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MATHEMATICAL MODELLING OF FLOW AND TRANSPORT AS LINK TO IMPACTS IN MULTI-DISCIPLINE ENVIRONMENTS

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Abstract

Examples of numerical modelling of surface water hydrodynamics and water quality are presented. Their meaning for the development of the EIA 3D model system is analyzed from the almost 70 tracer studies (mainly 1971–1974) until the 3-dimensional (3D) solutions which became dominant since 1982. Up to summer 2008, the number of 3D applications has increased to almost 230 while the number of all applications exceeds 300.

The specific applications considered are from: Porttipahta reservoir in Northern Finland (I), Porttipahta and Lokka reservoirs (II), combination of reservoirs, lake, river sections, Kemi estuary and the sea (III), Kemi estuary and other coastal applications in the Gulf of Bothnia (IV), Lake Haukivesi in Eastern Finland (V), Lake Näsiselkä in South-West Central Finland (VI), and Kymi River and Kotka estuary in Southern Finland (VII).

A detailed description of the 3D model system is given in the application of Näsiselkä (VI). It is completed with drastically changing water levels, drying and wetting of immersed areas, characteristics of pulsing system, and internal loading in the application of Porttipahta (I). The application of the Kymi River and Kotka estuary (VII) shows the sensitivity of tracers as transport indicators and the validity of the transport model. In Lokka and Porttipahta (II) the methods of validity tests are extended to include field tests, laboratory experiments, and comparisons with expert evaluations and analytical solutions.

A strong indication of model validity is obtained in Näsiselkä (VI). When the loading after the model work was changed according to a plan included in the computation, the observed changes of water quality corresponded closely with those predicted by the model. Another severe indication of the model validity is from Porttipahta and Lokka (I, II). With the parameter values based on data from 1967–1986, a recent application indicated a close agreement with the observed data from 2000–2006. In Haukivesi (V) and Näsiselkä (VI) the agreement between the model and observed results is extended to the biological indicators of the algal biomass.

The integrated application to the network of a planned and two existing reservoirs, a strongly regulated lake, river sections, Kemi estuary and the sea (III) shows the usability of the model system to all types of water bodies. As a practical result it highlights the decay of the effects of a new impoundment with time and distance, including fast dilution in the estuary and the sea.

Keywords: ecology, hydraulics, hydrodynamics, mathematical modelling, models; modeling, three-dimensional, transport, water quality
Acknowledgements

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The countless number of co-operation institutes, colleagues, co-authors and field staff, customers and other supervising and funding organizations are thanked for the causes, possibilities, specification, interaction, background information, data and requirements of the application and development work. In a special position among them, are Kemijoki Oy and the Regional Environment Centre (REC) of Lapland as the initiators and enablers of the largest single model effort. Many other REC’s and formerly the Finnish Environment Institute have also had a central role in the arrangement and organization of the local model applications. Applications of the coastal areas of the Gulf of Bothnia were contributed by North-Ostrobothnia, West Finland, Southwest Finland and Central Finland REC, Lake Näsiselkä by Pirkanmaa REC, Kymi River and Kotka estuary by Southeast Finland REC, and Lake Haukivesi by South-Savo REC who provided there the most excellent, fluent and comprehensive data supply and work administration.

The supervisors of this study are thanked for their provocation and stimulus of the work, for their advice, interest, suggestions and encouragement. Prof. Björn Klöve is thanked for his constructive, judicious and supportive discussions and supply of office staff for the formal finalisation of the work, Prof. Erkki Alasaarela for his initiation, persuasion and forcing of the work, for his imperative pressing and practical requests and his help to keep things going and for his long co-operation since the middle of the 1970’s. Finally, Dr Seppo Hellsten is thanked for his support and encouragement, for his constructive and judicious discussions, and for the friendliest, forbearing, favourable, sincere and tight co-operation relations since the 1980’s. The financial support of EnviroNet, the joint graduate school of the University of Oulu, Thule Institute and NorNet, for the finalization of the work is acknowledged.

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Markku Virtanen
Used abbreviations and symbols

