst/}

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}
NASA Earth observatory	{http://earthobservatory.nasa.gov/}

ABOUT THE AUTHOR

Hubert CHANSON received a degree of 'Ingénieur Hydraulicien' from the Ecole Nationale Supérieure d'Hydraulique et de Mécanique de Grenoble (France) in 1983 and a degree of 'Ingénieur Génie Atomique' from the 'Institut National des Sciences et Techniques Nucléaires' in 1984. He worked for the industry in France as a 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 Ph.D. project. He was awarded a Doctor of Engineering from the University of Queensland in 1999 for outstanding research achievements in gas-liquid bubbly flows.

Hubert CHANSON is a reader in environmental fluid mechanics and water engineering at the University of Queensland since 1990. His research interests include design of hydraulic structures, experimental investigations of two-phase flows, coastal hydrodynamics, water quality modelling, environmental management and natural resources. He is the author of four 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). His publication record includes over 170 international refereed papers and his work was cited over 580 times since 1990. Hubert Chanson has been active also as consultant for both governmental agencies and private organisations.

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His Internet home page is http://www.uq.edu.au/~e2hchans. He also developed a gallery of photographs website {http://www.uq.edu.au/~e2hchans/photo.html} that received more than 1,300 hits per month since inception.