T KEYNOTE

RUBBISH, STINK AND DEATH: THE ROOTS, EVOLUTION, AND FUTURE OF WATER-QUALITY MODELING

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The roots, historical evolution and current state-of-the-art of water-quality modeling are reviewed. Emphasis is placed on models as (a) problem-solving tools and (b) integrative frameworks. The future of the field is explored including the identification of major research needs. Throughout the talk, a special effort is made to highlight the interactions between physical processes and biochemical transformations.

Biosketch of Steven C. Chapra

Professor Steve Chapra presently holds the Louis Berger Chair for Computing and Engineering in the Civil and Environmental Engineering Department at Tufts University. Dr. Chapra received engineering degrees from Manhattan College and the University of Michigan. He has authored seven textbooks including *Numerical Methods for Engineers*–which has been used at over 150 universities throughout the world. He has also authored the book *Surface Water-Quality Modeling*, the standard text in that area.

Before joining the faculty at Tufts, Dr. Chapra worked for EPA, NOAA, Texas A&M University and the University of Colorado. He has also served as the Associate Director of the Center for Advanced Decision Support in Water and Environmental Systems (CADSWES), and has been a visiting professor at Duke University, the Imperial College of Science, Technology and Medicine (London), the University of Reading and the University of Washington.

He was originally drawn to environmental engineering by his love of the outdoors. He is an avid fly fisherman, snorkeler, and hiker. His primary professional goal is to apply engineering, mathematics and computing to maintain a high quality environment in a wise and cost-efficient fashion. He feels blessed to have found a profession where he can meld his love of mathematics and science with his passion for the natural environment. In addition, he gets to share it with others through his teaching and writing.

His specific research interests focus on surface water-quality modeling and advanced computer applications in environmental engineering. His research has been used in a number of decision-making contexts including the 1978 Great Lakes Water Quality Agreement. In addition, he was the 1993 recipient of the ASCE's Rudolph Hering Medal for the outstanding paper in the field of environmental engineering.

Aside from his activities in environmental engineering, he has written several texts on computing and engineering for which he was awarded the 1987 Meriam-Wiley Distinguished Author Award by the American Society for Engineering Education. He has taught over 65 workshops on water-quality modeling in the United States, Mexico, Canada, Europe, South America, Africa, and Oceania.

Finally, he has been recognized as the outstanding teacher among the engineering faculties at both Texas A&M (1986 Tenneco Award) and the University of Colorado (1992 Hutchinson Award). He is also the first recipient of the AEESP Wiley Award for Outstanding Contributions to Environmental Engineering and Science Education in the Autumn of 2000.

T01

NEAR-SHORE CIRCULATION MODELING IN SOUTHERN LAKE MICHIGAN

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A nested grid version of the Princeton Ocean Model for the Great Lakes was applied to the coastal area in southern Lake Michigan. The model uses 3D boundary conditions derived from the whole-lake hydrodynamic model to simulate circulation in a small coastal area at very high (100 m) horizontal resolution in 2004 and 2005. Model results are tested with current observations and data from tracer release experiment in the vicinity of Burns Ditch, Indiana. This tributary to Lake Michigan is known to contain high levels of coliform bacteria and is adjacent to the Indiana Dunes National Lakeshore. In the tracer experiment, the inert gas sulfur hexafluoride was introduced into the tributary and the plume was tracked using a shipboard-based gas chromatography system for several days after the release, and also with a particle transport model applied during the same period.

T02

MODELLING THE IMPACTS OF CLIMATE CHANGE ON LAKE ERIE HYPOXIA

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A significant decline in the water quality of Lake Erie occurred during the 1960s due to increased anthropogenic influx of phosphorus. As the capacity of the lake to absorb waste

was exceeded, eutrophication and hypoxia occurred. Billions of dollars have been spent on remedial programs aimed at improving water quality by controlling phosphorus loads. These measures eliminated eutrophication, but hypoxia remains over a roughly 10,000 km^2 region of the central basin. The hypoxia is a coupled result of biogeochemistry and the shallow basin morphology (~20 m depth), causing the metalimnion to intersect the sediments over a large off-shore area.

In this study, we apply *vertical* and *vertical-longitudinal* numerical models to investigate the biophysical factors controlling hypoxia in Lake Erie. Our results show that the structure of the dissolved oxygen profile is determined by a coupling between stratification/mixing in the water column and the sediment oxygen demand, while the absolute oxygen values are determined by the biogeochemistry.

We further predict the impacts of climate change on stratification and hypoxia by modelling the water column response to inter-annual climate variability during 1979-2005. Kling et al. (2003, *Union of Concerned Scientists*) suggest that under climate change, warmer air temperatures will lead to a longer summer stratification period, increasing the probability of hypoxia, declines in cold water fish species, increased algal blooms and invasions of nonnative organisms. However, they do not consider that the storm frequency is expected to double by 2100 (Wuebbles and Hayhoe 2004; *Mitig. Adapt. Strat. Glob. Change*).

Preliminary model results show that atypically warm years with typical wind speeds (e.g. 2005) will indeed have a warm epilimnion and typical thermocline depth; however, years with typical air temperatures and atypically variable winds are characterized by a deep and diffuse thermocline with a cool epilimnion. The additional storm events thus enhance vertical mixing of the water column, leading to deepening of the thermocline, warming of the hypolomnion and weakening of the thermal stratification via entrainment. Therefore, when evaluating the response of a waterbody to climate change, the impacts of changes to both air temperature and storm frequency must be explicitly considered.

T03

COUPLED BUBBLE PLUME/RESERVOIR MODELS FOR HYPOLIMNETIC OXYGENATION

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Bubble-plume diffusers are increasingly used to replenish DO in the deepest layers of lakes and reservoirs while preserving stratification. While bubble plumes are successful at adding oxygen, the added energy may induce large-scale hypolimnetic mixing. Plume-induced mixing changes the thermal structure of the reservoir, and plume performance depends strongly on the ambient density gradient. A model for a linear bubble plume used for hypolimnetic oxygenation was coupled to two reservoir models [CE-QUAL-W2 (W2) and Si3D] to simulate their complex interaction. In simulations with a rectangular basin, predicted oxygen addition was directly proportional to the update frequency of the plume model entrainment and detrainment parameters. W2 calculated less oxygen input to the basin than Si3D and significantly less mixing within the hypolimnion. These effects were likely due to lateral averaging within W2, which diluted the near-field DO accumulation and distributed the plume detrainment momentum across the entire width of the basin. With a plume update period of 0.5 hr, the coupled models were then applied to a simplified test of a full-scale linear diffuser in a water supply reservoir. Both the W2 and Si3D coupled models predicted bulk hypolimnetic DO concentrations well. Warming within the hypolimnion was overestimated by both models, but more so by W2. The coarser vertical resolution of the reservoir grid in W2 caused the plume rise height to be over-predicted, enhancing erosion of the thermocline. Using the simplified diffuser test case, coupling of the linear bubble-plume model with both W2 and Si3D has produced encouraging results. Therefore, the coupled models will be more extensively evaluated using additional full-scale diffuser data collected over a range of operating conditions. This future work will be complicated by the presence of pumped inflow into the reservoir during diffuser testing, which formed a high-flow, underwater plume that discharged vertically. Accurate modeling of this single-phase plume and the ultimate location of its detrainment will be critical to reproducing temperature and DO profiles well.

T04

EFFECTS OF GLOBAL WARMING AND CLIMATE CHANGE ON LAKE TAHOE (CA-NV)

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Meteorological activity is the driving force for lake internal heating, cooling, mixing, and circulation, which in turn affect nutrient cycling, food-web characteristics and other important features of lake/reservoir limnology. Therefore, climate changes may affect the physical, chemical and biological attributes of lakes and reservoirs because of the change in (1) the thermodynamic balance across the air-water interface, (2) the amount of wind-driven energy input to the system, and (3) the timing of stream delivery into lake/reservoir. These processes can exert changes across the entire water column depth. Many existing problems may be exacerbated by climate change, yet extreme uncertainty exists as to the extent of climate change. This study focuses on an assessment of how various climate change scenarios would affect Lake Tahoe internal mixing dynamics and circulation patterns.

Records of last 35 years shows that (1) the volume weighted mean temperature of Lake Tahoe increases at an average rate of 0.015 ^{o}C per year and, (2) the resistance of the lake to mixing increases. If this trend continues, the lake may ultimately be permanently stratified (i.e. limiting to full or more than ~ 200 m mixing) throughout the year resulting in water quality changes over time. To examine the impact of global warming and climate change on Lake Tahoe, the one-dimensional model DLM is used to simulate the lake mixing dynamics. Trends in the predicted meteorological variables (air temperature, precipitation, solar radiations, wind speed, relative humidity, etc.) from different global climate models (GCMs) for different global green house gas (GHG) emissions rate scenarios are used. Stream water temperature is estimated using predicted meteorological variables. Results of 40-year simulations show that with continued climate change there are pronounced changes in winter mixing patterns, the summer surface temperatures, and the overall stability of the lake.

T05

FAR FIELD PREDICTION OF THE GRAND RIVER PLUME

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The nearshore behavior of the Grand River plume as it enters Lake Michigan is modeled in three dimensions. Simulation of the mixing and transport mechanisms in the near field and transition to far field is of particular concern. Far field models typically incorporate grid sizes that are larger than the scale of near field processes by orders of magnitude. Hence, predictive capability is usually sought by refining the far field model grid size or coupling the far field model with a near field model. In this study, the Princeton Ocean Model (POM) is used to simulate the dispersion of the Grand River plume near the local beaches with a grid size of 100 m in a 24 x 6 km domain. The open water boundary conditions are obtained from a whole-lake hydrodynamic simulation with a 2 km grid resolution. The model predictions are compared with extensive field observations. The model has been tested for some idealized cases to study the effect of near field parameters on plume far field behavior. Variation of river discharge as a near field parameter along with ambient velocity change the plume shape and the tracer concentration level in the far field. This reveals the necessity of using a separate near field model to represent the smaller scale processes. The results of this research will improve numerical modeling of nearshore water quality.