a  constant ~ 20 (in eq. 15)
A  the total amount of tracer found in a survey after release (GBq)
Ao  the total amount of tracer released into the water (GBq)
A.D.  Anno Domini, according to the present chronology of years
AISH Association Internationale des Sciences Hydrologiques (= IAHS)
a.s.l  above (the average or other reference) sea level
b  constant ~ 0.63 (in eq. 17)
B  lateral, width dimension (in connection of D), river width, breadth
B.C.  before the start year of the present calendar or chronology of years
BESK Binär Elektronisk SekvensKalkulator (= Binary Electronic Sequence Calculator, in Swedish)
BIL  Binary Inter-Leaved (format), Band Interleaved by Line
BMW Benchmark Models for Water Framework Directive (EU project)
BOD  biological oxygen demand (mg/l)
c  concentration (or strength of a quantity) (e.g. mg/l)
c_i(t)  concentration at point i at the moment t
C_o  initial (mean or steady-state) concentration injected at time t_o into the water
c_i(t)  concentration at the injection point at the moment t
D  -dimensional (preceded with a number, possibly followed by a letter)
d  differential operator for derivation or integration
DEM  digital elevation map
DHI  Danish Hydraulic Institute
dt  infinitesimal difference of time
DTPA  diethylene triamine penta-acetic acid
dx  infinitesimal difference in longitudinal x-direction
dy  infinitesimal difference in transversal y-direction
dz  infinitesimal difference in vertical z-direction
e  superposition of Ekman drift estimate to vertical average (with D)
E  efficiency of radiation detector ((Bq/l)/(counts/s))
EIA  Environmental Impact Assessment Centre of Finland Ltd.
EIA Ltd  EIA
ENIAC  Electronic Numerical Integrator And Computer
\( \epsilon \)  dissipation rate of turbulent kinetic energy, energy cascade rate (m^2/s^3)
EU  Union of 27 West European states
EUREKA  European network for market-oriented research and development
exp  exponent function
FIRM  Finnish Institute of Marine Research
g  acceleration caused by gravity
G  count rate detected by radiation detector (counts/s)
GIS  geographical information system
H  horizontal (Length x Width, in connection of D), water depth
HN  hydrodynamisch-numerisch (= hydrodynamic-numerical in German)
HUT  Helsinki University of Technology
i  impermeable interface, isolated layer (in connection with D), place index
I  the surface slope
IAEA  International Atomic Energy Agency
IAHS  International Association of Hydrological Sciences
IBM  International Business Machines Corp.
ICES  International Council for Exploration of the Sea
IIASA  International Institute for Applied Systems Analysis
k  kinetic energy of turbulent eddies (m²/s²)
K  dispersion coefficient for turbulent mixing (m²/s), \( K = K_0 \left( \frac{L}{L_0} \right)^m \)
KL  longitudinal dispersion coefficient for turbulent mixing (m²/s)
K₀  basic value of dispersion coefficient for the reference length scale \( L_0 \)
KP  transversal dispersion coefficient for turbulent mixing (m²/s)
KV  vertical dispersion coefficient for turbulent mixing (cm²/s)
L  longitudinal, length dimension (in connection with D), length scale
L₀  reference length scale of turbulent mixing (km), \( L = 3 \sqrt[3]{S H^2} \)
lg  Briggs' (10-based) logarithm function, \( \lg(10) = 1, \ \lg(100) = 2, \ \lg(1000) = 3 \)
ln  natural (Naperian, hyperbolic) logarithm function, inverse function of \( \exp \)
ln2  about 0.693147, so that \( \exp\{\ln 2\} = 2 \)
m  exponent for dependence of turbulent dispersion coefficient \( K \) on scale \( L \)
MHQ  mean high flow, average of the yearly maximum flow rates
MNQ  mean low flow, average of the yearly minimum flow rates
MQ  annual mean flow rate (m³/s)
OPCOM  Operational Modelling for Coastal Zone Management (EU project)
OPMOD  Operational Modelling of Coastal Waters and Marginal Seas
p  profile-type (vertical distributions as serial sum of fixed functions)
PC  personal computer
Q  flow rate, both for rivers and wastewater discharges (m³/s, km³/a)
R proportion of other flow influences to flow velocities (= V_o / U_f)
REC Regional Environment Centre
R_i dilution ratio, concentration at point i divided with that at the release point
S influence ratio of flow velocity U_f on transport velocity U_c
S^2 horizontal variance of distribution (m^2), (S^2 = S_x^2 + S_y^2)
S_p^2 transversal variance of distribution across a river
S_x^2 variance of distribution around the centre of gravity in x-direction
S_y^2 variance of distribution around the centre of gravity in y-direction
SIL Societas Internationalis Limnologiae (= International Association of Theoretical and Applied Limnology)
SITRA Finnish National Fund for Research and Development
SMHI Swedish Meteorological and Hydrological Institute
SOD sediment oxygen demand (g/m^2/d)
ss self-similarity (fixed function form for vertical or transversal distributions)
STUK Finnish Radiation and Nuclear Safety Authority
SYKE Finnish Environment Institute
t time
\(t_k\) previous moment for start of integration or other consideration
\(t_{k+1}\) next moment for end of integration or other consideration
\(t_m\) measurement time, moment of measurement
\(t_o\) injection time, moment of injection
T_{0.5} half-life, period during which concentration decays to half
TVD total variance diminishing (numerical method)
u flow velocity component in x-direction
U_c transport (moving) velocity of quantity in water (= V_o + S* U_f)
U_f flow velocity of (ambient) water
u_{max} maximum longitudinal flow velocity of a cross-section in river
v V (in connection with D), flow velocity component in y-direction
V vertical, depth dimension (in connection with D)
V_o other (own) velocity contribution to transport U_c in addition to flow U_f
va non-hydrostatic inclusion of vertical acceleration (with D)
VISIMAR Visualization and Simulation of Marine Environmental Processes
VTT Technical Research Centre of Finland
w flow velocity component in vertical z-direction
WFD Water Framework Directive
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>x</td>
<td>principal co-ordinate axis, usually to East, or along length dimension</td>
</tr>
<tr>
<td>$x_c$</td>
<td>location of the centre of gravity of a distribution in x-direction</td>
</tr>
<tr>
<td>$x_m$</td>
<td>location of measurement point in x-direction</td>
</tr>
<tr>
<td>y</td>
<td>co-ordinate axis counter-clockwise perpendicular to x, usually to North</td>
</tr>
<tr>
<td>$y_c$</td>
<td>location of the centre of gravity of a distribution in y-direction</td>
</tr>
<tr>
<td>$y_m$</td>
<td>location of measurement point in y-direction</td>
</tr>
<tr>
<td>YVY</td>
<td>Community Water and Environment (SITRA project)</td>
</tr>
<tr>
<td>z</td>
<td>vertical co-ordinate axis, positive upwards</td>
</tr>
<tr>
<td>$z_c$</td>
<td>location of the centre of gravity of a distribution in z-direction</td>
</tr>
<tr>
<td>$z_m$</td>
<td>location of measurement point in z-direction</td>
</tr>
</tbody>
</table>
List of included publications


The present report synthesizes the above original papers which are referred to by their Roman numerals I–VII. The order of the papers is determined by the geographical locations of the application areas from North to South. All the Papers I–VII have formally been referred and accepted for publication by the peer review process. Some of them have also been edited to some extent by the editors of the journals, series or books.

