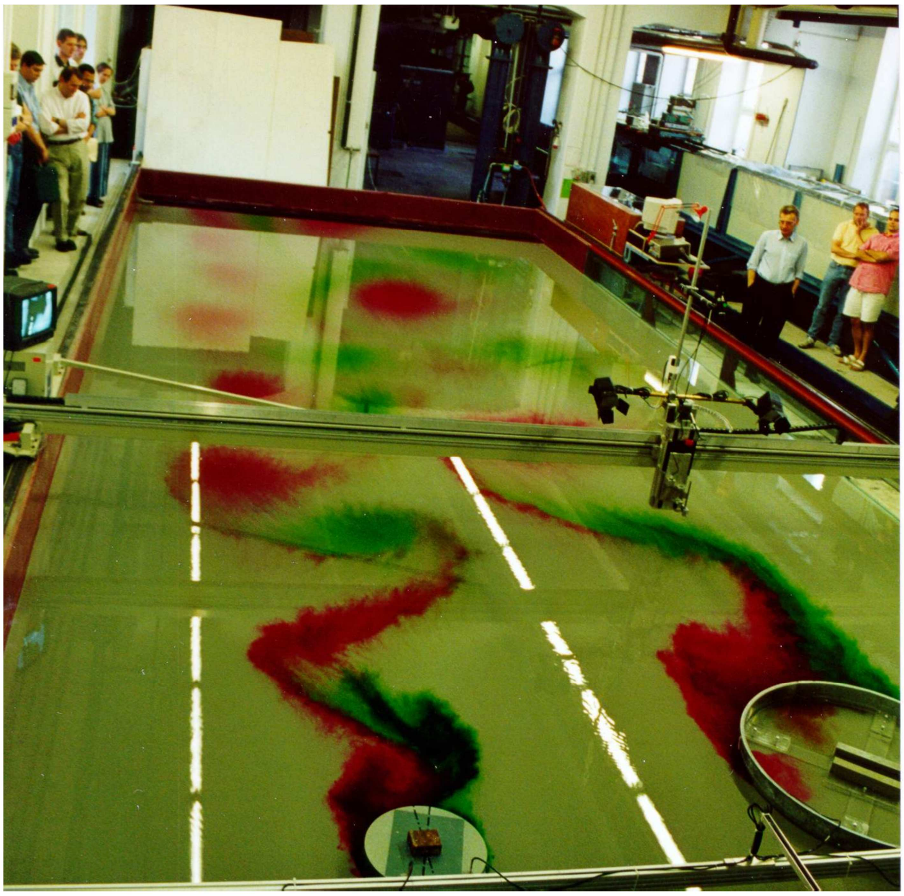
Gerhard H. Jirka Memorial Colloquium

on Environmental Fluid Mechanics

June 3 – 4, 2011, Karlsruhe Institute of Technology (KIT)
Karlsruhe, Germany

ABSTRACTS

of Scientific Presentations



Colloquium Organizers:

Institute for Hydromechanics (IfH)
Karlsruhe Institute of Technology (KIT)
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The Gerhard H. Jirka Memorial Colloquium on Environmental Fluid Mechanics is held at the Karlsruhe Institute of Technology (KIT) in honour of Prof. Gerhard H. Jirka who passed away unexpectedly on February 14, 2010. Prof. Jirka was widely known for his outstanding work in the area of Environmental Fluid Mechanics. When invited as speakers to the Memorial Colloquium, 23 eminent world-leading experts in this field agreed spontaneously to present keynote lectures in appreciation and recognition of Prof. Jirka's work and achievements. The lectures provide high-quality state-of-the-art scientific information and will cover several key areas of Environmental Fluid Mechanics such as Fluvial Hydraulics, Shallow Flows, Buoyant/Stratified Flows, Gravity Currents, Mass Transfer and Small-Scale Phenomena and include experimental, theoretical and numerical studies. The abstracts of the individual presentations are given in this booklet. The full papers will be published after the colloquium in a Memorial Volume in the IAHR series by CRC Press/Balkema (Taylor & Francis Group).

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Booklet of Abstracts

Contents

Horizontal mixing in shallow flows

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Many environmental flows can be considered as shallow. Clear examples are found in low-land rivers, lakes and coastal areas. The large width to depth ratio of shallow flows can give rise to vertical flow structures that have two-dimensional characteristics. Those eddies with vertical axes contribute to the transverse exchange of mass and momentum and are therefore important for mixing processes. In most cases large eddies are generated in the wake of an obstacle or in the unstable shear layer further downstream. With a strong vertical confinement and little dissipation, large structures could be formed by the merging of vortices of equal sign (upcascading).
In this paper various experiments will be addressed that were aimed at revealing the mechanisms of the generation and evolution of large eddies in shallow flows. A whole-field PIV-technique is used to visualize the structure in the flows whereas the single point LDA-technique was used to perform a spectral analysis of the velocity fluctuations. The flow configurations comprise the shallow mixing layer, shallow grid turbulence and the flow around groynes.
The experiments reveal that all large eddy structures carry the signature of the vertical confinement. The growth in length scale can be due to large-scale instability of the shear layer, selective dissipation of small-scale turbulence, and merging of vortices. The latter is difficult to observe in a dissipative flow containing 3D-turbulence because of the disturbing effects of the fluctuations and the limited lifetime of an eddy.
The observations made with the experiments provide us with information regarding modeling approaches. When a full 3D-LES modellling is not feasible, the 3D-turbulence can be parameterized whereas the flow structures can be resolved. However, care should be taken of the effect of the 3D-fluctuations on the evolution of the large eddies.