T06

EXPERIMENTS ON THE FATE OF BOUNDARY-MIXED FLUID IN A LAKE

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Field observations in stratified water bodies suggest that turbulence created at the boundaries is responsible for most of the mixing. While much work has been done to investigate mixing at boundaries, less attention has been paid to the fate of this mixed fluid. We conducted tracer release experiments to track fluid from the boundary into the interior of the south basin of Ada Hayden Lake, which has a maximum depth of 15 m. A 10 m long streak of Rhodamine WT was injected at the northeast boundary of the lake under different winds. The dye cloud was surveyed daily with a tow-yo technique, and

temperature microstructure profiles were measured concurrently. Throughout the experiment, the wind forcing and internal wave field were measured by a lake station that included meteorological instruments and a thermistor chain. Two additional thermistor chains were deployed to observe the spatial variability of the internal wave field. An upward looking ADCP measured water column velocities, and a high resolution acoustic current profiler measured currents in the bottom boundary layer. During periods of weak wind—or high Lake number, the dye stayed near the shore, while during periods of strong wind—or low Lake number, the dye moved offshore into the lake interior. We examine the possibility of intrusions generated by a turbulent bottom boundary layer activated by breaking critical waves or seiching currents. Critical internal waves were present; in some locations the low vertical mode seiches were also critical. Enhanced eddy diffusivities of 10-5 to 10-4 m2/s were also observed after strong wind events. The propagation speed of the dye into the interior matched the theoretical intrusion velocity proposed by Gloor et al. (2000).

T07

VARIATIONS IN PENETRATIVE CONVECTION DRIVEN BY ICE-COVER HETEROGENEITY IN A TEMPERATE LAKE

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Radiative penetrative convection was investigated under-ice in Pavilion Lake, a mid-size temperate lake (5 km^2) in the interior of British Columbia, during the initial onset of spring thaw in February 2007 and February 2008. The convection was observed using a conductivity-temperature-depth (CTD) sensor, mounted on an autonomous underwater vehicle (AUV) that was flown repeatedly along horizontal transects (~450 m in length) at selected depths during a 1-5 hour time period. Four distinct thermal layers occur beneath the ice (~50 cm thick): a stratified diffusive layer just beneath the ice; a well-mixed convective layer; an entrainment layer; and, a weakly stratified quiescent layer (to bottom). It was demonstrated that, although this thermal structure was consistent, the relative depths of each layer varied between the two field seasons. Each layer was sampled by the AUV transects, flown at constant depth with a 5 cm depth tolerance. The collected temperature data revealed a wide, central region of the basin displaying evidence of penetrative convection, surrounded by regions with negligible heat changes. In addition to the AUV transects, vertical temperature measurements were collected with both a CTD profiler and a thermistor chain at one location during each of the AUV missions. Heat flux values, estimated from these three measurement platforms, were then

compared to the estimated heat flux from meteorological data. A survey of the ice surface along the AUV transect (50 m intervals) revealed that the region displaying penetrative convection was subject to an increased daily heat flux resulting from decreased snow cover. This work provides insight into previously unresolved physical dynamics of the well-mixed layer under-ice during the initial onset of spring thaw that would have been impossible without the use of an AUV platform.

T08

CIRCULATION OF VERY DEEP, PURELY THERMALLY STRATIFIED, HORIZONTALLY HOMOGENEOUS LAKES

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In very deep freshwater lakes, stratification and deep recirculation show remarkable differences to shallower lakes. We consider cases where only temperature is responsible for density gradients. If sufficiently deep, lakes do not produce full overturns during T_{md} (temperature of maximum density) transition in autumn or spring. Peculiar features of the temperature profiles are derived for cases, when surface temperatures cross 4°C during the annual cycle:

1) asymmetry between autumn and spring circulation,
2) proximity of temperature to the T_{md} profile over a wide depth interval
3) isothermal deep water

We compare conceptual model results with measurements in very deep caldera lakes in Japan (Lakes Ikeda, Tazawa, Toya, Kuttara and Shikotsu; in Japanese referred to as Ikedako, Tazawako, Toyako, Kuttarako and Shikotsuko). Fine resolution profiles of temperature, electrical conductivity, dissolved oxygen and pH have been acquired. Measurements have been conducted just after deep circulation from end of March till end of May 2005. Lake Ikeda did not undergo a complete turnover and showed meromictic features with a clear interface separating the recirculated mixolimnion from the deeper monimolimnion. Lake Tazawa and Lake Toya showed complete overturns in winter 2004 / 05, while in Lake Kuttara and Lake Shikotsu, a deep water body remained throughout winter due to pressure effects on T_{md}. Although these deep waters were never fully recycled into the mixolimnion, they presented themselves as well supplied with oxygen and well circulated within themselves. Where overturns had not been complete, small gradients in the oxygen profile, pH profiles and electrical conductivity profiles could be

detected. Between oligomictic lakes and thermobarically stratified lakes, we find lakes with a full overturn in winter despite of their enormous depth. At the end, we discuss susceptibility of deep water temperatures to climate variability which we support by comparisons with single point measurements from the 1920s and 1930s.

T09

SF6 TRACER EXPERIMENT TO INVESTIGATE TRANSPORT PROCESSES IN A SMALL MEROMICTIC MINING LAKE

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We studied groundwater exchange and vertical transport in a small mining lake (maximum depth ~4.6 m) in Lusatia, Germany. The lake is at least some ten years meromictic with an anoxic monimolimnion. The monimolimnion is enriched in dissolved iron and the transition to the mixolimnion (chemocline) shows a sharp increase in electrical conductivity (0.4 mS/cm within 25 cm). The mixolimnion is oxic throughout the year and the meromixis is probably due to, or at least supported by, the iron cycle. The depth of the chemocline is changing seasonally with a deepening in summer and lowering during the cold season (range: 0.9 m to 1.9 m). A SF6-spike, where we injected ~0.45 mg SF6 at the lake bottom, was used to investigate the transport processes. Monthly sampling and measurement of the vertical distribution was performed with a vertical resolution down to 10 cm. SF6-concentrations in the monimolimnion before spiking were far below the modern atmosphere equilibrium, indicating a groundwater influence.

The vertical movement of the SF6-cline and budgeting the SF6 inventory below the SF6-cline were used to evaluate two scenarios to calculate the groundwater exchange rates. The first scenario assumes the change of the chemocline depth solely due to difference of groundwater in- and outflow, while the second allows an export of SF6 into the mixolimnion caused by chemocline erosion as a result of daily convective mixing in the mixolimnion. Both scenarios lead to a rather stable value of 5 to 10 m3/d inflow without seasonality and an outflow of groundwater of about 5 m3/d during winter time. During summer, while the chemocline is descending, the first scenario leads to an outflow of 10 - 15 m3/d, whereas the second gives a reduced value of about 10 m3/d. The mean inflow rate of 7m3/d is equivalent to a renewal rate of the monimolimnion of 89% per year. In the first scenario the outflow to the (deep) groundwater is balanced, whereas in the second the vertical transport due to chemocline erosion amounts to 12% and is balanced by mixolimnion groundwater exchange.

T10

ISOLATION TIME AND HYPOXIA IN A DENSE GRAVITY CURRENT

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Estuarine hypoxia has been consistently linked with vertical haline stratification. In most coastal systems, such stratification develops from incoming riverine fresh water flowing over denser saline ocean water. However, in Corpus Christi Bay (Texas) episodic hypoxia has been recently linked to dense hypersaline gravity currents exiting from adjacent bays, which form a 0.3 to 1 m benthic layer that may persist for multiple days despite moderate winds on the order of 6 m/s over the shallow bay (~4 m depth). A simple Lagrangian dissolved oxygen (DO) transport model, parameterized by field data, provides a rough estimate of benthic oxygen demand that is consistent with prior field studies. This model is used to demonstrate that vertical fluid exchange between the underflow and the ambient Corpus Christi Bay water is relatively small as the underflow spreads across the flat bay bottom. An examination of vertical mixing scales and mixing energy sources indicates that the time scale for vertically mixing the water column with typical winds over Corpus Christi Bay is longer than the time scale for consuming the DO in the thin underflow layer. Thus, the development of hypoxia in this system is governed by the relationships between vertical mixing rates, net oxygen demand, and thickness of the underflow layer. We demonstrate that the relationships between the underflow water's isolation time from the atmosphere and the net oxygen demand per unit volume provide useful metrics for predicting the episodic conditions that are conducive to hypoxia in Corpus Christi Bay.

W01

THE WATER QUALITY OF A SHALLOW SHELF AS FORCED BY UPWELLING AND TRIBUTARY FLOW EVENTS

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Cayuga Lake (Ithaca, NY, USA) is a long (60 km) and narrow (4 km) lake with a shallow southern shelf to which discharges 40% of the watershed via tributaries which are characterized by naturally occurring and anthropogenically intensified sediment loads, as well as agricultural and urban nutrient and pollutant inputs. Additionally, two municipal waste water treatment plants and a utilities cooling project also discharge to the southern shelf of the lake. The residence time of the southern basin is established by a subtle balance of hydrodynamics processes but importantly, as shown by Rueda and Cowen (2005, *Limnology & Oceanography* 50), this balance is never in equilibrium and the mean (over time) residence time at a given location can be dominated by two types of events: tributary runoff and basin scale internal waves (i.e., upwelling events).

Using a decade long water quality monitoring record augmented by hydrodynamic measurements we will demonstrate that the water quality of the shelf, and hence the residence time, is characterized by event frequency and magnitude, analogously to the lake-embayment findings of Rueda and Cowen (2005). Hence year-to-year variability of water quality on the shelf is driven by the number of events that occur in a given year. We will also describe individual events, in particular upwelling and shoaling internal waves, and demonstrate that they lead to strong local-in-time nutrient, sediment, and organism fluxes that are important biologically, and which ultimately result in spatial variability in phytoplankton as measured by chlorophyll-*a* levels.

We will conclude with comments on the viability of low frequency (in time) monitoring data to assess year-to-year variations in water quality and the challenges of bias in quantities such as annual means due to the correlation of sampling times with monitoring dates.