Contribution of the present author and roles of papers in the composition are characterized as follows:

I explains the basic structure and results of the most advanced three-dimensional (3D) model system developed for the calculation of the strongly
regulated reservoirs. The work is based on the original suggestions of flood pulse
and loading dynamics by Kari Kinnunen together with the ideas and experience of
the multidimensional flow and water quality modelling by the present author and
Jorma Koponen. Olli Nenonen supplied to the work deep basic information and
most fluent practical arrangements. Seppo Hellsten was responsible for the
biological, bio-geo-chemical and ecological aspects and understanding, and the
plans, arrangement and interpretation of the field tests, sampling and laboratory
analyses. The role of the present author was the research leader, contribution to the
model applications, participation in the field campaigns, and writing the project
and model descriptions to the paper.

II combines the different ways to test the model validity. The role of the
present author was the research leader, outline and search for the possibilities
together with other authors, derivation of the analytical solutions, and check of the
manuscript.

III combines the reservoir models to their effects in the downstream waters.
The role of the present author was the research leader, outline of the combination
of the effects together with other authors, writing the text and plotting the figures,
development and application of the longitudinal transfer model for the river
sections, and participation in the 3D model applications.

IV compares the estuarine and coastal model of III with the earlier
applications of the same area and reviews also the other model applications done
for the coastal areas of the Gulf of Bothnia. Writing of the paper and most of the
model applications are done by the present author.

V extends the model applications to a natural lake and to most successful
simulation of the indicator of algal biomass. The present author is responsible for
the model work, writing and figures, while the most comprehensive set of input
data is from Pertti Manninen and their combined use is made interactively.

VI explains the original structure of the 3D model system and its application
to the simulation of algal biomass where 3D solution was found necessary. The
model and result descriptions are written by, the model work done under the
supervision of, the trunk of the model structure transferred and the way to use the
flow fields for transport calculation developed by the present author. Jorma
Koponen is responsible for the development and application of the model, and
Juha Sarkkula for the flow velocity measurements and project implementation.
Kim Dahlbo is responsible for the bio-geo-chemical data, aspects and
understanding, with contribution to the model applications, interpretation of
results, and writing of the paper, too.

VII presents the role of tracer studies as the most sensitive means to test the
model validity both in the river and estuary. The present author is fully responsible
for the paper.
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1 Introduction

1.1 Purpose and scope of the work

The main purpose of the present work is to summarize the experiences and developments gained in the studies of the transport dynamics in surface waters, their dependencies on water currents and further influences on distribution and strength of the indicators of water quality. Different aspects of work and development are illustrated with examples of case studies that have been published previously. These aforementioned studies are evaluated with regard to their role in development and are supplemented with views taken from current studies.

The main focus of this presentation is directed to the computation of water currents and hydrodynamics as these determine the transport of concentrations and other properties of water and form the basis for transport estimates and results. Computationally their solution is also the most demanding part of the applications. Selections made for their solution determine irreversibly the corresponding limits to the computation of transport and bio-geo-chemical changes of the water quality indicators. For example these include the extent of the model area, its resolution, resolved dimensions, and other approximations.

Despite of the central emphasis of this study being upon hydrodynamics, the methods themselves and their uses belong to and combine contributions from numerous branches of the sciences. The mathematical models used and developed in the work, the interactions taken into account, input data and results belong to the fields of hydrology, meteorology, sedimentology, geology, hydraulics, hydrodynamics, fluid mechanics, oceanography, thermodynamics, form of existence and heat sciences, mechanics, physics, chemistry, biology, microbiology, bio-geo-chemistry, limnology, and water resources.

The development, implementation and model solutions require knowledge of mathematics, applied mathematics, computer sciences, systems analysis, information sciences, communication sciences, illustration, visualization, graphical design, interaction dynamics, and user interface theory. Measurements, on their parts, have also required skills of various techniques and survival skills in relation to nature. The backgrounds and reasons for studies, use of the results and their interpretations extends the disciplines further to botany, zoology, fisheries, physiology; water supply and sewerage, engineering and management techniques, economy, national economy, business economy, society planning; ecology, sociology, health sciences, and national health sciences.
However, any list cannot be described as comprehensive or exhaustive as the definitions and interfaces of scientific disciplines can be vague and varying with time, author and school. The branches of science mentioned above can be compared with those included in limnology (Wentzel 2001) and those attached to discourse within all the leading sciences and technologies since the 1940's (Lyotard 1979): including fonology, linguistics, communication sciences, cybernetics, algebra theories, informatics, computer sciences and their languages, general linguistics and translation theories, data storage and data bank techniques, telematics and paradoxology. It has also been suggested (e.g. Kummu et al. 2006, Kummu 2008) that the hydrological, ecological and socio-economical divisions and sub-branches are only illustrative reflections of the traditions of academic research, while in reality the contents form a continuum from the physical characteristics of water to abstractions of human cognition without clear borders between the different disciplines.