Onset and Development of Instabilities in Shallow Shear Flows

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Large scale coherent structures are prominent in free surface flows including estuaries, oceans, lakes and rivers. The structures are in the form of vortices with vertical axis which extend from the bed to the water surface and possess diameters that are far larger than the water depth. Understanding of such coherent structures is important for the mixing and transport of mass (e.g., pollutants and sediments), momentum and energy in surface water flows. The life of the structures involves birth, growth with downstream distance for part of the flow domain followed by decay and ultimately full disappearance. The mechanisms leading to birth and growth are believed to involve flow instabilities which, because of the near two-dimensionality of the flow, evolve under the constraint of enstrophy and energy cascade. The energy and enstrophy constraint—a result of the suppression of vortex stretching due the vertical confinement by the bed and free surface—promotes growth via vortex merging. On the other hand, the bottom friction, which represents the effect of the background three-dimensional turbulence on the large scale quasi-two dimensional turbulence, suppresses the large scale instabilities, limits their growth and causes them to eventually disappear with distance downstream. In this talk, the role of linear, weakly nonlinear and nonlinear hydrodynamic stability theories in illuminating the mechanisms of formation, growth and then decay of large scale structures in free shear flows is explained. For illustration purpose, the shallow mixing layer is used.

Laboratory experiments on shallow flows

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Many geophysical and environmental flows can be considered as ‘shallow’, their horizontal dimensions being much larger than their vertical extent. Examples of such flows can be found in rivers, channels, lakes, estuaries, and also in density-stratified oceanic and atmospheric flows. Shallow flows have been studied in the laboratory in a number of different configurations. In this contribution we will discuss laboratory experiments performed in a set-up consisting of a shallow layer of electrolyte, in which the motion is created by electromagnetic forcing. For this purpose an electrical current is passed through the fluid between two electrodes placed on opposite sides of a square container. A permanent magnet placed underneath the tank bottom then generates an approximately horizontal Lorentz force, resulting in a dipolar vortex motion in the fluid. By arrangements of multiple magnets, one may generate flows that have a more complicated structure. The fluid motion can be visualized by adding small tracer particles to the fluid, their motion being recorded from above. Quantitative information about the flow can be obtained by stereo-PIV measurements.

In this contribution, the attention will be focused on two different experiments: (*i*) a dipolar vortex (generated by a single magnet) moving over a sloping bottom, and (*ii*) a quasi-two-dimensional (quasi-2D) turbulent flow field generated by an array of magnets of alternating polarity. The first topic relates to the dynamical behaviour of dipolar vortex structures in coastal areas; in particular, the dipole moving down the slope serves as a model of the head of a rip current, as commonly observed near beaches. The second experiment is motivated by a study of the properties of 2D turbulence, under the commonly adopted assumption that laminar shallow flows are quasi-2D. Recent experiments and numerical simulations have demonstrated, however, that significant 3D effects may be present, which distort the 2D nature of the large-scale shallow flows.

Characteristic Scales and Dynamics of Large-Scale Horizontal Coherent Structures in Shallow Open-Channel Flows: an Experimental Investigation

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Abstract

This lecture concerns the large-scale horizontal coherent structures (HCS's) in open-channel flows. In contrast to large-scale vertical coherent structures, HCS's have not yet been the focus of directed, systematic studies, and as a result the exact role they play in sediment transport, contaminant transport and river morphodynamics remains elusive. Considering this, we have recently initiated at Queen's University an extensive laboratory study directed to developing an understanding of the characteristic scales, dynamics and morphological consequences of HCS's. The purpose of this lecture is to outline the results obtained so far, after completing the first two stages of this study.

In the first stage, the size of the largest horizontal coherent structures (HCS's) of a shallow, alternate bar inducing flow was investigated experimentally on the basis of three series of flow velocity measurements. These were carried out in a 21m-long, 1m-wide straight channel, conveying a flow with a flow depth equal to 4cm. The bed consisted of silica sand having a grain size of 2mm; its surface was flat. The bed slope was such that the shear stress acting on the bed was substantially below the threshold for initiation of sediment motion. The measurements were carried out with the aid of a Sontek 2D Micro ADV, mounted in an upstream-facing configuration. The horizontal burst length was found to be between five and seven times the flow width. The effect of the HCS's on the mean flow was also investigated. A slight internal meandering of the flow caused by the superimposition of burst-sequences on the mean flow was clearly detectable.

As the second stage of this study, three new series of flow velocity measurements, this time synchronized, were carried out as an attempt to penetrate the dynamics and life-cycle of the HCS's. For this purpose, quadrant analysis was used; the cross-sectional distribution of relevant statistical turbulence-related parameters was investigated; and cross-correlations of flow velocity along the flow depth and across the channel were performed. The analysis indicates that the HCS's originate near the channel banks, with the location of ejections and sweeps being anti-symmetrically arranged with regard to the channel centerline, and then evolve so as to occupy the entire depth of water and the entire width of the channel. This is consistent with the hypotheses previously raised by Yalin (1992) and Yalin and da Silva (2001) regarding the origin and temporal and spatial evolution of HCS's.

This lecture will conclude by addressing the following questions related to the morphological consequences of HCS': It is possible for HCS's to deform the bed? And if yes, under what conditions does this happen? What exactly is the "imprint" mechanism?

Waves and Currents: Hawking Radiation in the Hydraulics Laboratory

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We are all aware that nothing, not even light, can escape from a black-hole. Well, maybe not! Hawking (1974) proposed that black holes emit a form of radiation, which has become known as Hawking radiation. This radiation originates at the black hole horizon – the spherical surface inside of which light is trapped. The black hole horizon is effectively a hydraulic control for light: the interior of the sphere is said to be superluminal and the exterior, subluminal. The theory is that at the black hole horizon particle-antiparticle pairs are formed, one of which falls into the hole while the other escapes and reduces the energy in the black hole.

Unruh (1981) showed that is a mathematical analogy between the process described above and the behavior of water waves in the presence of currents. I will report on the results of Weinfurtner et al. (2011) who have tested this analogy in a 6.2 m long and 0.15 m wide flume. The fate of free surface water waves propagating upstream toward the crest of a streamlined obstacle has been examined. As the waves propagate toward the crest of the obstacle they slow down, both because the flow velocity in the channel increases and because their phase speed decreases as they shoal. As their wavelength decreases so too does their group velocity eventually the waves are arrested, and they are converted into pairs of short waves. Both waves have a downstream group velocity, but one has an upstream phase velocity and the other a downstream phase velocity. These wave pairs are analogous to the particle-antiparticle pairs of Hawking radiation and represent the closest analogy to Hawking radiation observed to date.