W02

CHARACTERISTICS AND IMPLICATIONS OF WAVES IN LAKE LITTORAL ZONES

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In lakes, waves provide an important energy source and thus hydrodynamic disturbance in the littoral zone, where most of the wave energy is dissipated. Waves are associated with currents in the water column that interact with the sediment surface and biota. The impact of waves on the littoral ecosystem was investigated by measuring a variety of physical and biological parameters simultaneously to wave measurements. In field experiments, we found strong linkages between wave field properties and the occurrence of resuspension that also altered the underwater light climate by increasing the light attenuation coefficient. During winter, when the water column in the littoral zone is only weakly density stratified, resuspension was sufficient to generate turbidity plumes, which may play an important role for deep water renewal. In wave mesocosm experiments, we investigated the implications of wave motion on biota, e.g., the reduction of periphyton biomass, the reduced grazing activity of snails, and the reduced activity of juvenile cyprinids that is accompanied with reduced somatic growth.

W03

SOURCE WATER DISTRIBUTION OF A GROUNDWATER-FED, BUT OTHERWISE (PHYSICALLY) UNREMARKABLE LAKE

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Pavilion Lake, British Columbia, Canada is known for massive carbonate structures actively accreting on the lake bottom through microbial activity. Similar carbonate structures known as microbialites are found globally in many lakes that are usually “extreme” in some way, for example having high salinity or alkalinity. The unremarkable nature of Pavilion Lake presents a challenge to understanding why microbialites form here. Pavilion Lake is a “typical,” small (5.7 km long, 0.8 km mean width and 65 m maximum depth), dimictic, freshwater, mountain lake with annual ice-cover. From a

physical point of view, Pavilion Lake's only abnormality is that it has no permanent surface inflows. All surface flows in this arid catchment subduct prior to reaching the lake. Identifying and characterizing groundwater discharge into Pavilion Lake is an ongoing challenge as no discrete underwater springs have been identified – rather inflows are suspected to be low-flow-rate, diffuse sources percolating through the fine carbonate flour that makes up much of the lake floor. Given the complexity of the local geology (siliceous-argillite and karst bedrock with alluvium below creek subduction zones) groundwater characteristics are found to be extremely heterogeneous with adjacent well having salinity higher and lower than nearby lake water salinity. Thus, groundwater entering Pavilion Lake will have temperature and salinity characteristics subtly different from ambient lake water at the point of entry. The end result of this complexity in the distribution and character of source waters entering Pavilion Lake is a complex distribution of water within the lake. In particular, we focus on the semi-annual accretion and removal of relatively saline bottom-water. While this bottom salinity stratification is weak, it consistently appears between seasonal turnover events. Between April and December turnover this bottom layer grows to a distinct salinity stratified layer ~10 m thick. During the weakly forced, ice-cover period this bottom salinity stratification is observed to support inverse thermal stratification. Data are presented from moored and profiling *in situ* temperature and electrical conductivity sensors over a three-year period. This bottom water is shown to be derived from saline groundwater entering the lake through various, unidentified sources and flowing to the lake bottom.

W04

LOW-COST GPS-TRACKED DRIFTERS IN LAKE CIRCULATION STUDIES

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The technique is presented of quasi-lagrangian lake currents observations based on tracking of submerged drifters by satellites using the NAVSTAR GPS navigation system. The construction of the drifters is extremely simple, includes practically no custom parts and can be easily adjusted to any from a number of the commercially available compact GPS receivers.

Comparison of lake currents achieved from the drifters against acoustic current profiler measurements was performed in order to estimate the wind drag force at the surface float containing the receiver. It suggests little effect of the wind drag on the drifters' movement at wind speeds up to 5 m/s that makes the method suitable for many lake applications.

The drifters' performance at higher wind speeds can be further improved by reducing of the surface float size that is possible since the small-size GPS receivers became available. Further improvement of the method accuracy can be achieved by using of the GPS augmentation systems (WAAS in the USA and forthcoming European EGNOS) that opens broad perspectives for its application in limnological studies.

A series of drifter experiments were performed in the small German Lake Stechlin. They revealed several circulation features hardly available from convenient point measurements of the current velocity profiles, such as formation of coherent mesoscale vortices by lake topography. Mesoscale coherent structures such as quasi-2d vortices are poorly investigated in small lakes but can potentially affect redistribution of the wind energy in the lake interior as well as transport of dissolved and particular matter. According to the observations, the vortices appear quasi-regularly in the deep part of the lake, associated with excitation of a certain horizontal seiche mode, and transport the captured kinetic energy to the lake shore being destroyed within 1-3 days. Lagrangian observations on mesoscale vortices formation were supported by results of 3d modeling of circulation in Lake Stechlin.

W05

THE INTERNAL SOLITARY WAVE BREAKING ON A SLOPE: ENERGETICS, VORTICITY AND BOUNDARY LAYER SEPARATION

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The breaking of shoaling internal waves and associated mixing is a complex process with important implications. It provides an important sink of energy, a source of sediment resuspension, and the vertically mixing nutrients are important for biogeochemical processes. There is speculation that breaking internal waves play a role in setting the bottom slope on wide regions of the oceanic continental shelf. The shoaling and breaking of internal waves has been the subject of several laboratory experiments and numerical studies.

In many regions of the coastal ocean and in many lakes internal solitary-like waves are commonly observed towards the shore. These waves are the focus of this talk in which results of high-resolution two-dimensional numerical simulations of internal solitary waves shoaling on a sloping bottom are discussed. The stratification consists of a single thin pycnocline intersecting a bottom slope. The evolution of the available potential and kinetic energy is discussed. Using a variety of waves the role of boundary layer separation and vorticity production on the process of wave breaking is described.

W06

MIXING OF METALIMNETIC WATERS BY FIRST AND SECOND VERTICAL MODES INTERNAL WAVES IN A SMALL SHALLOW LAKE: CONSEQUENCES FOR PHYTOPLANKTON DYNAMICS

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High frequency time series of the thermal and current structure in a small dimictic lake (Lake Bromont, Canada) during the summer of 2007 revealed the occurrence of recurrent internal waves. The daily variability in wind intensity and direction induced 2 to 3 cycles of a first vertical mode seiche (V1H1), followed by a second vertical mode seiche (V2H1). The dissipation of energy during the second vertical mode being lower than that of V1H1, the V2H1 last for a few days. The presence of the second vertical mode in Lake Bromont can be explained by the general shape of the thermal density structure with a large metalimnion. Although the lake is small (41 ha) and shallow (mean depth of 4m and maximal depth of 7.2m), the response of the thermal structure of the lake to wind forcing is very similar to deep and alpine lakes. Amplitude and frequency of the internal wave modes were characterized, depending on wind and stratification conditions. The vertical excursion of the metalimnion together with its mixing characteristics by turbulent diffusion influenced both light availability and nutrient fluxes, leading to a higher biomass and diversity in the metalimnetic phytoplankton community. The short-term phytoplankton dynamics was thus characterized in terms of primary production, biomass and species composition and related to the internal waves activities.

W07

THE IMPACT OF VARIABLE INTERNAL WAVES ON SEDIMENT OXYGEN UPTAKE RATES

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The sediment oxic zone controls many of the chemical and biological processes occurring within the sediment, including trace metal speciation, nutrient retention, and the structure and distribution of sediment microbe communities, that directly impact the bottom boundary layer (BBL) of the water column via sediment-water fluxes. Sediment-water

fluxes (e.g., dissolved oxygen (DO) and soluble metals) are governed by the diffusive boundary layer (DBL), which is a viscous sub-layer of water at the sediment-water interface that establishes the rate-limiting step to oxygen diffusion. While eddy diffusion dominates vertical transport in the turbulent BBL, molecular diffusion is the primary vertical transport mechanism within the DBL. Transport through the DBL is a function of both the concentration gradient and also turbulent mixing in the overlying BBL; however, because DO and soluble metal levels change relatively slowly in the BBL of most water bodies, sediment-water fluxes are primarily controlled by DBL thickness as a function of BBL turbulence.

Fluctuating turbulence levels in the water column have been shown to have a significant impact on rates of DO diffusion into the sediment, with increased velocities in the overlying water driving DO further into the sediment and subsequently increasing the sediment oxic zone. Thus, it is important to define how temporal variations in BBL turbulence levels impact sediment-water fluxes and corresponding changes in the sediment oxic zone. We have performed a study on Lake Alpnach (located near Lucerne, Switzerland) that focused on quantifying how periodic variations in turbulence as a function of wind-forced seiching impact oxygen penetration depth into the sediment. An in-situ profiling lander (MP4, Unisense A/S) was used to obtain high temporal-resolution microprofiles at a sub-millimeter depth scale at the sediment-water interface to measure changes in the DBL and corresponding variations in DO fluxes under variable, periodic forcing within the BBL. Data from this study show significant variation in the DO microprofiles obtained throughout the 12-hour campaign. Results suggest that the periodic seiche velocity has a significant impact on the DBL thickness, DO penetration depth into the sediment and associated sediment-water biogeochemical processes.

W08

AN ANALYTICAL SOLUTION FOR WIND-DRIVEN LAKE CIRCULATIONS IN AN ELONGATED BASIN

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The response of a closed basin to wind forcing has been studied extensively in the past, but the role of turbulence anisotropy coupled with spatial wind in homogeneity has never been considered explicitly. In this contribution an analytical stationary solution is presented, considering the central part of a constant-depth, elongated basin with a laterally varying wind, and a constant, yet anisotropic, eddy viscosity tensor. The solution

is derived both for a single layer and for a two-layer basin, which is representative of a stratified lake with a well-developed thermocline. The comparison with the results of a complete three-dimensional numerical model in some test cases shows a noticeable agreement. Since the baroclinic terms are neglected in the analytical derivation, their relevance is discussed and the limitations of the solution are shown when horizontal density gradients are created by the overall circulation. In any case, the solution is valid as a first reaction to wind forcing and determines the type of lake circulations. In particular, the development of planimetric (depth-averaged) circulations superimposed to circulations in the vertical plane can be determined as a function of wind lateral variation and few dimensionless parameters (only one parameter in single-layer systems, describing the anisotropy of the eddy viscosity and the relative depth of the basin; four parameters in the two-layer system, describing also the second layer characteristics and the shear stress transmission at the interface). The relevance of such analytical solution is twofold. Firstly, the knowledge of the prevailing circulations can help in the choice of the best type of numerical model (three-dimensional vs. two-dimensional, depth- or lateral-averaged). Secondly, it shows the importance of correct estimates of both vertical and horizontal eddy viscosity, whereas the latter is not usually considered as an important parameter in lake hydrodynamics.