1.2 Structure of the report

In this presentation, a few broad classifications are reviewed for the beginning to specify the scope of the work and its relations to the other possible approaches. After the basic alternatives to obtain information from nature are given, the possible combinations to eliminate dimensions from model solutions are shown. These are followed by a further look at the main possibilities of interpolations, intermediates or transitions between the explicit resolution and full elimination of a space dimension, with main attention given to the approximation of vertical distributions in the horizontal flow velocity fields. Finally, the main possibilities to transfer the flow velocities for transport calculation are briefly reviewed.

To provide background, the historical development of the sciences which form the basis for models is at first briefly surveyed, with the main emphasis upon hydro-physics. Thereafter attention is directed to the origins and first examples of model approaches and to later surveys of model use trying to illustrate the spread of the model applications until the present day. A general view of the model efforts in Finland is accompanied with a more detailed analysis or summary of contributions to the model applications by the author. For comparison, a similar review is presented for the radioisotope tracer studies, which formed the origin and basis for the author’s own model development. Concise remarks on the continuous use of tracer techniques until the present day are attached.
The main characteristics of the applications and the areas considered in the original publications I–VII are summarized. The central features of the main model used in the applications is described quite generally as more detailed mathematical descriptions of the models are included in the original publications. The practice and different steps and stages of the model applications are described in more detail. This is followed by a similar description of the practical arrangements of the radioisotope tracer studies, and completed with description of the different methods for analysis, interpretation and condensation of tracer results, including also their mathematical details.

When analysing the results, main attention is given firstly for the role of the original publications in the model development and then, as a more general summary, the most frequently met general regularities in the model output and experiences. The meaning of the physical processes are analyzed and their relation to the selection of the model structure and determination of the model parameters are discussed. The main benefits and meaning of tracer studies for the original model development is summarized briefly. Based on a discussion of the measurements with regard to evaluation of the validity, usability and reliability of the applications, general aspects and possibilities of validity evaluations are considered. The practical benefits and meaning of the case studies – their use for the evaluation of the acceptability or mutual preference of the tested loading, discharge, regulation, impoundment, construction or other planning alternatives, which have been the original reasons for and the determining purpose of the application – are briefly reviewed before the conclusion of the experiences is given.
2 Alternatives available

2.1 Approaches

Several types of methods and approaches are available for environmental research, for acquisition of information on environment, its state, processes, causal relations and dynamics. These include e.g.

- observations and measurements
- test arrangements, experimental studies
- isolations with possible scale deformations
- analogies with other fields of experience, and
- mathematical descriptions.

The first three of these can also be called empirical approaches while the last two of them are more mental, abstract or conceptual. They all are based on and can contribute to more or less widely accepted theoretical generalizations, and individually to subjective experience which can also be used for future estimates as expert evaluations.

In surface waters there are numerous techniques for observation, measurement and recording of water levels and water currents, their speed and direction. Also many other properties of water can be directly (in situ) measured and recorded, e.g. temperature, electric conductivity and plenty of other ones, especially those with relation to optical or radiation responses. For these also remote sensing can be utilized. Much wider spectrum of water quality indicators can be further analyzed from water samples in laboratories. Conscious look around with eyes has wide range of application possibilities as a way of observation, also without numerical records.

Test arrangements or experimental studies differ from (passively receiving) observations and measurements by their active and intentional, known and restricted forcing, supply of a certain change into some part of the system, and then looking at its responses. Examples of these are tracer studies where known amount of some foreign substance is injected into the water at fixed time and place, and its concentrations are then measured. Compression tests, as another example, put known pressure onto the bottom sediment surface, and measure the released concentrations. Furthermore, in lake-management or bio-manipulation tests some component of the system is tried to remove, isolate or add, and its consequences
are further observed. Removals can be directed to certain fish species, birds or plants, isolation can be coating of bottom with sand or fiber, and supplies can mean chemicals (e.g. lime-stone), oxygen, or planting of vegetation, fish or other animals.

Isolated extractions go further than field experiments in their control of external conditions. Examples of these are physical scale models to study the effects of construction changes or vessel shapes on flow velocities, waves, flow resistance, shear and drag. Measurements of oxygen consumption or nutrient releases from sediment samples under controlled conditions are further examples of isolated extractions. Several types of aquarium, glass house or more complex model ecosystems can also be used to study the nature behaviour and interactions of selected ecosystem components under controlled conditions.

Distinction between different forms of measurements is not always sharp. E.g. accidental or permanent wastewater discharges or continuous natural releases can be considered as tracers. Sediment traps, sediment plates, and bottom tubes to show oxygen consumption in still water are examples of isolations measured under naturally varying field conditions.

In principle, the level of active influence and control can be thought to have implications on interpretation of results and uncertainties. According to that, statistical correlation were a typical outcome of passively received data, mainly one-way causal relations could be shown by test experiments, and at best more complex interaction networks could be found by isolated studies under controlled conditions, in principle. In practice, however, the differences are not that clear, if any. Especially hardly any examples are known of interaction networks found directly from isolated extractions. Also causal relations can be deduced from the results of passively received observations with the support of common sense.