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Turbulent Flow and Sediment Transport Phenomena in Natural Waterways: Insights gained by Large-Eddy Simulation

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The numerical simulation of turbulent flow and sediment transport processes in real-life natural streams poses a formidable challenge to even the most advanced computational methods available today. A major source of complexity in such flows stems from their geometry, which, among others, is characterized by irregular and arbitrarily complex bathymetry, the shallowness of the flow, and the presence of multiple nature- and man-made obstacles, such as boulders, tree trunks, in-stream structures, etc.

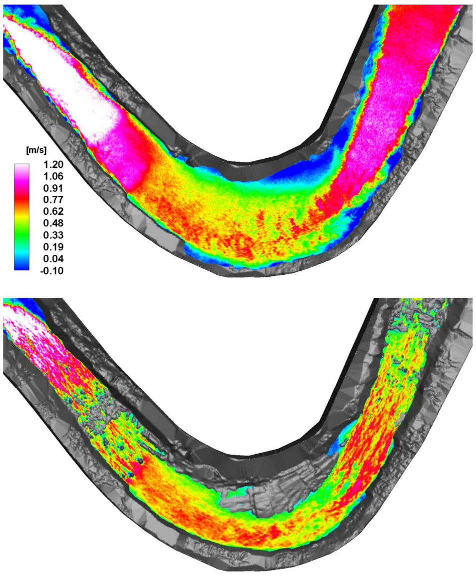

Figure 1: Instantaneous streamwise velocity contours at the water surface (top) and at the near-bed plane (bottom) of a natural meander bend simulated with LES.

Motivated by these challenges, we have developed a powerful computational framework that is specifically tailored to enable simulation of turbulence and sediment transport phenomena in natural waterways at high numerical resolution. The model employs the curvilinear immersed boundary method (CURVIB) extended to carry out URANS and LES with wall models in arbitrarily complex channel geometries (Kang et al. 2010) with embedded hydraulic structures. The model can also simulate non-linear free surface effects using a two-phase flow, level-set approach (Kang and Sotiropoulos, *Adv. in Water Res.*, submitted 2011) and carry out coupled hydro-morphodynamic simulations by solving the Exner equation via a novel approach compatible with the CURVIB framework (Khosronejad et al. 2011). A novel transport equation for simulating the impact of near-wall turbulent velocity fluctuations on bed-load transport has also been developed and applied to simulate bed form dynamics in scour holes past bridge pier geometries (Escauriaza and Sotiropoulos 2011).

The numerical method has been applied to carry out LES in a field-scale natural meandering stream (Kang and Sotiropoulos 2011) as well as simulate sediment transport and scour past hydraulic structures ranging from bridge piers to various stream-restoration rock structures. The talk will summarize major modeling advances and present novel physical insights into the structure of turbulence in natural waterways gained by numerical simulation. Such insights include, among others, the dynamics of the so-called center region and outer bank secondary flow cells in meander bends and their linkage with regions of flow convergence at the water surface, the role of turbulence anisotropy in natural waterways, and the importance of coherent structures as scour inducing mechanism in the vicinity of hydraulic structures.

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Morphodynamic equilibrium of tidal channels

Abstract. While the morphodynamics of fluvial channel has received considerable attention (e.g. Seminara, 2010) the morphodynamics of tidal channels is not equally understood. We explore some progress made in recent years on the problem of morphodynamic equilibrium of channels bounded seaward by a tidal sea and shoaling landward as observed in coastal lagoons and estuaries. These channels are typically landward converging, meandering and bounded by tidal flats periodically flooded by the tidal wave.

The questions that one would then like to answer parallel closely the similar questions that have been posed and mostly settled in the fluvial case. How is equilibrium defined for tidal channels? And what mechanisms control the establishment of an equilibrium state? Do tidal channels have an equilibrium length? Can the average bed profile be predicted? Why are channels typically converging? What fundamental differences exist between lagoon channels and estuaries? We tackle these problems identifying three distinct cases.

The first (*coastal*) case concerns the 'short' tidal channels found in coastal wetlands and lagoons: their distinct feature is the absence of an upstream supply of fresh water and sediments. This case has been fully explored. In particular, the asymptotic analysis of Seminara et al. (2010) has shown that: (i) rigorous conditions of static equilibrium require that the sediment flux must vanish at each instant throughout the tidal cycle; (ii) equilibrium profile and length of tidal channels can be obtained in closed form; (iii) the equilibrium channel shortens as convergence, roughness or tidal amplitude increase; (iv) the equilibrium length is proportional to the inlet depth; (v) 'Short' microtidal channels at equilibrium satisfy the so called O'Brien law. Results have been substantiated by detailed laboratory measurements of Tambroni et al. (2005).

The second (*fluvial*) case concerns the transition of a river into a tidal channel characterized by fairly 'small' tidal oscillations: hence, the fluvial discharge of water and sediments dominates or is as important as the tidal transport. We derive a perturbation solution as well as a numerical solution for flow and bed topography showing that equilibrium arises from a balance between the aggrading effect of channel divergence and the opposite effect of the residual sediment flux driven by the effect of tide propagation. Results are substantiated by field data for the microtidal estuary of the Magra River (Italy).

The third (*estuarine*) case concerns the transition of a river into a tidal channel characterized by fairly 'large' tidal oscillations: hence, the tidal transport dominates over the fluvial discharge of water and sediments. We derive a perturbation solution for flow and bed topography showing that equilibrium is dominantly controlled by the effect of tide propagation with some correction with respect to the coastal case, driven by the need for the hydrodynamics to allow for the stress required to accommodate the fluvial transport.

The paper is concluded with some discussion of a number of open issues related to features of the process ignored so far (e.g. tidal bars, tidal meandering, tidal flats).