W09

THE EFFECT OF CHANGES IN WIND, RIVER INFLOW, AND AIR TEMPERATURE ON DEEP CONVECTION IN A SWISS LAKE

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Evidence of the effect of global warming on lakes is accumulating rapidly. A one-dimensional, seiche-extended, k-epsilon model was assembled to simulate the response of a small to medium-sized lake in Central Switzerland to various climatic forcing scenarios. Pfäffikersee is a eutrophic, hard-water lake with a maximum depth of 35 m, an average depth of 18.8 m, a volume of 0.057 km^3, and a surface area of 3.03 km^2. Prior to 1993, the lake experienced ineffective vertical mixing during some winters, resulting in relatively low oxygen levels in the hypolimnion during the subsequent summer. Based on historical measured monthly profiles, the lake experienced complete mixing in roughly 60% of winters. In 1993, a mixing/aeration system was installed and used during the winter to enhance deep circulation of oxygen-rich water. Average water column salinity data were used to calculate salt fluxes as a function of time and depth. River inflow and outflow data were used to determine net salt input, as well as the density of

the influent river water as a function of time. These excellent data sets, collected prior to as well as after the introduction of the aeration system, enabled the development of a model that simultaneously incorporates the effects of primary production, meteorology, and net river inflow, thereby simulating the conditions that control stability.

The calibrated lake model was used to examine the effect of different climate change scenarios on deep winter mixing. Three different effects were considered: 1) a step-change to a new steady-state air temperature of either +2^{o}C warmer, +4^{o}C warmer, or +6^{o}C warmer; 2) an increase in wind speed of 20%; and 3) a 30% increase in river inflow in winter and a 30% decrease in river inflow in the summer. These effects were imposed on the lake model over a 12 year period to establish how winter mixing is altered. The criterion used to establish whether or not the lake was "completely mixed" was a relative density gradient of less than 2 ppm (taken from 1 m below the surface to 1 m above the bottom). Gradients of 3 and 4 ppm gave essentially the same results. For the baseline case, the lake was completely mixed for 153 days (out of the 12 year period), with complete mixing occurring in 11 winters. These mixing events had an average duration of only about 6 days, and were presumably not always captured by the historical monthly profiling. With warmer air temperatures of +2 ^{o}C and +4 ^{o}C, the number of completely mixed days decreased from 153 to 119 and 58, respectively, while the number of winters experiencing deep mixing decreased from 11 to 10 and 4, respectively. A warming of +4 ^{o}C will therefore have a substantial effect on the ecology of the lake. For an increase in air temperature of +6 ^{o}C, the lake is predicted to become permanently meromictic. The effect of an increase in wind speed of 20% over the entire year had a substantial impact on winter mixing with the number of completely mixed days increasing from 153 to 456 and with complete mixing experienced every winter. This illustrates how sensitive deep winter mixing is to the energy introduced by the wind. The effect of changing the river inflow had the opposite effect to the wind, with the number of completely mixed days decreasing from 153 to 55, while the number of winters experiencing deep mixing decreased from 11 to 7. This is to be expected because the increase of 30% flow in the winter adds salt to the bottom of the lake (a stabilizing effect) and the decrease of 30% flow in the summer means that less salt is added at the top (also a stabilizing effect). Potential changes in meteorology are therefore expected to have profound ecological consequences.

W10

THE IMPACT OF TOP-DOWN IMPELLER-BASED CIRCULATORS ON STRATIFICATION IN GOOGONG RESERVOIR

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There has been a rapid increase in the use of impeller-based systems (e.g. SolarBee and WEARS) to enhance circulation in lakes and reservoirs in order to improve water quality. Such systems promise a much-more energy efficient alternative to the more common compressed-air bubble plume method of reservoir destratification. Both methods work by displacing large volumes of water vertically and then allowing gravitational forces and entrainment to produce large scale circulation in the water column - typically as an intrusive flow bounded above and below by return flows towards the vertical plumes. Although there is a large amount of anecdotal evidence that suggests such systems have profound effects on water quality there has been little rigorous study and assessment of their performance.

Googong Dam, near Canberra, Australia, began operation of a WEARS top-down circulator system in March 2007. The system uses 4 pumps to shift 24 $m^3\ s^{-1}$ of surface layer water downwards through a 20 m-long draft tube where it is released into the reservoir. During the present study period the volume of the storage was approximately 60 GL with a surface area of 480 ha and a maximum depth of ca. 35 m. Thermistor chain data and water quality profiler data show the impact of the mixers on thermal stratification as well as oxygen redistrbution in the water column. Following the onset of operation during the autumnal cooling period, there was a 10-day period during which the surface layer became shallower. After approximately 2 months the entire water column had been circulated. The system transported heat downwards throughout most of the water column during early spring. As heating became more intense at the water surface the influence of the circulators extended only to the bottom of the draft tubes. There was no significant impact of the circulators on the depth of the surface mixed layer.

Operation of the mixers raised dissolved oxygen concentrations to the depth of the draft tube but there did not appear to be an increase in the total mass of oxygen in the reservoir, i.e. the circulators appear to have redistributed the existing amount of oxygen within the water column. This implies either air-water exchange of oxygen at the water surface is a limiting factor or that the induced large increase in water temperature in the lower water column has raised in situ oxygen demand sufficiently to compensate for any increased flux into the water column across the reservoir surface.

W11

RELEASE OF METHANE-DEPLETED DEEPWATER AFTER GAS EXTRACTION IN LAKE KIVU

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This contribution describes the approach for an optimized strategy for the safe and efficient exploitation of the >60 km^3 of methane (CH_4) dissolved in the deepwater of Lake Kivu. The challenge of harvesting this resource is set by the constraints, that (i) the CH_4 is stored below 100 m depth with increasing concentration to the maximum depth of 485 m and (ii) the natural biological cycling should not be disturbed in the top ~50 m surface layer. The obvious solution is to release the CH_4-stripped deepwater into the upper pycnocline, between ~50 and ~170 m depth. However two crucial boundary conditions have to be considered: (i) the density of the re-inject water is much larger (due to high salt and CO_2 content) and (ii) the re-inject water is ~500-times richer in nutrients (N, P) than the surface water. Using a one-dimensional advection-diffusion-reaction model, we simulate the stratification (temperature, salinity), the gases (CH_4 and CO_2) and phosphate within the water column for 100 years for different methane extraction scenarios. The options are evaluated based on the strength of the overall stratification, the energetic resistance to supersaturation, the amount of harvested methane, and the amount of methane lost by oxidation (water and atmosphere).

The simulations demonstrate that adding dilution water from the surface to adjust the density of the re-inject water would have a devastating effect on the upward nutrient fluxes. But also releasing water above ~200 m depth causes too high nutrient fluxes to the surface. The reason is the unusual - but unavoidable - upwelling, caused by sub-aquatic sources (rainwater falling on high-porosity volcanic ground). We identified two scenarios of deep re-injection of the methane-depleted deep water which change the lake's overall structure to an acceptable extent and allow continuous electric power production of several 100 MW. The main - but acceptable - disadvantage is some losses of "harvestable" methane via dilution by re-inject water. Currently we improve the evaluation with additional criteria, which take into account that some of the important assumptions on the characteristics of the aquatic system may not be that well-defined. For a robust planning it is important to choose a strategy which is not too sensitive to system uncertainties.

W12

THE IMPORTANCE OF DOUBLE DIFFUSION FOR MIXING PROCESSES IN LAKE KIVU

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Lake Kivu, one of the large East African Rift lakes, is mainly known for the huge amounts of methane dissolved in its deep waters. The methane is expected to be used as an important energy source for the region in the near future. It is also a major hazard, as it could provoke a catastrophic gas eruption. The accumulation of the methane is only possible since the deep water of the lake below 250 m depth is practically decoupled from the surface, with a residence time for the gases on the order of 1000 years.

The build-up and maintenance of the extremely stable stratification in the lake is supported by double-diffusive convection. This phenomenon, first observed in Lake Kivu by Newman in the 1970's, allows heat to be transported out of the deep water more efficiently than salts and dissolved gases, preserving the stabilizing salinity gradient and weakening the destabilizing temperature gradient.

Here we present a detailed analysis of 9 temperature microstructure profiles taken in Lake Kivu in February 2004. Between 230 and 350 convectively mixed layers with an average vertical extent of ~0.5 m were identified in these profiles. The pronounced convective activity was highlighted by the fact that temperature gradients within the mixed layers were typically two orders of magnitude weaker than within the interfaces. Most temperature steps were on the order of a few mK. Vertical fluxes of heat and salt through the double-diffusive staircases were estimated using different flux laws. The calculated apparent diffusivities were one order of magnitude larger for temperature than for salt. The quality of the temperature profiles was sufficient to resolve the temperature structure and variability within the mixed layers. This temperature variability was used to estimate energy dissipation, which ranges between 10^{-11} and 10^{-10} W kg^{-1}, at the lower end of dissipation rates observed in natural waters.

W13

ACOUSTICAL AND OPTICAL REMOTE SENSING AND FIELD VALIDATION OF METHANE EMISSIONS FROM NATURAL SEEPS IN COASTAL WATERS

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Methane is an extremely important greenhouse gas that has increased significantly in post-industrial times. One of the more important mechanisms of methane gas emission from shallow marine and lake sediments is bubbles. These bubbles exchange gas with the surrounding water as they rise through the water column. At the sea-surface, the bubbles release their methane directly to the atmosphere, but indirect transfer also occurs from dissolved methane that diffuses to the atmosphere. Although estimated to be of global budget importance, quantification of these highly spatially and temporally variable sources presents unique challenges.

Two remote sensing approaches, imaging spectrometry and multibeam sonar return, were used in conjunction with in-situ flame ion detection and gas chromatography (GC) for field validation. AVIRIS (Airborne Visual Imaging Spectrometer) data was acquired over the Coal Oil Point (COP) seep field, offshore California. The COP seep field is among the largest in the world, with its accessibility and predictable seep-emission locations making it an ideal test bed for methodology development and validation. Spectral data was analyzed by modeling residual spectral anomalies from methane absorption with the MODTRAN radiative transfer model, specifically, in the 2200 to 2350 nm region.