Analogies can be used to illustrate the structure or dynamics of some system by similarities with those of a more familiar system. Old example is the correspondence between electric current and water flow, and between voltage difference and water level difference, in electric circuits and water route networks. Between closer branches of sciences, further analogies can be found e.g. between winds and water currents. Also the interface between air and water can be used as an analogy of a sharp pycnocline (halocline or thermocline) within water. In strictly defined form, analogies are based on the same mathematics describing each of the comparable branches of science. Thus they can be analyzed also mathematically, as they usually are. Independently of mathematics, however,
analogies can be fruitful in background thinking, and from these they can hardly be totally eliminated.

The relations and dependencies found, assumed or proved by field or laboratory work or by remote sensing can be crystallized mathematically in compact and concise form. These are easy to apply repetitively and their validity can be tested strictly. The range of validity of mathematical descriptions can vary from generally valid laws of nature, to case dependent (ad hoc) relations and to place and case dependent statistical relations.

In principle, the validity of mathematical descriptions of nature systems can be only tested as comprehensively as possible, and falsified (proved to be insufficient, inappropriate or false if important differences from test data appear) but not utmost verified (proved to the only one true, the truth, always and everywhere valid). Honest possibility for falsification with versatile and widely varying test data under widely varying conditions is the most what can be presented to maintain, support and assert the credibility and reliability of mathematical descriptions. Furthermore, however, test data is not needed from every place and every moment because the causal relations behind the mathematics couple and connect the model results anytime and everywhere together, so that agreement with test data at any single place can not be artificially forced without influences throughout the system (Popper 1934, Oreskes et al. 1994, Allender 1976, 1977, Allender & Saylor 1979).

Simple equations in simple geometry can sometimes be solved analytically, in closed (function) form. In general cases and natural geometry (where border shapes are not expressed as simple functions) numerical solution is utilized. The difference between analytical and numerical solutions is not mainly in their accuracy but in the labour needed for solution. From analytical functions the numerical values of any point at any moment can be solved directly and instantly without attention to other points or moments, whereas for the same result numerical solution needs values of all the other points from all preceding times having influence on it. For accuracy, the number of digits in computer and also the finite space resolution of numerical solutions are usually well sufficient.

2.2 Model dimensions

For numerical solution the water volumes modelled are usually divided into smaller pieces or boxes, finite in size. These are then used to replace approximately the infinitesimally small changes of continuous partial differential equations. In selection of box sizes, integration in any direction can be extended
over the whole model area. Differences of these directions are thus eliminated from the equations and solutions. This may help and simplify their treatment and calculation.

With attention to the dimensions resolved (Fig. 1), the models can be classified as follows (D=dimensional, V=vertical (Depth), L= longitudinal (Length), B=lateral (Width), and H= horizontal (Length x Width)):

- **3D** = Length x Width x Depth, Three-dimensional with all space directions
- **2DH** = Length x Width, Two-dimensional, vertically integrated
- **2DV** = Length x Depth, Two-dimensional, laterally integrated
- (**2DB** = Width x Depth, Two-dimensional, longitudinally integrated)
- **1DV** = Depth, One-dimensional, horizontally integrated
- **1DL** = Length, One-dimensional, longitudinal
- (**1DB** = Width, One-dimensional, lateral)
- **0D** = None, Without space dimensions, volume average.

Specific dimensions may be needed for proper description of some processes.

The two-dimensional horizontal (vertically integrated, 2DH) models can be appropriate often for shallow water areas. For calculation of vertical circulation and stratified currents, two-dimensional vertical (laterally integrated, 2DV) solutions or full three-dimensional (3D) models are needed. Development of stratification, mixing and many other processes can be described also with horizontally integrated one-dimensional vertical (1DV) models.

Water quality development of small ponds or other well-mixed areas is often computed without any space resolution (with 0D models). For water quality and flow fluctuations in rivers and narrow lakes, one-dimensional longitudinal, vertically and laterally integrated (1DL) solutions are often used. Especially in wider water areas, the distinction between longitudinal and lateral directions is mainly a question of definition or stipulation. This leaves the lateral alternatives (2DB and 1DB) in practice non-existent and equivalent to their longitudinal counterparts (2DV and 1DL).

Time-dependent solutions can be obtained for any combination of space dimensions. Also direct equations and solutions for stabilized steady-state are possible under constant conditions. In general case, however, their solution needs iteration which is essentially very similar (or even equivalent) to time progress. Therefore the time-dependent forms of equations are dominantly preferred, as the non-constant conditions are quite common in natural waters and environment.
Non-trivial steady-state solutions for closed-circuit flow need at least two space dimensions.

Fig. 1. Schematic illustrations of a few of the model dimensions and their transitions.
2.3 Dimension transitions

Distinction by dimensions resolved is not always sharp. Many modifications, transitions, combinations and further approximations can be applied to them. Several columns or boxes of horizontally or volume integrated (1DV and 0D) models can be coupled side by side or one after the other, and water exchange between them can be estimated, deduced or guessed by measurements or experience. In this way interaction between the deepest areas and more shallow coastal areas aside can be approximately described.

Longitudinal (1DL) models of river channel can be coupled with parallel lane(s) of flood fields or storage basins on its side. Thus also the influence of slow currents in the flood fields compared to those faster in the main channel can be distinguished from each other.