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Flow Structure and Sustainability of Pools in Gravel-bed Rivers

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Abstract:

Pool-riffle channel morphology in gravel-bed streams creates a range of micro-habitats that are important for maintaining ecological diversity. The US Bureau of Reclamation's Columbia Snake Salmon Recovery Office (CSRO) is taking measures to improve and restore salmonid habitat impacted by the construction of federal dams. These mitigation efforts include the design and implementation of specific habitat features for several lifestages of salmonids in rivers throughout the Northwest. This study is motivated by the need to restore sustainable spawning and over-wintering pool habitat for salmon. For several decades the velocity reversal hypothesis (for example, Gilbert 1914, Keller 1971, 1972) has been used as a potential mechanism for the sustainability of pools (Gilbert 1914, Keller 1971, 1972, Lisle 1979, Clifford and Richards 1992, Keller and Florsheim 1993, Wohl 2000, Milan et al. 2001). Velocity reversal implies that the velocities are smaller through the pool than across the riffle at low and intermediate flows. At high discharges this condition reverses and velocities through the pool may exceed the velocities across the riffle. The reversal creates the conditions where the pools could scour and the sediment flux through the pool exceeds the flux across the riffles. Recent criteria have been developed that utilize the bathymetric characteristics of the channel to ascertain whether or not velocity reversal will occur. These criteria were used to predict the occurrence of velocity reversal for a wide range of published data. However, it is unclear whether the velocity reversal criterion predicts pool sustainability under all flow conditions and if limitations to this approach exist. Results from field studies, laboratory models and numerical simulations are used to assess various conditions to determine the functionality of the criteria in ensuring the sustainability of pools under current conditions, or other projected future conditions and whether pools will persist once restored. The role of jet formation and dissipation in sediment deposition and subsequent scour processes is investigated under different flow conditions in stable and transient pools.

Most pool features within this region exist in supply-limited gravel bed streams, many of which are subject to periodic sediment overload due to fire, debris flows or bank instability within the upstream reaches. This study demonstrates that although velocity reversal provides a useful indicator of the persistence of pool features, bed shear stress and sediment flux reversal do not occur at the same discharge or location as the velocity reversal. Additionally, the ratio of sediment delivery to transport capacity through the pool before pool features are lost beyond self-recovery is also investigated.

Influence of Vegetation on Flow Resistance and Flow Field

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Recent interest in river restoration, environmental flood management, and the application of bioengineering techniques has stimulated interdisciplinary research in environmental hydraulics. An important aspect in this research area is the development of sustainable river management strategies which are in accordance with both ecology and flood management. The key for the development of such strategies is the better understanding of the complex interaction between flow and vegetation. Vegetation exerts a major control on the conveyance capacity of rivers by increasing flow resistance and changing backwater profiles but, at the same time, is also an integral part of riverine ecosystems.

The present paper provides an overview on the current knowledge on flow resistance in vegetated riparian areas. Some aspects will be highlighted in more detail using data obtained in a research project carried out in the hydraulic laboratory in the Leichtweiß-Institute for Hydraulic Engineering and Water Resources. In this study, drag forces exerted by up to 10 flexible elements were measured simultaneously for different experimental boundary conditions using an innovative experimental setup which is shown in Figure 1.

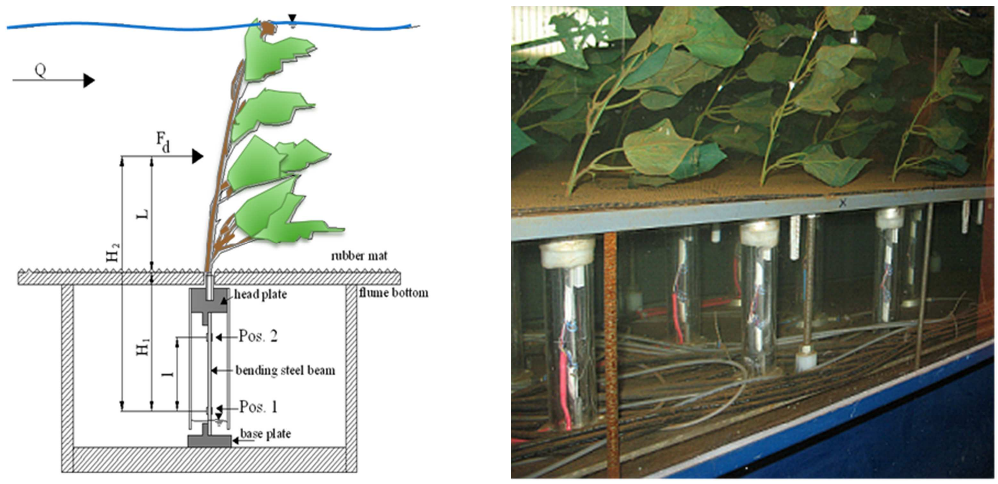

Figure 1a) Technical drawing of the drag force measurement system and b) setup of multiple drag force sensors within the flume test section.

The data obtained from the drag force sensors are used to outline a novel methodology providing some guidance to choose appropriate flexible artificial elements for laboratory studies which represent properties of natural flexible plants. The drag force and flow data are further used to highlight and discuss the spatial heterogeneity of drag forces within a canopy, the relationship between drag force and mean flow velocity for both single isolated elements and canopies, the influence of leaves on the drag forces and flow resistance, as well as the contribution of bed friction to total flow resistance. Recommendations for further research into the highly complex interaction flow-vegetation are provided.

Flow-Biota Interactions in Aquatic Systems: Scales, Mechanisms, and Challenges

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It is now widely recognised that many factors that shape biological communities in streams, estuaries, lakes and seas are largely controlled by flow hydrodynamics. Such control is often executed through two sets of interconnected processes: (i) physical interactions between flow and organisms (e.g., due to the interplay between flow-induced forces and reaction forces generated by organisms); and (ii) ecologically relevant mass-transfer processes (e.g., due to molecular and turbulent diffusion).