Methane validation was with a gas chromatograph configured with two channels for total hydrocarbon and two for speciation. The GC is deployable on small (7-m) boats and is navigated to create spatial maps of seep gas plumes arising from bubbles and water-air exchange.

Sources identified in the remote sensing data were correlated with the spatial emission distribution of seepage determined from sonar surveys. Chirp sonar return was recorded along transect lines covering active areas of seepage. From this data the RMS sonar return, s, in a low-noise (not near seabed or sea-surface) depth window of the water column was calculated. Using navigation, s was gridded to generate seep maps. Close correlation was demonstrated between the seep sonar and spectrometric data sets.

TH KEYNOTE

SOME APPROACHES TO PREDICTING THE PERFORMANCE OF RIVER RESTORATION

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During the past five years there has been increasing interest in establishing clear restoration objectives for river and wetland restoration activities and associated performance metrics to assess whether these objectives are achieved. This presentation will provide a brief overview of the findings of the 2006 National River Restoration Science Synthesis and other similar reviews of major ecosystem management programs, with particular reference to the western states. Based on this context, the results of a systematic series of research projects conducted to assess the effectiveness of restoration actions at the watershed scale will be described.

The effective discharge or channel forming discharge (tidal prism is coastal wetland restoration) is a key variable that is the cornerstone of many restoration design approaches. A brief analysis will be presented to determine whether this is a robust variable to use and if the faith in the concept is justified. Restoration projects based on multiple objectives may result in conflicting outcomes, not only for competing habitat mosaics but also in changes in the physical processes that may result in trends opposite to the desired outcome. An example of these conflicting objectives will be given at the Red River Wildlife Management Area for several metrics including temperature.

A common restoration objective is to modify the existing temperature regime, for example to reduce summer peak temperatures in streams to eliminate thermal barriers, create thermal refugia or to reduce thermal stress in the summer months. Conversely, in the winter months it is often desirable to increase stream temperatures and minimize areas of the stream freezing completely during the winter. During the past few years, some large programs have been moving away from reach scale restoration projects, particularly for addressing excess temperature in spawning areas as it is assumed that the elevated temperatures are due to watershed management practices in the upstream watershed, and these issues should be addressed before attending to downstream reaches. The results of a detailed monitoring and modeling study will evaluate the effectiveness of local restoration effects on the overall temperature regime compared with changes in the upstream conditions.

The final example considers the problem of the sustainability of pool-riffle sequences in gravel bed streams. What are the reasons for some streams maintaining pool-riffle geomorphology under major watershed perturbations such as wildfire or intense grazing within the stream corridor, whereas the pool morphology in other streams subject to lesser disturbance disappears? This problem is of particular concern if one of the restoration objectives is to create sustainable pool-riffle sequences without artificial interventions such as barbs or weirs. This problem will be described through recent research that considers a mathematical explanation, detailed field measurements of the turbulent structure through pool-riffle sequences and 3-d model simulations.

Biosketch of Peter Goodwin

Education

University of Southampton, United Kingdom	Civil Engineering	B.Sc.,	1978
University of California, Berkeley	Civil Engineering	M.S.,	1982
University of California, Berkeley	Civil Engineering,	Ph.D.,	1986

Appointments

2004-present Director and Founder, Center for Ecohydraulics Research, University of Idaho
2002-present Professor, Department of Civil Engineering, University of Idaho
2001-present DeVlieg Presidential Professor, University of Idaho
1998-present Adjunct Professor, Department of Biological and Agricultural Engineering, University of Idaho

Research and Teaching Interests

River and estuary restoration; hydrologic, hydrodynamic and morphological modeling; integrated modeling of physical processes and biological response.

Relevant Recent Publications

Goodwin, P., K. Jorde, C. Meier and O. Parra, 2006. Minimizing environmental impacts of hydropower development: transferring lessons from past projects to a proposed strategy for Chile. Journal of Hydroinformatics. 8(3). 1-19.

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Palmer, M.A., E.S. Bernhardt, J.D. Allan, P.S. Lake, G. Alexander, S. Brooks, J. Carr, S. Clayton, C.N. Dahm, J. Follstad Shah, D.L. Galat, S.Gloss, P.Goodwin, D.D. Hart, B. Hassett, R. Jenkinson, G.M. Kondolf, R. Lave, J.L. Meyer, T.K. O'Donnell, L. Pagano and E. Sudduth, 2005. Standards for ecological successful river restoration. *Journal of Applied Ecology*, April.

Goodwin, P., 2004. Analytical Solutions for Estimating Effective Discharge. *Journal of Hydraulic Engineering*. ASCE. 130(8). 729-738.

Professional Activities

- Science Board, Louisiana Coastal Action Plan (rebuilding the ecosystem and wetlands of coastal Louisiana post- Hurricane Katrina). http://el.erdc.usace.army.mil/lcast/ and http://lacoast.gov/
- NSF CLEANER Science Plan Committee for CLEANER: 2005-06.
- Independent Science Board: CALFED San Francisco Bay-Delta Program (2005-present).
- Scientific Steering Committee, Patagonia Ecosystems Research Center (CIEP). A multi-national research initiative for the sustainability of Patagonia, Chile (2005-present).
- Elected to the Council, International Association for Hydraulic Research, 2003-2007. Elected Vice-President, 2007-present [www.iahr.org].

Recent Awards: Fulbright Award (Chile), 2003-4.
University of Idaho, College of Engineering Outstanding Faculty Award, 2006;
Lemley International Award for the Environment, 2007;
Research Professor of the Year Award, University of Idaho, 2008

TH01

MOBILE HOT SPOTS AND DEAD ZONES: MODELING SPATIOTEMPORAL OXYGEN DYNAMICS IN VEGETATED SHOALS ALONG THE TIDAL HUDSON RIVER

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We modeled the impact of the floating leaved plant, *Trapa natans*, on dissolved oxygen (DO) levels and biogeochemical cycles within a vegetated embayment and, through tidal exchange, the entire river ecosystem. *T. natans* reduced DO levels because oxygen production occurred primarily via floating leaves whereas respiration occurred mainly subsurface. At peak midsummer plant biomass, 20% of the 1.2-km wide embayment remained anoxic; the remaining 80% had strong tidal variation in oxygen levels. The degree of anoxia and the proportion of each respiration product (e.g. methane) is a function of tides, river stage, and shoal width and depth. Running the model over the entire tidal freshwater portion of the river, the total biochemical impact of replacement of native grasses by *T. natans* is calculated.

Critical to our model was quantifying advection and dispersion of oxygenated water across the embayment and net exchange between the embayment and river. We constrained the hydrodynamic components of our model with a heat budget, which was possible because the canopy shaded and thus cooled the marsh by up to 4^{o}C. The heat budget was based on five months of continuous, high-frequency temperature and water elevation data collected throughout the embayment and air-bay heat exchange measured from a floating micrometeorological station. Met data included net radiation and eddy covariance sensible and latent heat fluxes.

TH02

SIMULATING CLIMATE AND LAND USE IMPACTS ON LAKE WATER QUALITY USING A COUPLED CLIMATE-WATERSHED-LAKE ECOSYSTEM MODEL

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A lake ecosystem model, a catchment model and a climate model have been linked to simulate the impacts of climate change and land use intensification on mesotrophic, polymictic Lake Rotorua, New Zealand. The land use effects are of particular significance due to the progressive increase in nitrate load to the lake as the aquifer quality begins to reflect a transition to higher intensity agricultural land use that has already taken place over a number of decades. This change is of particular significance to Lake Rotorua, in which limitation of phytoplankton productivity is closely balanced between both nitrogen and phosphorus. The lake model includes a physical model (DYRESM- 1D or ELCOM-3D) and a water quality model (CAEDYM). The 1-D lake model (DYRESM-CAEDYM) was used for water quality model calibration, with boundary conditions provided by the catchment model and the climate model. High frequency water quality and meteorological monitoring data are available from a buoy at the center of Lake Rotorua. Simulated output compares favourably with high frequency observations of temperature, dissolved oxygen and chlorophyll fluorescence with correlation coefficient values greater than 0.85, while routine observations of total phosphorus, total nitrogen and suspended sediment concentrations are also reproduced well in model simulations. The water quality submodel (CAEDYM) was also coupled with the 3-D hydrodynamic model (ELCOM) to specifically focus on spatial variations in water quality associated with the 99 spatially discrete surface water and groundwater inflows that were assigned as boundary conditions. The most significant spatial variation was due to a turbid geothermal inflow in the south part of the lake. Increasing air temperature, reflecting a climate change scenario, has a small influence on both simulated discharge and loads from the catchment model and on the simulated frequency of stratification events in the lake. Lake Rotorua generally becomes stratified when wind speed are less than 3 m s^{-1}, suggesting that any alternations in wind speed with climate change have the potential to have the most significant impact on lake water quality. These events result in oxygen depletion of bottom waters and favour phosphorus and ammonium releases from the bottom sediments.

TH03

TURBULENCE IN THE BENTHIC BOUNDARY LAYER AND ITS INFLUENCE ON SEDIMENT-WATER FLUXES

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Turbulent fluxes at the sediment-water interface often play a critical limiting role in chemical and biological processes in the benthic boundary layer (BBL). The role of turbulence in these processes has seen only basic research with little attention paid to the structure and intensity of the turbulence. Adapting the Random Synthetic Jet Array Stirred Turbulence Tank of Variano and Cowen (2008, Journal Fluid Mechanics, Accepted) to a smaller chamber commonly used in sediment oxygen demand studies (2007, Journal of Environmental Engineering,133) more realistic levels and turbulence structure are applied to the study of processes at the sediment-water interface. Velocity data collected in the BBL of a medium sized, dimictic lake during the late stratified season using acoustic velocimetry indicates baroclinic forcing is the main driver of the mean currents. Velocity data from multiple ADVs is processed for direct calculation of turbulent quantities, including TKE, Reynolds stresses, and dissipation.The bed shear stress and friction velocity are directly calculated from these measurements. A high-resolution Doppler profiler was co-located with the ADVs for a portion of the measurement period and provides indirect estimates of dissipation by fitting the mean profile to Prandtl□s smooth wall boundary layer model in a least squares sense. The friction velocity, u*, is the fit parameter and bed stress and dissipation are calculated from this using standard formulations. The comparison between these two instruments and measurement techniques is overall very good, with excellent agreement in the mean and very good agreement when examining bed stress and dissipation. The field measurements are used to calibrate a small sediment chamber (~12 cm diameter with ~12 cm of water above the bed) where turbulence is generated by a quasi-random array of jets. Despite the limitations of the sediment chamber, namely the restriction to peristaltic pumps with a relatively slow response time due to the chemistry being studied, the chamber design is shown to be a fundamental step forward in studying turbulence effects on chemical and biological processes over the single, always on jet used by Beutel et al. to generate turbulence.