Between the vertically integrated (depth-average, 2DH) and the vertically divided (3D, multi-layer or multilevel) models the transition steps or intermediate possibilities are especially numerous, including e.g. the following alternatives:

1. Bare two-dimensional, vertical average single-layer models (2DH) without any approximations for the vertical structure or profile (e.g. Hansen 1956, Uusitalo 1960, Sündermann 1966, Leendertse 1970, Laevastu 1974, Virtanen 1977b);
2. Self-similarity models (2Dss) which assume certain shape for vertical distributions and structure, and compute these, perhaps with a few parameters; a similar approach is used also for cooling water discharges in longitudinal (1Dss) plume models with assumptions for both transversal and vertical distributions (Prych 1972, Weil 1974, Virtanen 1974b, Kämäräinen 1978; Nowlin and Reid 1967, Tamsalu et al. 1994);
3. Profile-type models (2Dp) which compute the vertical distributions as a weighted sum of elementary profiles, the weights being solved from specific conditions in the model (Heaps 1971, Bengtsson 1973a, Rämö 1976);
4. Combinatory surface layer models (2De) with superposition of vertical-average and direct wind drift estimates (e.g. Ekman 1905, Welander 1957, Ambjörn et al. 1981);
5. Focussed layer models (2D+) where the computation has been focussed to one specific layer by modifying the 2DH solution with additional assumptions (Sarkkula and Virtanen 1983, Rautalahti-Miettinen et al. 1986);
6. Focussed extracts (3D-) of 3D models which use the results of one or a few layers of multilevel models for further calculations (Vepsä et al. 1992, Koponen et al. 1994, Inkala 2001);

7. Impermeable interface or mass-isolation models (3Di) which compute the varying interfaces and movements of separate water masses throughout the water column (Häkkinen 1984, Myrberg 1990);

8. Multilevel models (3D) most often called multi-layer models where the vertical dimension is subdivided in the same way as the horizontal ones, resulting in own values for each of the fixed model layers at fixed depths (Simons 1980, Koponen 1984); and

9. Non-hydrostatic models (3Dva) where the vertical accelerations are computed as the horizontal ones without utilizing the hydrostatic assumption for pressure (Marshall et al. 1997a, b).

Simons (1980) calls impermeable interface models as type II multi-layer models while multilevel models are type I for him. Since 3Di models were less frequently used for practical purposes, the denotation multi-layer model is established mainly in practice to (type I) 3D solutions, although it might better characterize 3Di properties. Interest in non-hydrostatic full-equation (3Dva) models has increased when horizontal resolutions are refined to approach the vertical ones and below the water depths. In their solution also quasi-hydrostatic approximations (3Dqh) can be utilized (Marshall et al. 1997a).

2.4 Flow changes and effects on transport

In wide water areas – lakes, reservoirs, coastal areas, and seas – the gravity waves are in practice always much faster than the flow and transport velocities. In the numerical solution it is therefore beneficial to use for each process its own time-steps according to the quickness of its changes. This is done with the principle of fractional time-steps (e.g. Roache 1974), also called as time-splitting or multi-step procedure.

Even more advantage can be received by separating the computation of quickly changing water currents and water level elevations totally from that of the slower developing transport (advective and convective motion and mixing) of concentrations and other properties of water. Several alternatives or approximations are then available to transfer the water currents and flow fields from the flow model to be used in the transport calculation, e.g.
1. storage of varying flow fields with short intervals, e.g. as hourly or daily averages, from the whole computation period;

2. storage of the flow fields from weather sequences typical e.g. to each season, and chaining these to best resemble the real conditions of the computation period;

3. storage of flow fields from a few basic situations, and approximating the flow fields of each situation as a combination of these, weighted by the last observed conditions of each moment of the computation period;

4. the same as above (3) but interpolation of the flow fields or condition changes to introduce a time lag and smooth change (instead of stepped change in 3) to the flow fields;

5. continuous computation of flow abreast of transport calculations.

Minimum requirements for the basic situations of alternatives (3) and (4) are two winds not parallel with each other. Own flow fields are needed also for each set of boundary flows (river inflows and outflows, external sea flows, cooling water discharges and intakes, largest wastewater discharges) varying independently of (without correlation with) the others and having significance for the flow velocities. As the simplest alternative, stabilized steady-state flow fields and linear interpolation and extrapolation have been used. The success of these very simple approximations has been favoured or made possible by the shallowness of the application areas, by weak or non-existent density differences and by the relative narrowness of the coastal zones of applications (Virtanen & Koponen 1985).

At the times of slow computers, the simplest alternative (3) had a central role for early accumulation of experiences of coupled modelling of flow fields and water quality. At the same, the validity of approximation(s) was repeatedly tested in every application by comparing the results with those of tracer studies, flow velocity recordings and water quality measurements.

Recently with faster computers, the importance of approximations has significantly reduced, and the extreme alternatives (5 and 1) are predominantly used. Continuous computation of flow (5) has always been needed for transport calculation of quantities having influence on the water density, because through stratification these (mainly water temperature, salinity, highest wastewater concentrations sometimes) affect the flow velocities themselves. Storage of varying flows fields, on its part, is needed especially for backward calculations of the routes and origin of the observed objects or spills (e.g. Koponen et al. 1993, Kokkila 1995).
The transport velocity $U_c$ of a quantity in water is a combination of the influences of the flow velocity $U_f$ of water and of other flow influences $V_o$, $U_c = V_o + S \cdot U_f$, where $S$ is the dependence or sensitivity of transport velocity on water flow. Based on the relation $S$ and on the relative importance of other flow influences compared to the flow velocities $R = V_o / U_f$, several transport types can be distinguished, e.g.