These interrelated processes occur in a wide range of scales and depend on how physical scales match biological scales such as organism dimensions, patch/community dimensions, life cycles, and others. Depending on the scale of consideration, the flow variability affects ecosystem structure and function differently. A survey of publications shows that research on the effects of hydrological and geomorphologic variability on ecosystems is a lot more extensive than studies of the turbulence range effects, although they are much more relevant to organisms. There are at least four reasons for such unevenness in the current knowledge: (1) flow and organism measurements at small scales still represent major challenges and data related to this scale range remain very scarce; (2) the biomechanical properties of organisms are still a missing dimension in studies of flow-organism interactions making data interpretation and conceptualisation vague; (3) the subject of small-scale flow-organism interactions lies on the borders between fluid mechanics, ecology, and biomechanics, i.e., at the discipline interfaces which are typically avoided by researchers; and (4) the absence of an appropriate unifying framework(s) that would serve for flow-biota coupling at the organism scale and for integration (i.e., up-scaling) of physical interactions and mass-transfer processes. The paper will outline the current trends in addressing these shortcomings considering flow-biota interactions in streams, rivers, and benthic boundary layers in estuaries and lakes as examples. These trends relate to the appearance of new promising measurement capabilities (i.e., use of high-resolution laboratory and field stereoscopic and tomographic PIVs at the organism scales), employment of advanced turbulence concepts in flow-biota considerations, accelerated advances in organism biomechanics, conceptual developments in multi-scale descriptions of multi-component systems, and formation of new generation of interdisciplinary researchers well skilled in fluid mechanics, ecology, and biomechanics.

All these reflect the emergence of a new subject area, Hydrodynamics of Aquatic Ecosystems, that bridges fluid mechanics, biomechanics, and aquatic ecology together and that can be defined as a study of flow-organism interactions in running waters with particular focus on relevant transport processes and mutual physical impacts occurring at multiple scales from the sub-organism scale to the organism patch mosaic scale (comparable to the flow width). The challenges that this new discipline is expected to meet will be identified and discussed.

Interaction of Flows and Particles in the Sub-Micrometer Scales

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Abstract

The flow effects on Brownian motion of nanoparticles suspensions are measured by back scattering diffusing wave spectroscopy (CCD-DWS) method. At 1% weight concentration, a series of experimental studies were carried out for different flow velocities in two flow cells: 1mm by 1mm and 3mm and 3mm cross sections, respectively. First, at static condition where only Brownian motions exist, the autocorrelation functions of natural particles were obtained. As flow velocity increased, it was found that the autocorrelation functions started to change slightly when the Peclet number ($Pe=U/k_0D$) reached 1.8. Further flow velocity increasing caused significant reduction in the slopes of the autocorrelation curves. The effects of Brownian motion persisted approximately up to the Peclet number = 200. The above classifications gave a very good indication for determining the regions dominated by Brownian motion and flow motions respectively, as well as the transition. In addition, the autocorrelation functions could be fitted by a general exponential function including the effects of flows and particle size.

ENVIRONMENTAL ASPECTS IN WASTEWATER HYDRAULICS

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ABSTRACT

Two basic sewer flow types are considered in this research, namely transitional and supercritical flows related to wastewater hydraulics. For transitional flows from the sub- to the supercritical regimes as occur for instance on spillways, the free surface and velocity profiles are known to be continuous, whereas the bottom pressure profiles may become rapidly-varied, depending on the degree of curvature variation. A similar flow pattern is established a slope breaks from mild to steep slope, associated with sewer flows. The hydraulics of these are discussed both for the open rectangular as also the closed circular profiles. Because curvature effects are demonstrated to be small in terms of the free surface effects, the hydraulic approach may be employed for the latter case, resulting in an expression for the minimum tailwater sewer diameter to inhibit choking flow conditions.

The second problem presented relates to junction manholes under supercritical approach flow, for which again flow choking may become a high risk, associated with 'geysering' flow. These manholes include the through-flow and the bend manholes as particular cases, so that a general analysis is amenable, based on laboratory observations and a systematic data analysis. In contrast to standard knowledge, the maximum filling ratios of the approach flow and the discharge capacities of the three manhole configurations are detailed, along with a design basis that was successfully laboratory-tested. The results of both basic special manholes may thus be considered a significant advance in sewer hydraulics, by which undesirable sewage loss onto public space is prevented.

Keywords: Curvilinear flow, Geysering, Hydraulics, Junction manhole, Manhole, Open channel, Transitional flow

Small scales in natural waters - two examples

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Natural waters are density stratified all-year to some degree in one way or the other. Hence, diapycnal processes are usually of small-scale nature only and biogeochemical constituents in the stratified water column are substantially affected by processes at the smallest scales: usually by both transformations (production and consumption) as well as by diapycnal mixing. In this talk, two such examples, which have great practical implications, will be presented.

Oxygen consumption in stratified deep-waters occurs partly within the water volume and usually to a larger extent as a flux into the sediment. Using rapid microsensor profiling (~0.01 mm-scale), we have been able not only to estimate those molecular fluxes at the water-sediment interface, but also to resolve their short-term variability, which is typically in excess of an order of magnitude in stratified waters. Because the vertically integrated oxygen content of the uppermost sediments (< few mm) is typically in the range of some 0.01 mmol m^{-2} in those waters, their sediments become anoxic within minutes-to-hours when the supply from the oxygen-rich waters above is weak. Subsequently, reduced substances diffuse in parallel into the overlain water where they cause oxygen consumption. As a result of these dynamics, oxygen depletion rates are larger than - often incorrectly - estimated from oxygen fluxes into the sediment. With this conceptual model we can quantify how bulk oxygen depletion is related to (i) the depth of stratified waters (storage), to (ii) the level of organic sediment content (sink) and specifically (iii) we can now understand the partly counter-intuitive depletion rate estimates in long-term monitoring programs of lakes on the Swiss Plateau.