TH04

ARCTIC LAKES ARE SEIVES: WILL CLIMATE WARMING CLOSE THE PORES?

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Ten years of high frequency temperature data obtained in lakes at the Arctic Long Term Ecological Research (LTER) site have been analyzed to show changes in heat content, Lake numbers, L_N, and eddy diffusivities, K_z. L_N indicates the degree of instability of the internal wave field and is inversely proportional to eddy diffusivity. Large stratified lakes have lower L_N than small ones and greater connectivity between the epilimnion and hypolimnion. L_N in small lakes (1.6 ha) also indicate unstable waves occur. K_z in arctic lakes increase during low L_N events to values 10 to 1000 times molecular diffusivity. Our ten-year time series captured a warm period at the beginning of the record, several years of cold, and now a trend of increasing heat content. Lake numbers are trending upwards such that K_z is near molecular values for longer periods of time. Processes such as remineralization, which increase the specific conductivity in the lower water column, will increase upward trends in Lake number. Further, increased remineralization in near bottom waters under the ice increases density in the lower water column and reduces the potential for mixing by penetrative convection. Instead, mixing is driven by wind forcing of internal waves. Mixing after ice off in small, arctic lakes with their limited fetch may be incomplete. The limited mixing in these lakes has consequences for biogeochemical cycling.

TH05

PHYSICAL TRANSPORT MECHANICS OF SUB-ARCTIC LAKE LAGARFLJÓT, ICELAND

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Air temperature, rainfall and glacial runoff are predicted to increase in the coming years as a result of global warming. This will affect the physical behaviour of natural water systems, in particular lakes' thermal response and river inflow dynamics. Consequently, the fate and transport of materials in natural water system may change. Therefore, it is important to better understand current physical transport processes in order to predict future response to global warming.

This paper characterizes the physical mechanisms affecting the fate and transport of dissolved and particulate matter in sub-arctic Lake Lagarfljót, one of Iceland's largest and deepest lakes. Lake temperature and suspended sediment records monitored for the National Power Company over the past decade are analyzed in order to better understand lake stratification behaviour, differential heating and cooling, wind generated seiches, and glacial river inflow dynamics.

Results show that despite low summer temperatures and strong winds, the sub-arctic lake exhibits interesting density driven behaviour which differs from previously studied lakes at lower latitudes. Temperature measurements show that the lake stratifies weekly for a short 2-month period in late summer. Once stratified, winds may generate unusually slow internal seiches with periods of 4-8 days which are vital to stirring up materials at the bottom of the lake. This stirring is amplified by sediment rich plunging inflow. In wintertime when the lake is not stratified, river inflows have less sediment loads and may enter the lake at the surface. Lastly, differential heating and cooling may contribute to significant lateral transport from littoral to pelagic regions of the lake.

TH06

LINKING PHYSICAL FORCING AND PHYTOPLANKTON COMMUNITY STRUCTURE: DOES CELL SIZE MATTER?

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Vertical mixing is one of the key variables that conditions the growth performance of individual phytoplankton species within the water column as mixing processes are usually accompanied by changes in resource availability of light and nutrients. Modification of the balance between stratification and mixing due to long-term climatic change is expected to alter phytoplankton size structure. The present contribution illustrates that intensified stratification in Lake Tahoe over the last decades is associated with a floristic shift towards small-sized algal cells, which likely affected ecosystem functioning. Increasing vertical density stratification altered the size structure of diatoms, a key phytoplankton group in this lake. Especially smaller-sized diatoms were associated with increasing stability, while large-sized cells were favored under stronger vertical mixing conditions. This suggests that less turbulence provides a competitive advantage for small-sized cells over large-sized cells. Small centric planktonic diatoms with rapid growth rates have become dominant enough to reduce average cell size within this functional group. An empirical model showed that a shift in phytoplankton species composition and cell size was consistent within different depth strata, indicating that altering nutrient concentrations were not responsible for the change. In addition to diatoms, picophytoplankton contribute to a substantial portion of primary production in

Lake Tahoe, and exhibit distinct temporal and spatial niche partitioning. Variation in the strength of vertical stratification appears to play a key role in shaping seasonal and vertical distribution of picophytoplankton. The dominant role of autotrophic picoplankton under intensified stratification and the shift in phytoplankton size structure may explain in part the increasing trend in primary productivity in Lake Tahoe. As the thermal stratification of lakes and oceans is strongly linked to climate, the present study indicates that climate warming affects the reorganization of phytoplankton structure and suggests that intensified stratification will favor the expansion of small-sized species.

TH07

SPIRAL EDDIES IN A LARGE STRATIFIED LAKE

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High-resolution satellite images acquired at Lake Tahoe, California-Nevada, USA, have revealed the presence of multiple small-scale eddies on the lake's surface, which are visible in both thermal and sun glitter patterns in the satellite data. The eddies range from 2 – 6 km in scale and have been observed in co-rotating cyclonic groups along density fronts, following wind-driven upwelling events. Surface current velocities indicate rotational periods of approximately 24 hr. Their small scale, predominantly cyclonic rotation, and "cat's-eye" structure suggest that these could be categorized as spiral eddies. Spiral eddies, or "sea spirals", are common sub-mesoscale features on the surface of the world's oceans, having frequently been observed from space in sun glitter patterns and synthetic aperture radar images. However, spiral eddies have not previously been documented in lakes. The dimensions of the eddies observed at Lake Tahoe are consistent with the relative effects of stratification and rotation, with smaller eddies associated with periods of stronger stratification. A time-series of MODIS images shows the generation of a cool-core eddy during a wind-driven upwelling event, its propagation across the lake's surface, and its decay, over a period of 3.5 days. The scale of the spiral eddies, their distribution across the lake's surface, and their general proximity to the shore, as documented by the satellite images, suggest that they play a significant role in the dynamics of Lake Tahoe and in other lakes of similar size. Spiral eddies may be important mechanisms in along-shore and cross-shore transport, dispersion of nutrients and contaminants, and dissipation, storage, and transfer of energy in the surface layer, particularly following wind-driven upwelling events.

TH08

MODELING THE SENSITIVITY OF PRIMARY PRODUCTION TO ENVIRONMENTAL CHANGES IN PERI ALPINE LAKES

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Primary production is a vital link in the cycling of carbon between living organisms and inorganic sources in aquatic systems. Anthropogenic activities in the watersheds of lakes can significantly impact their primary production. Based on numerical simulations, we present two case studies of such anthropogenic impacts: 1) The effects of upstream hydropower operations on primary production in Lake Brienz (BE, Switzerland) and 2) Long-term changes of primary production in Lake Tahoe, (CA, USA).

Case1: Retention in upstream storage dams of Lake Brienz results in modified riverine water and particle discharge patterns, altering the seasonal dynamics of light attenuation in the lake. A numerical model was applied to experimental ^{14}C assimilation rates and *in-situ* light measurements to compare present gross production to gross production under light conditions for a hypothetical situation without upstream hydropower dams. The simulations show that hydropower operations shift particle inputs from summer to winter. As a consequence, such peri-alpine lakes become more turbid during winter and less turbid during summer, influencing the seasonal light regime and subsequently the dynamics of phytoplankton growth. While annual production under 'no-dam' light conditions would remain close to present values, gross production would be about 40% lower in summer but up to 18% higher in winter, indicating a significant seasonal displacement of primary production.

Case 2: Lake Tahoe, in the Sierra Nevada Mountains, at the border of California and Nevada has exhibited increasing primary productivity and decreasing water clarity since the 1960's. To assess these changes, we applied the numerical model (same as for Lake Brienz) to measured in situ carbon assimilation rates over 17 years (1970-2004). Monte Carlo simulations indicate that our model predicts annual areal primary production with an accuracy of ~10%. Since 1987 primary production has increased by ~66%, mainly in the top 50 m of the lake with maximum growth between 20 and 30m depth, resulting in lower water clarity. Hypothetical model calculations with constant water clarity and temperature reveal little effect on production. It is therefore concluded that plankton composition and increasing nutrients supply to the lake have to be responsible for the increase in primary productivity.

TH09

EFFECTS OF CHANGES IN WATER LEVEL ON IN-LAKE PHOSPHORUS CONCENTRATIONS AND PRODUCTIVITY

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Most climate-change models predict changes in precipitation and evaporation, which in turn may affect runoff. Changes in precipitation, evaporation, and runoff may cause either long-term changes or increased variability in the hydrology and water levels of lakes, especially lakes not controlled by outlet structures. Water-level changes are expected to be largest in closed-basin lakes. To determine how changes in water level affect lakes, we examined two relatively pristine, closed-basin lakes in northern Wisconsin: a seepage lake and a terminal lake with tributaries. Both lakes have undergone large changes in water level over the past 10–20 years. The hydrology of the seepage lake is dominated by precipitation and inflow and outflow of ground water, whereas the terminal lake is dominated by precipitation and tributary input. The differences in hydrology resulted in relatively large differences in the loading to and water quality of these lakes. Changes in the water level of the seepage lake, being primarily controlled by changes in precipitation, was associated with small changes in phosphorus loading, and resulted in small changes in in-lake phosphorus concentrations and productivity. Changes in the water level of the terminal lake, being primarily controlled by tributary loading, was associated with large changes in phosphorus loading, and resulted in large changes in in-lake phosphorus concentrations and productivity. Changes in tributary loading were sufficient to cause the terminal lake to change from being oligotrophic during low lake levels to being almost eutrophic during high lake levels, whereas the changes in the seepage lake were less dramatic with the lake approaching mesotrophic conditions only after prolonged high water. Numerical eutrophication models accurately predicted the small changes in the seepage lake associated with small changes in loading and the changes in water quality associated with prolonged changes in water levels in the terminal lake; however, the models over-predicted the interannual variability in the water quality of the terminal lake because the lake had not reached a new equilibrium state. Results of this study demonstrate that hydrological affects of climatic change may not only affect the physical properties of lakes but also their chemistry and productivity.