1. Active swimmers (with $S = 1$, and $R > 1$), e.g. fish, mammals and other macro-animals, also people when alive and awake;
2. Drifting organisms (with $S = 1$, and $0 < R \ll 1$) which can modify, resist or regulate their movement with water currents to minor extent by horizontal or vertical motion but are seldom strong enough to swim against the water currents, e.g. algae and other plankton, at least and especially when not floating as dense concentrations on the water surface;
3. Completely dissolved concentrations (with $S = 1$, and $R = 0$) which move exactly with the water currents, e.g. all dissolved substances;
4. Quantities partly influenced by water currents (with $0 < S < 1$, and $R \sim 1$), e.g. crayfish or walking mammals on the bottom, or sharply stratified oil slicks or algal blooms at the water surface;
5. Slowly or very slowly, perhaps only occasionally moving quantities (with $0 < S \ll 1$, and $0 < R \ll 1$), e.g. surface sediments as bottom loads, or micro-organisms on the bottom;
6. Fixed, non-moving quantities (with $S = 0$, and $R = 0$), e.g. substances fixed or taken by rooted plants, or substances accumulating or organisms growing on other fixed surfaces.

The direction of the other flow influence $V_o$ can depend on or be determined by e.g. concentration gradients in water, bottom slopes, or winds at the surface. In addition to the directed, time-average flow influences, both components of flow influences can include also mixing effects to all directions, caused by turbulence of water, molecular diffusion, and activity of micro-organisms.

The time scales of bio-geo-chemical changes of water quality indicators are often slower than or comparable to those of the transport influences. Their effects are then calculated with their own time-steps abreast of the transport calculation. On the other side, very fast, almost instantaneous reactions are described as direct final balance between its components, e.g. adsorption – desorption – reactions as their main examples.
3 Development background

3.1 Founding base lines of modelling

The main background and prerequisites for multi-dimensional numerical modelling of water systems include the development of

- hydraulics, hydrodynamics and fluid mechanics in general (Goldstein 1964, Landau & Lifshitz 1959, Lamb 1932, Starosolszky 1975),
- mathematics, applied mathematics and numerical methods for solutions (Roache 1974, Ames 1969, Richtmyer 1957), and
- computers, data management, information techniques, and communication means (Platzman 1979).

Main attention in the development review will be in fluid mechanics (e.g. Rouse & Ince 1957, Darrigol 2005, Narasimha 2006; Struik 1948) which has close relations to the development of mathematics as well. More recent developments of oceanology and limnology will be reviewed thereafter. Interconnected developments of meteorology, applied mathematics and computers are shortly treated in the next chapter, in connection with the progress to water systems modelling.

The basis for hydrostatics as a science was laid by the Sicilian mathematician Archimedes (287–212 B.C.) (Heath 1897). It was completed by Frenchman Blaise Pascal (1623–62) (Pascal 1663) almost two thousand years later. Recordings of hydraulic constructions and arrangements, however, are known for more than six thousand years ago, and the history of hydraulics as an art is considered to be older than recorded history (Rouse & Ince 1957).

Aristotle (384–322 B.C.) contributed to a wide variety of subjects ranging from physics to metaphysics, including e.g. observations on tides. Tides were observed also by Strabo (63/64 BC–ca. AD 24) in his 17-volume Geographica (Meineke 1853). Leonardo da Vinci (1452–1519) made hydraulic observations of jets, waves, eddies, and the flight of birds, and formulated the basic principle of
continuity for streams, in his notes lost for several centuries (ref. Duhem 1913, Leonardo reprint 1923)

Galileo Galilei (1564–1642) added experimentation to observation, and threw initial light on the problem of gravitational acceleration (Galilei 1590, 1600). One of his students, Benedetto Castelli (c.1577–c.1644), rediscovered the principle of continuity (Arredi 1933). The French scientist Rene Descartes (1596–1650) tried to reconcile the Aristotelian teachings adopted by church with the mechanics of the solar system (Descartes 1644). His name has left to the Cartesian coordinate system, too, as one of his contributions to different fields of sciences (Descartes 1637, Fermat unpublished at the same times).

In England Isaac Newton (1642–1727) used the principle of momentum to evaluate the orbits of planets (Newton 1687), conducted a variety of experiments on the fluid resistance, formulated the basis of viscous shear, an equation for drag, and the speed of sound in air. His "theory of fluxions" formulated the basis for the study of limits, derivatives, integrals, and infinite series. At the same times in Germany Gottfried Wilhelm von Leibniz (1646–1716) developed the principle of energy (Leibniz 1686) and also presented his form of the limits and series with notations of derivative and integral used to this day.

Leibniz's calculus was applied (and contributed with some of the nomenclature still used today) by Swiss Johann Bernoulli (1667–1748) (Bernoulli reprint 1968). His son Daniel (1700–82) published in 1738 the original treatise *Hydrodynamica* (Bernoulli 1738), presenting e.g. use of manometers for pressure measurements, the kinetic theory of gases, and jet propulsion. Their comrade Leonhard Euler (1707–83) deserves credit for a number of equations of hydraulics, including his equations of acceleration for the conditions of steady, irrotational flow under gravitational action. Also the Bernoulli equation was derived and presented by him (Euler 1755).