In the second example, double-diffusive upward-directed fluxes play a fascinating role in the accumulation of ~60 km^3 of methane dissolved in the 485 m deep and permanently stratified Lake Kivu. Driven by a weak geothermal heat flux of only ~30 mW m^{-2} and density-stratified by salt and carbon-dioxide fluxes, originating from deep subaquatic springs, a double-diffusive favourable stratification has evolved: From 150 m down to maximum depth, temperature and salinity are increasing from ~23 to 26 ^{o}C and from ~2.5 to 6 psu, respectively. For most of the deep-water volume the density-ratio R_ρ varies in the range of ~2 to ~10 and as a result, an unprecedented spectacular staircase has developed extending over more than a range of ~300 m depth. Approximately 350 individual sharp interfaces (some as thin as 2 mm) and individual well-mixed layers (average ~50 cm thick) have formed as a result of the double-diffusive favourable conditions. Typical interface thicknesses are ~10 and ~20 cm for salt and temperature, respectively and with corresponding steps of typically 5 mK and 0.010 psu, respectively. From the first observation by Newman in the 1970s, we can conclude that the staircase is present since at least 40 years, but most probably since centuries or even millennia. Because the stability of the stratification is very strong ($N^2 \approx 10^{-4}$ s^{-2}) and the seasonal wind forcing rather weak, the deep-water turbulence is negligible and restricted to the convectively-driven double-diffusive layers. As a result, the upward directed (sink) flux from the subaquatic input is comparably large for heat but weak for all dissolved constituents. Therefore, not only salt and carbon-dioxide have accumulated in the deep-water but also methane. It has reached enormous concentrations of up to 20 mol m^{-3} and is now a resource - with a value of ~20 billion dollars - to be harvested in the next decades.

Mixing of Multiple Buoyant Jets

Adrian Lai[1] and Joseph H.W. Lee[2]

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Abstract: Multiple buoyant jets discharging in proximity interact dynamically as a result of the pressure field induced by the jet entrainment flow. The mixing characteristics of interacting jets can be remarkably different from that of a series of individual jets treated in isolation. Examples of such jet groups include submarine outfall discharges from alternating diffusers, rosette jet clusters, and multiple point plumes in ventilation problems.

A general semi-analytical model has been developed to predict the mixing of an arbitrarily-inclined buoyant jet group in stagnant ambient. The external flow field induced by the buoyant jets is computed by a distribution of point sinks along the unknown jet trajectories. The buoyant jet trajectories are determined by an iterative solution of an integral jet model accounting for dynamic pressure and exact momentum conservation and that of the external irrotational flow. Model predictions of buoyant jet mixing characteristics (jet trajectory, centerline velocity, merging height and dilution) are in good agreement with laboratory experimental data of (i) clustered jet groups; (ii) twin turbulent plumes; and (iii) rosette buoyant jet groups. The extension of the model to the case of a weak ambient crossflow will be discussed.

Jets, Plumes and Double Diffusion under Confinement

– And their Role in Fluid Mechanics of US Strategic Petroleum Reserves

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The U.S. Strategic Petroleum Reserve (SPR) is the nation's first line of defense against a petroleum shortage. It is an emergency supply of crude oil stored at four sites created in large underground salt caverns along the Texas and Louisiana Gulf Coast. Salt caverns are carved out of underground salt domes by "solution mining," which involves drilling into a salt formation and injecting massive amounts of fresh water to dissolve the salt. By controlling the freshwater injection process, salt caverns of the desired dimensions are created. A typical cavern holds 10 million barrels with 200 (diameter) x 2,000 (deep, in feet). Owing to mixing of oils from different sources, a compositional gradient is introduced, which, when subjected to the natural geothermal temperature gradient, leads to double-diffusive layering (convective layers separated by diffusive density interfaces). With time, gaseous compounds seep in and dissolve in oil, which needs to be degassed periodically. This is accomplished by removing oil from the cavern near the bottom and injecting back at the top after degassing, whence the presence of density interface helps keep the upper and lower layers unmixed (i.e. to maintain a slug flow) if the interface can be maintained without breaking up. While much work has been done to study diffusive interface of double diffusive convection, the presence of container walls (low aspect ratio) in this case and the potential of a downward-directed jet at the top of the cavern causes the flow evolution much different from the cases considered by previous researchers.

An experimental, theoretical and numerical research program is afoot to (i) study the formation and evolution of diffusive interfaces in confined containers, (ii) the evolution of jets in stratified low-aspect-ratio vessels, and (iii) the interaction of jets and density interfaces in a closed system with flow recirculation between layers. It was found that the confinement leads to new physical phenomena. Drastic flow regime changes occur when turbulent eddies in the container become affected by the walls, in which case they elongate vertically or break up into multiple eddies. When a jet is present, an additional adverse pressure gradient is introduced, breaking up the jet within several container diameters, thus dissipating vertical momentum. Coincidentally, some of these new phenomena are beneficial to SPR operations as they help develop and maintain layering in the container as well as avoid their breakup in the presence of a jet. Results of on-going experimental and theoretical studies will be discussed.

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Modelling internal solitary waves in shallow stratified fluids

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A review is presented of recent work by the authors on the behaviour of internal solitary waves (ISWs) in shallow, stably-stratified, multi-layer fluid systems, for cases in which the amplitude of the wave is comparable with the total depth of the system. Such waves are typical of many observed in the ocean (Duda *et al*., 2004; Helfrich & Melville, 2006; Osborne, 2010), where they can propagate on the pycnocline over large distances (100s of km) without significant change of form, preserving a balance between nonlinearity and dispersion.

Recent laboratory work by the authors has focussed on several aspects of ISW behaviour, namely, (i) the generation of transient boundary currents on the bottom solid boundary, (ii) the instability characteristics of such boundary currents, (iii) the influence of irregular bottom topography upon the propagating ISW and the transient boundary currents, (iv) the differences in behaviour between ISWs of elevation and depression, (v) the stability characteristics of ISWs in fluid systems of constant depth and (vi) the consequences of wave breaking for vertical mixing.

Experimental data are presented to illustrate the properties of the above flows and comparisons are made, where appropriate, with predictions from theory and numerical models and field observations.

Optical Methods in the Laboratory: Application to Density Currents

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ABSTRACT

Experimental results on density currents will be presented, with the dual objectives of describing our findings for these flows as well as highlighting the strengths and challenges of the optical techniques used. Particle Image and Particle Tracking Velocimetry (PIV; PTV) provide the spatial and temporal resolution to examine the velocity field; Laser Induced Fluorescence (PLIF) does the same for the density field. Simultaneous measurements of these techniques - that resulted in the development of novel measuring and processing methodology - are extensively used to characterize the flow, as they show in detail the evolution of instabilities of the front interface, and in general of the mixing processes.