DINNER SPEAKER CHARLES R. GOLDMAN

Distinguished Professor of Limnology, Department of Environmental Science and Policy, University of California, Davis, Davis, CA; USA

Biosketch of Charles R. Goldman

Charles R. Goldman, Distinguished Professor of Limnology in the Department of Environmental Science and Policy, has been with the University of California, Davis, since 1958. He developed the first courses in limnology and oceanography at UC Davis, served as Chair of the Division of Environmental Studies from 1988-1992, and was founding Director of the Institute of Ecology, serving from 1966-1969 and again in 1990-92. Prior to his 50-year tenure at UC Davis, he earned Bachelor and Masters degrees from the University of Illinois and a Ph.D. in Limnology-Fisheries from the University of Michigan. He has supervised 100 graduate students and 32 postdoctoral researchers during his nearly five decades at UC Davis. Professor Goldman's many prestigious awards include an NSF Senior Postdoctoral Fellowship in 1964 for limnological research in the Arctic (Lapland), a Guggenheim Fellowship in northern Italy in 1965, the "Goldman Glacier" in Antarctica named in 1967, served as President of the American Society of Limnology and Oceanography in 1967-68, awarded the Antarctic Service Medal by Congress in 1968, and elected a Fellow by the California Academy of Sciences in 1969. In 1973-74, he was elected Vice President of the Ecological Society of America, and accepted a Fulbright Distinguished Professorship to Yugoslavia in 1985. He was awarded the Vollenweider Lectureship in Canada in 1989, the Chevron Conservation Award and Culver Man-of-the Year in 1991, the Earle A. Chiles Award in 1992, the UC Davis Distinguished Public Service & Research Lecturer awards in 1993, the inaugural UC Davis Distinguished Graduate Mentoring Award in 2002, the Nevada Medal and UC Davis Distinguished Professor in 2003, and the American Society of Limnology and Oceanography's Alfred Redfield Lifetime Achievement Award in 2004. He was elected Vice President of the International Society of Limnology (SIL) for 1992-98, presented the prestigious Baldi Lecture at the triennial SIL Congress in Ireland in August 1998, and currently serves as an elected national representative to the world body. He was appointed the inaugural President of the World Water and Climate Network in 2003. Dr. Goldman has published four books and over 400 scientific articles, and has produced four documentary films that are in worldwide distribution. He has served on many national and international committees and is frequently sought for consultation and research missions to foreign countries on major environmental problems. In 1990 he was a member of a UNESCO team to qualify Lake Baikal as an International Heritage Lake and Senior Scientist for the National Geographic Baikal project. His single most important and sustained contribution is the four decades of research on Lake Tahoe. Professor Goldman is Director of the Tahoe Research Group and has pursued long-term ecological research simultaneously at Lake Tahoe and Castle Lake, California, since 1958.

He successfully combined effective research and social action with his pioneering studies of lake eutrophication. These have been directly applied to engineering solutions, social needs, and legal decisions. This work has recently included the development of artificial wetlands and research on alternatives to conventional road salt for deicing highways. This relationship of basic science to political change has been of particular importance to the Lake Tahoe basin. During the summer of 1997, Dr. Goldman hosted President Clinton and Vice President Gore aboard the UC Davis research vessel *John Le Conte* during the Lake Tahoe Presidential Forum. Similar studies have extended Dr. Goldman's research-social action efforts to analysis of lakes like Baikal in Russia and hydroelectric impoundments throughout the world. Thus, while aggressively pursuing basic research on lake dynamics, he has also been able to translate the findings directly to state, national and international policy decisions, contributing decisively to the conservation and judicious use of aquatic resources from the Antarctic to the lakes and wetlands of South and Central America, New Guinea, Africa, Asia, Europe and the United States. Professor Goldman's career work has been honored with a most prestigious award: the 1998 Albert Einstein World Award of Science, presented at a formal international ceremony held in New Zealand. The Einstein Award, bestowed annually to a single individual by a council of eminent scientists that includes 25 Nobel laureates, recognizes those who have accomplished scientific and technological achievements that have advanced scientific understanding and benefited humanity.

F KEYNOTE

MIXING, STRAINING AND MIGRATION IN THE FORMATION AND MAINTENANCE OF THIN LAYERS OF BIOLOGICAL ACTIVITY IN THE COASTAL OCEAN

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Over the past decade, the use of high-resolution fluorometers in the coastal ocean has exposed the presence of thin layers of high biological activity. These layers have vertical lengthscales of 10s of centimeters to meters, but extend broadly in the horizontal directions and persist for hours or days. In the summers of 2005 and 2006, through ONR's Layered Organization of the Coastal Ocean (LOCO) program, I have pursued detailed observations to understand the physical and biological processes responsible for forming and maintaining the observed layers.

Our observations, as well as previous studies of thin layers, indicate that layers are not necessarily associated with low levels of turbulent mixing, which has sometimes been assumed. Instead, layers are associated with regions of moderate mixing, or in transition regions between high and low turbulent levels. As a result, for a layer to be persistent in time and space, the diffusive effects of turbulent mixing must be counteracted by a convergence mechanism. Considering balances between turbulent diffusion and candidate convergence mechanisms, including straining, settling and swimming, I will present a framework that allows steady-state layer thicknesses to be estimated.

Finally, I will present a detailed analysis of layers observed in Monterey Bay in the summers of 2005 and 2006. During these periods, diurnal migration patterns led to the formation of nighttime layers, which were frequently associated with intruding low-salinity water masses. Turbulence microstructure measurements, collected from the same profiling package as the fluorescence, are used to calculate turbulent fluxes throughout the water column. The resulting turbulent diffusivities are then combined with the fluorescence measurements in a one-dimensional vertical analysis to infer migration rates. The results suggest that during the formation of the layer, migration is occurring at nearly the maximum swimming rates observed in laboratory settings for the species present. After formation is complete, however, the layer is maintained by a reduced swimming rate, suggesting a less directed migration, but sufficient to counteract turbulent mixing.

Biosketch of Mark T. Stacey

EDUCATION:

1991	B.A.S.	*Stanford University* Dual degree in Physics and Political Science
1993	M.S.	*Civil Engineering, Stanford University* Environmental Fluid Mechanics and Hydrology
1996	Ph.D.	*Civil Engineering, Stanford University* Environmental Fluid Mechanics and Hydrology

ACADEMIC EXPERIENCE:

7/04-Present	**Associate Professor**, Civil & Environmental Engineering, UC-Berkeley
7/99-6/04	**Assistant Professor**, Civil & Environmental Engineering, UC-Berkeley
1/99-6/99	**Assistant Research Engineer and Lecturer**, Civil and Environmental Engineering Department, UC-Berkeley
4/97-12/98	**Post-Doctoral Scholar**, Integrative Biology Dept., UC-Berkeley

HONORS AND AWARDS:

1987	Jordan Scholar, Stanford University
2001	NSF CAREER Award
2002	Distinguished Teaching Award Finalist, UC-Berkeley
2004	"Best Professor" Award, ASCE Student Chapter, UC-Berkeley

RECENT PUBLICATIONS:

Stacey, M.T., Fram, J.P. and Chow, F.K. "The role of tidally periodic stratification in the creation of estuarine subtidal circulation," *Journal of Geophysical Research*, v.113, Article C08016.

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Stacey, M.T. and Ralston, D.K., "The Scaling and Structure of the Estuarine Bottom Boundary Layer," Journal of Physical Oceanography, V.35(1), pp. 55-71, 2005.

F01

NUMERICAL SIMULATIONS AND EXPERIMENTAL MEASUREMENTS OF THE HYDRODYNAMIC FIELDS IN THE STAGNONE LAGOON

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The “Stagnone di Marsala” is a small coastal lagoon of great naturalistic relevance in the Mediterranean area due to the peculiarity of several local vegetation and animal species. The lagoon is currently undergoing a degenerative process, due to the progressive reduction of the water volume exchanges with the open sea. During last decade a number of field surveys have been carried out, aimed to understand the lagoon hydrodynamics and to plan possible actions to prevent the loss of the local species. In this paper, the results of numerical simulations of the hydrodynamic fields in the lagoon are compared with experimental measurements of velocities and water levels. Measurements are carried out in several places using both acoustic-doppler and electromagnetic anemometers. The simulations are performed using a three-dimensional non-hydrostatic numerical model based on the finite-volume method, in order to discretize the Reynolds-averaged momentum and mass balance differential equations. The numerical model, which is second-order accurate both in time and space, employs the k-ε model to represent the turbulent Reynolds stresses. Since the shallowness of the lagoon (the mean water depth is about 1.1 m) the bottom roughness has a significant impact on the water currents. Since the roughness distribution is mainly dependent on the type and densities of vegetation on the bottom, it has been obtained by means of airborne remotely sensed multispectral images analysis. The importance of accounting for the effective distribution of the bottom roughness is highlighted by comparing the results obtained using a constant and a space-dependent roughness distribution. The effect of the wind stress acting on the water surface and those of the tidal motion on the water currents are separately analysed, in order to identify the relative contribution of these forcing phenomena.

F02

A COMPARISON OF PARAMETERIZATION AND SIMULATION SCHEMES OF TURBULENT MIXING IN THE GULF OF FINLAND, THE BALTIC SEA

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We carried out a comparative study of different Richardson number based eddy diffusivity parameterization schemes as well as simulations derived from the two equation k-ε turbulence closure (General Ocean Turbulence Model, GOTM) with "measured" eddy diffusivities. For two out of the three measured time series eddy diffusivities calculated via a Richardson number based parameterization and via simulation using the k-ε model agreed well with the experimental data. However, in the case of relatively high current velocity shear and weak background density stratification both applied methods resulted in a marked discrepancy against the measured eddy diffusivity. Therefore we introduced a new parameterization scheme which is based on the super-inertial band of internal wave kinetic energy density. Calculations with the new parameterization scheme fitted well for all the three time series. Also the modified k-ε simulations where we substituted the commonly used constant turbulent kinetic energy minimum value by a time varying function of the super-inertial band internal wave kinetic energy density matched better to the measured profiles.