Gravity currents are flows that occur when a horizontal density difference causes fluid to move under the action of gravity; density currents are a particular case, for which the scalar causing the density difference is conserved. The front of the current is a very small region of it, but in many cases determines the conditions in which the flow evolves. The front is rich in structures of different scales, arisen from shear and baroclinic instabilities. A defining characteristic of the front is the intense mixing that occurs at its interface. The laboratory facility used allows the study of the front in a stationary setting, and also in its natural advancing state, for the case of a constant input of dense fluid to the system. These two settings are complementary, as the former highlights the mixing processes at the interface of the front, while for the latter the interaction between the current and the channel bed can be examined. Results from these experiments are presented, which characterize the flow in terms of the front velocity, the dimensions of the front, the mixing rate and the bed friction coefficient; the variability of these two last quantities is examined in detail.

Effect of Self-stratification due to Suspended Sediment: Rivers versus Turbidity Currents

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Sediment suspension in rivers is classically formulated in terms of the Vanoni-Rouse formulation. This treatment, which applies to flow that is steady and streamwise-uniform, characterizes the vertical profile of streamwise flow velocity in terms of standard logarithmic function. It characterizes the vertical profile of suspended sediment concentration in terms of a power relation based on the eddy viscosity implied by the logarithmic law. It has been known for some time, however, that flows that suspend sediment also self-stratify. That is, under equilibrium conditions, a finite sediment fall velocity implies a higher concentration lower in the flow, and a lower concentration higher in the flow. As a result, the water-sediment mixture has a density that decreases upward from the bed, creating conditions of stable-self-stratification. Self-stratification tends to a) damp the turbulence, resulting in a lowered “effective” Karman constant, and b) reduce the ability of the flow to hold sediment in suspension. Here the effects of self-stratification in open channel suspensions are studied using three closure relations for turbulence: a) the algebraic formulation of Smith and McLean; b) the differential k-ε formulation and the differential Mellor-Yamada formulation. The same methodology is used to study a simplified configuration for turbidity currents which allows steady, uniform solutions: the Turbidity Current with a Roof. The effect of self-stratification can be substantial in the case of rivers. In the case of turbidity currents, however, the effect can be even stronger, because of the fact that turbidity currents are driven by gravity acting on the sediment phase, rather than the water phase, of the sediment-water mixture.

Revisiting gravity currents and free shear flows

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ABSTRACT: The rate at which free shear flows widen, and gravity currents deepen along their path can be specified in terms of depth-averaged models by invoking the concept of entrainment. A different approach was proposed by Prandtl, who considered the widening of jets as being due to a diffusion of momentum and vorticity into the undisturbed ambient fluid. His diffusion relation has since been successfully modified for depth-averaged models of free shear flows. In the present contribution we apply it to supercritical gravity currents, in which the diffusion is mainly due to KH billowing, as it is in free shear flows. We also show that the diffusion and the entrainment approaches agree for all uniform gravity currents. The conventional shallow water equations for gravity currents are consistent with the Bresse equations for open channel flows. A further topic we address here is that the underlying depth and velocity scales for the two flows differ. For gravity currents the scales are derived from the velocity distribution in analogy to previous work on free shear flows, whereas they are based on the vertical extent, and flux, of the dense liquid phase in open channel flows. To avoid this disparity, we define a set of scales for both flows in terms of the distribution and flux of excess mass. To compare entrainment and diffusion rates for gravity driven flows in terms of velocity- and mass-based scales, we reanalyze field data on katabatic winds, which are similar to gravity currents. The computed entrainment and diffusion rates are quite different, which clearly shows that the flows were not uniform, but accelerating along the slope. This acceleration could be one of the reasons why both the entrainment and diffusion rates were higher than those expected on the basis of laboratory experiments.

On the effect of drag on the propagation of compositional gravity currents

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Highly resolved 3-D Large Eddy Simulation (LES) are used to study the effects of the additional drag induced by the presence of obstacles on the propagation of a lock-exchange Boussinesq gravity current (GC) in a straight horizontal channel. Two types of configurations are considered. In the first case, an array of identical obstacles in the form of square ribs or 2-D dunes is mounted on the bottom surface of the channel. The additional drag acts only over the lower part of the GC as the obstacle height is smaller than the height of the GC. In the second case, a number of identical rectangular cylinders are uniformly distributed over the whole depth and length of the channel. This test case corresponds to a GC propagating in a porous medium of uniform porosity in which the additional drag induced by the cylinders acts over the whole height of the GC. Both cases are relevant for practical applications, as in most environmental applications GCs propagate over a rough bed (e.g., GCs at the bottom of rivers and oceans), interact with flow retarding devices (e.g., snow avalanches) or advance in a porous medium (e.g., a layer of vegetation). The structure of the GC propagating over an array of large scale roughness elements and in a porous medium is compared to the widely studied case in which the lock-exchange GC propagates over the flat bottom surface of a non-porous channel. The comparison is made for Reynolds numbers that are typical of the ones at which scaled model studies are conducted in the laboratory and for Reynolds numbers that are high enough to be representative of field conditions encountered in small rivers and lakes.

Simulation results show that below a certain value of the additional drag force per unit streamwise length induced by the bottom obstacles, GCs with a large volume of release propagating over an array of bottom mounted obstacles transitions to a regime where the average front velocity, U_f, is close to constant. Compared to the case of a GC propagating over a flat bed, the front velocity during the slumping phase is smaller if obstacles are present and is function of the degree of bluntness of the obstacles (e.g., it is smaller for GC propagating over an array of ribs compared to dunes of same height and wavelength). Above a certain value of the drag force per unit streamwise length induced by the obstacles, the slumping phase can be very short. In this case, similar to GCs propagating in a porous medium, the current transitions to a drag-dominated regime in which $U_f \sim t^{\beta}$, with $\beta=-0.28$, once the discharge of lock fluid at the position of the lock gate becomes close to constant in time. This value is close to the one ($\beta=-0.25$) predicted by theory for GCs propagating in a porous medium for which the total volume of lock fluid increases linearly with time.