F03

SIMULATIONS OF BAROTROPIC AND BAROCLINIC BALTIC SEA INFLOWS

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The aim of the present study is to simulate qualitatively salt water inflows from the North Sea into the Baltic Sea which may be reaching the Gotland Deep with the GETM (http://getm.eu) hydrodynamical model. Specifically we test the influence of different model settings, different initial conditions and of a variety of forcing conditions on the occurrences of baroclinic salt water inflows. The model area covers the whole Baltic Sea and North Sea, therefore no prescribed barotropic sealevel forcing in the Kattegat area is applied. Initial conditions and 3D boundary conditions are derived from climatological data. The tidal forcing at the open boundaries in the English channel and at the open North Sea are constructed from 13 partial tides taken from the TOPEX/POSEIDON harmonical tide analysis. Relatively coarse meteorological forcing available from ECMWF data was used. Despite of that coarse spatial resolution the main features of the inflow dynamics could be reproduced. For the river inflow we used climatological data for the 30 most important rivers within the model area. First we compare our results for the transition area to water level data and to salinity measurements at selected stations to show that the main characteristics of bottom and surface salinity are most of the time simulated sufficiently well. Further we are able to show, that for the larger events the inflowing salt water from the Belt Sea is progressing until it reaches the Gotland Deep. Finally we compare some of the modeled scenarios of the 2002 and 2003 inflows with measured data. From that we try to identify the most important necessary conditions that allow salt water inflows to occur and we try to better assess the range of uncertainty.

F04

EFFECTS OF SEASONAL STRATIFICATION ON NUTRIENT RETENTION IN A COASTAL LAGOON WITH HARMFUL CYANOBACTERIAL BLOOMS

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Excess nutrient supply is a common cause of eutrophication in coastal waters, where hydrodynamics strongly modulate the relationship between nutrient loading and productivity. This study addresses the physical processes that lead to nutrient retention, and subsequently harmful algae blooms, in a shallow, tidally choked, coastal lagoon. The project site, Rodeo Lagoon, is located in the Golden Gate National Recreation Area, California, and experiences intense blooms of the cyanobacteria *Nodularia spumigena* and *Microcystis aeruginosa.* Monthly transects of the lagoon taken over a span of more than two years show it is stratified by salt in winter, when freshwater inputs from the watershed and saltwater inputs from storm surge are both largest. In addition to monthly water quality monitoring via transects and grab samples, the study included several comprehensive, multi-week field observations of lagoon hydrodynamics contrasting turbulent mixing parameters under stratified winter conditions with well-mixed summer conditions. Wind is the dominant source of mixing, leading to the expectation of well-mixed conditions for this shallow site, where water depths are typically on the order of two meters. However, strong density gradients can seasonally reduce vertical turbulent exchange of nutrients throughout the water column. The phasing of salt-based stratification means that annual losses of nutrients via flushing are diminished in comparison to a well-mixed scenario.

F05

EAWAG EDDY CORRELATION STATE OF THE ART - SYNOPSIS OF LESSONS LEARNED IN FIVE YEARS

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Five years have passed since we first built our eddy correlation (EC) device for measuring turbulent oxygen fluxes over lacustrine sediment. We have now deployed our device many times in two different settings; a seiche-driven, prealpine lake and in a riverine reservoir; both with promising results. In the riverine reservoir, we collected an ~38 hour data set that clearly demonstrated the benthic DO production and consumption cycle. These EC DO fluxes compare well (within 10%) with those estimated from in-situ sediment microprofiles. During a later test, we conducted the first ever comparison of two simultaneously deployed and similar EC devices. The estimated DO fluxes showed that both signals have the same reaction in terms of oxygen consumption and production. Our tests in a seiche-driven lake were also promising, and demonstrated the periodic physical forcing of sediment oxygen uptake. Last year, we also obtained our first results using a fast temperature sensor (FP07; response time ~7 ms) simultaneously with the oxygen electrode in the same seiche-driven lake.

We continually strive to improve our EC device and analysis through laboratory and field tests and on-going modifications. Enhancements include sensor calibration and drift tests, response time tests, as well as background noise analyses. We now feel that we have gained considerable confidence both collecting and analysing EC data. We apply time lag corrections, appropriate detrending methods, spectral analysis and spectral enhancement as powerful tools to process and interpret eddy flux data. *A priori* investigations of the hydrodynamics of the selected system (expected eddy time scales) can help to identify hardware requirements. In this presentation, we will detail our developing EC protocol which will hopefully aid in determining hardware requirements (i.e. response time, sampling frequency) as well as data analysis and interpretation. We will highlight some of our more interesting results from various measurement campaigns, and share lessons we have learned along the way in terms of design, deployments and data processing. We hope to establish a comprehensible guideline of how to use the technique for a broad range of potential users and applications.

F06

SPATIAL AND METHODOLOGICAL VARIABILITY OF VERTICAL EDDY DIFFUSIVITY (K_Z) MEASUREMENTS IN A SMALL, TEMPERATE LAKE

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Result are reported of a project whose aims were (i) to compare values of vertical turbulent eddy diffusivity (K_Z) measured using four different techniques; and (ii) to determine the spatial variability of K_Z profiles within Esthwaite Water, a small lake in NW England. The four techniques compared were: the "heat budget" method of Jassby & Powell (1975, *Limnology and Oceanography* 20), which derives basin-wide average hypolimnetic values of K_Z from thermistor chain data; the "wind" method of Wüest et al (2000, *Limnology and Oceanography* 45), which estimates basin-average K_Z values from wind speed and stratification data alone; fitting Batchelor spectra to power spectra of microprofiler (SCAMP) thermal data; and finally using profiles of the concentration of Radon-222 emitted from the lake bed. Our results show that the optimum choice of method depends on what data are available, the scales for which the K_Z values are required, and the conditions in which data are required. Thus, we recommend (1) using the heat budget method where temporally-resolved, whole-lake vertical mixing rates are required and where continuous thermal profile data is available; (2) where spatial resolution is important, SCAMP must be used, but this requires significant temporal averaging; (3) in isothermal conditions, the radon method must be used, but this is only viable where there is a sufficient radon flux, and for near-bed depths; and (4) the wind method will provide depth-integrated average value for the hypolimnion. We also use SCAMP data to identify the spatial variability of K_Z values across the lake. We derive, from the K_Z values, time scales for turbulent mixing of material from the lake bed to the surface. We find that this time scale reaches its maximum values at locations in the lake where the depth is intermediate – in between shallow areas, where the water column is well-mixed and the deepest areas of the lake, which are also the most exposed, and are thus where wind-related and internal mixing mechanisms are at their most energetic.

F07

EVALUATION OF THE THORPE SCALE METHOD FOR ESTIMATING DISSIPATION OF TURBULENT KINETIC ENERGY

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Some researchers in oceanography and limnology use the Thorpe scale to derive estimates of the dissipation of turbulent kinetic energy and thus the eddy diffusivity. This method requires a constant value of the turbulent Froude number, or the ratio of the Thorpe and Ozmidov scales. Dillon (1982) used measurements in the interior of windforced surface mixing layers and the seasonal thermocline to show that LO = 0.8LT (or FrT= 0.86), but he warned that his result might hold only for weak forcing. In previous laboratory experiments on stratified grid turbulence with and without shear, the turbulent Froude number varies from 0.5 to 20; in fact, the Thorpe scale method can underestimate the dissipation by more than an order of magnitude when the Cox number is large. Furthermore, measurements in lakes (Imberger and Ivey 1991) show that a turbulent Froude number of the assumed value of 0.86 is a lower bound for the processes such as wind mixing, intrusion formation, hypolimnetic mixing, and boundary mixing. We add to the evaluation of the Thorpe scale method by comparing dissipation estimates from temperature microstructure and Thorpe scales. The dissipation from the microstructure measurements is computed from a Batchelor fit to the spectrum of the fluctuating temperature gradient, while the Thorpe scale is calculated using the same temperature signal (with noise reduction) and the constant Froude number assumption. We also use synthetic signals in which the dissipation is specified to evaluate the method and provide guidance for determining when the estimates from Thorpe scale method match those from microstructure.

F08

MIXING DYNAMICS WITHIN A TURBID BOTTOM BOUNDARY LAYER

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Mixing dynamics within a turbid bottom boundary layer in a littoral zone of the Mediterranean Sea is analyzed. Data were taken in June 2004 with a microstructure free falling profiler. Mesoscale dynamics in the region was influenced by the outflow of Ebre River and by the southwestern Catalan Current originated in the Gulf of Genova. The magnitude of the near bottom current was 5-8 cm/s and the flow was affected by inertial oscillations. During the whole field campaign, the wind of ~ 6 m/s was from the northeast. The mean depth of the upper mixed layer was about 15 m, the thermocline occupied the depth range between 15 and 30 m, and the thickness of the turbid bottom boundary layer varied from 8 to 12 m. Different stations ranged from 15 to 60 m depth.

Thorpe displacement, *Th,* was used to determine the turbulent patches and in general, Th_{max} within the patches and the Thorpe scale, *LTh,* were found to be highly correlated and linearly dependent: $Th_{max}= 2.6LTh$. If Th_{max} and *LTh* were calculated at equal-distance segments of the profiles, then $Thmax \sim LTh^{0.85}$. Within the bottom layer turbulent patches were found to affect 35% of the total depth of the layer. The median size of the patches was 41 cm and their median buoyancy Reynolds number was 252.

State of the turbulence within the bottom layer is discussed based on the turbulent Reynolds and the turbulent Froude numbers. According to the hydrodynamic diagram and the vertical profiles of the turbulent kinetic energy dissipation rate, different zones are identified, including an upper interface where Kelvin-Helmholtz instability is developed. Different structure of the turbidity profiles depending on the stations is related to the different mixing dynamics. Mean turbulent diffusivity of the turbid layer was obtained following Osborn approach and found to be 2 x 10^{-5} m^2/s.