Simulation results conducted for GCs with a large volume of release propagating in a porous channel show that for sufficiently high porosities, the interface elevation varies linearly with the streamwise position until close to the head of the current, regardless of the value of the Reynolds number. Consistent with experiments, LES shows that low Reynolds number currents transition to a drag dominated regime in which $U_f \sim t^{\beta}$, where $\beta=-0.5$. By contrast, high Reynolds number GCs, for which the cylinder Reynolds number (Re_D) is high enough such that the drag coefficient on the cylinders can be considered constant, transition first to a drag dominated regime in which $\beta=-0.25$. However, after a sufficient long time, such that Re_D becomes sufficiently low for the drag coefficient to become proportional to $1/Re_D$, the current transitions to a drag dominated regime in which $\beta=-0.5$.

Gas Transfer at Water Surfaces

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Gerhard H. Jirka Memorial Colloquium on Environmental Fluid Mechanics
June 3 - 4, 2011, Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany

The exchange of inert and sparingly soluble gases including carbon dioxide, methane, and oxygen between the atmosphere and oceans is controlled by a only 20-200 µm thick boundary layer at the top of the ocean. The hydrodynamics in this layer is significantly different from boundary layers at rigid walls, since the orbital motion of the waves is of the same order as the velocities in the viscous boundary layer and there is a strong interaction between nonlinear wind waves and the shear flow at the water surface. Because of limited experimental techniques, the details of the mechanisms and the structure of the turbulence in the boundary layer at a wavy water surface are still not known very well.

Therefore empiric or semi-empiric parametrizations of the gas transfer velocity versus wind speed are still state of the art, although it is well known - at least since the first International Symposium on “Gas Transfer at Water Surfaces” organized by Wilfried Brutsaert and Gerhard Jirka at Cornell University, Ithaca back in 1983 - that other parameters then the wind speed influence air-sea gas transfer significantly as well.

The presentation gives an overview of the present knowledge on the parameters influencing air-sea gas transfer. This includes

- the buoyancy of the air flow influencing the shear stress at the water surface,
- the state of the wave field, especially the wave age,
- the film pressure and surface elasticity of monolayers at the water surface,
- the effects of breaking waves including bubble-induced gas transfer, and
- the physicochemical properties of the volatile species to be transported.

For each of these parameters, it will be discussed what is known from theory and previous experiments, in which direction theory must be developed, and what kind of experiments and experimental techniques are required to answer critical open questions.

The discussion will also include the transfer of moderately soluble volatile species, where the transport resistance is partitioned between the air-sided and water-sided mass boundary layers. Present theory of the partitioning of the transfer resistance is only very crude and almost no experimental results are available so far. There are, however, a number of environmentally important tracers of this kind, including dimethylsulfide, acetonitrile, acetone, and acetaldehyde. This is why it is worthwhile to study the transfer of such tracers in more detail.

Mass Transfer from Bubble Swarms

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Bubble swarms are common in nature and industry. Examples include the swarm of bubbles created by breaking waves, bubbles entrained into the flow at hydraulic structures and at hydraulic jumps, and spargers installed in activated sludge tanks, bubble columns and air-lift reactors. However, mass transfer from bubble swarms to liquids and the corresponding mass balance have a number of factors that make computations challenging. Some recent simplifications to the mass balance have achieved results that are useful and illuminating about physical processes. This seminar will illustrate the resulting applications to aeration of lakes, reservoirs and activated sludge, to bubble columns and air-lift reactors, and to bubbles entrained into spillway discharges.

Modelling Bacteria and Trace Metal Fluxes in Estuarine Systems

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Abstract

In recent decades considerable advances have been made by hydraulic engineers and researchers in the development and application of computational hydraulics models, for predicting hydrodynamic and sediment transport processes in estuarine and coastal waters. These model advances have arisen as a result of: (i) improved numerical schemes, and (ii) enhanced coefficients etc., arising from the acquisition of a better understanding of the hydrodynamic and morphological processes in hydraulic basins, obtained from laboratory and/or field data studies. As water industry stakeholders have been increasingly enthusiastic for hydro-environment engineers and researchers to extend and apply these computational hydraulics models to water quality and contaminant transport process predictions, the models have been increasingly refined to include bio- and geo-chemical process predictions. However, whilst hydrodynamic and sediment transport processes are generally well represented in most existing computational models, there is still considerable scope for improving the representation of bacteria and trace metal flux processes within such models, and particularly as they interact with such parameters as sediments, turbidity and salinity.

In this paper details are given of the refinement of a numerical model for representing bacteria and trace metal fluxes in estuarine and coastal waters. The transport of enteric bacteria is influenced by many physical, chemical and biological factors, including sediments in the water column and on the bed. In this study field measurements were undertaken which showed that in the Severn Estuary the sediments often contained much higher bacterial population levels than previously assumed. The aim of the first part of the study was therefore to develop a modelling tool to predict the sediment-linked bacteria concentration levels in estuarine waters. The theoretical background of the enteric bacterial water quality model is first outlined in the form of a conceptual model, representing the flux of bacteria due to sediment movement, including deposition and suspension. Details are outlined of the solute and mass transport equations used to simulate the flow and transport of suspended sediments and enteric bacterial indicators. The enteric bacteria transport equation includes enhanced source and sink terms to represent bacterial kinetic transformation and the disappearance/reappearance due to sediment deposition or re-suspension. The model was then applied to the turbid water environment in the Bristol Channel and Severn Estuary, UK, with results being considered for the implications for the high profile Severn Barrage project and where the turbidity levels will change dramatically in the estuary if, and when, the barrage is constructed. The results showed that the bacteria decay levels were highly dependent upon turbidity levels and that the adsorption/desorption interaction between the bacteria and the sediments was a significant parameter.

In the second part of the study, details are given of laboratory tests to investigate the partitioning and adsorption/desorption of trace metals with sediments, both on the bed and in suspension. Doped plugs of metal contaminated sediments were studied in a flume, with the results showing that the partitioning was highly depended upon the salinity, confirming that the metal concentration is highly dynamic along any estuary and that this effect needs to be included in any numerical model. A new empirical formulation was developed for the metal partitioning as a function of salinity, based on laboratory data, and was tested for the Mersey Estuary in the UK, known to be one of the most heavily contaminated estuaries in the UK. The results highlighted that the new equation gave much improved metal concentration predictions for this UK estuary.