Onwards from the laboratory experiments, Italian Domenico Guglielmini (1655–1710) made extensive field measurements of river flow (Guglielmini 1697). In France Henri de Pitot (1695–1771) presented his tube for the flow measurements (Pitot 1732). The rotating arm to propel a body through air was developed in England by Benjamin Robins (1707–51) (Robins 1761). He also invented the ballistic pendulum. Scale-model tests were first conducted by John Smeaton (1724–92) in England (Smeaton 1759), soon followed by towing-tank tests of ship-model drag 1766 by Benjamin Franklin (1706–90) (Franklin 1769); and 1775 by Jean Lerond d'Alembert (1717–83), who 1752 had proved the d'Alembert paradox (d'Alaembert & Bossut 1777, d'Alembert 1752).
The studies of fluid resistance were continued by Antoine Chezy (1718–98) for streams (ref. Herschel 1897), and by Pierre Louis George Du Buat (1734–1809) who also wrote a textbook on hydraulics in 1779 (Du Buat 1779). The flows in tubes were extensively studied since 1839 in Germany by Gotthilf Ludwig Hagen (1797–1884), in France by Jean Louis Poiseuille (1799–1869), in England by Osborne Reynolds (1842–1912), in Germany by Paul Richard Heinrich Blasius (1873–1970), and later by Johann Nikuradse (1894–1979) (Hagen 1839, 1854, Poiseuille 1841, Blasius 1913, Nikuradse 1932, 1933). Hagen (1854) noticed that the flow was not always laminar, and Reynolds introduced the viscosity to form a parameter marking the borderline between laminar and turbulent flow (Reynolds 1894), now known as the Reynolds number.

The similarity law for scale model flow under the influence of gravity was announced 1852 by Ferdinand Reech (1805–80). It was first utilized 1888 by Reynolds in model tests of tidal action in the Mersey estuary. The law was named after William Froude (1810–79) who was the first to note the development of a boundary layer along the hull of ships 1872 (Reech 1852, Froude 1872, Reynolds 1888).

In 1822 the French bridge engineer Louis Marie Henri Navier (1785–1836) extended the Euler equations of acceleration to the flow of a viscous fluid. Further developed by Augustin Louis de Cauchy (1789–1857), and by Simeon Denis Poisson (1781–1840), they were finalized in 1845 by the Cambridge professor George Gabriel Stokes (1819–1903), who also applied the equations to the resistance of small spheres. In 1843 another form of the equations was developed by Jean-Claude Barre de Saint-Venant (1797–1886) (Navier 1827, Cauchy 1826/–1830, Poisson 1831, Stokes 1851, Saint-Venant 1843).

The theoretical hydrodynamics, was further developed by Lagrange (1736–1813), Laplace (1749–1827), Helmholtz (1821–94), Kelvin (1824–1907), and Rayleigh (1842–1919). In 1879 Horace Lamb (1849–1934) published the first edition of the treatise Hydrodynamics (Lagrange 1781, Laplace 1808/–1823, Helmholtz 1882/–1895, Kelvin 1882/–1911, Rayleigh 1899/–1920, Lamb 1932). In the mechanics of fluids the distinction and the meanings of the viscous boundary layer and the fluid outside the boundary layer were reasoned in 1904 by Ludwig Prandtl (1875–1953). His group also proceeded to formulate the essential principles of airfoil and propeller operation (Prandtl 1904, 1961). As one of his students Blasius (1908) provided a mathematical basis for boundary-layer drag.

Until the voyages of Louis Antoine de Bougainville 1766–1769, and James Cook 1768–1779, the explorations of the oceans were primarily limited to
cartography and to the creatures brought up by fishermen in nets. Depth soundings were taken by lead line. In 1840 James Clark Ross took the first modern sounding in deep sea. The three voyages of HMS Beagle resulted in four volumes of reports published by Fitzroy. From the second voyage 1831–36 Charles Darwin published 1840 a paper on reefs and the formation of atolls. James Rennell wrote scientific textbooks about currents in the Atlantic and Indian ocean around 1840. Matthew Fontaine Maury's Physical Geography of the Sea, 1855 was considered as the first textbook of oceanography. Edward Forbes' dredgings in the Aegean Sea founded marine ecology (Sverdrup et al. 2006, Steele et al. 2001).

Oceanography as a quantifiable science began in 1872, when Scots Charles Wyville Thompson and John Murray launched the Challenger expedition (1872–1876). Its results were published in 50 volumes covering biological, physical and geological aspects, including the discovery of 4417 new species. The first purpose-built oceanographic ship, Albatros, was built 1882. The oceanographic and marine zoological four-month North Atlantic expedition headed 1910 by John Murray and Johan Hjort led to a classic book The Depths of the Ocean in 1912.

The influence of Earth's rotation on motion appeared in 1778 in the tidal equations of Pierre-Simon Laplace. More generally the transfer of energy in rotating systems like waterwheels was expressed and emphasized 1835 by Gaspard-Gustave de Coriolis (1792–1843). He worked to extend the notion of kinetic energy and work (defined by him as the product of force and distance) to rotating systems and to present mechanics in a way that could readily be applied by industry (Coriolis 1835).

In meteorology and oceanography, the characterization of stratification with the relative density gradient was presented 1925 by Vilho Väisälä (1889–1969) and a few years later by David Brunt (1886–1965) (Väisälä 1925, Brunt 1928). Explorations of lakes were pioneered by Francois Forel (1841–1912) who's massive Lake Geneva monograph (Forel 1882/–1904) define the main fields of limnology (Edmondson 1994, LeBlanc 1912). The first limnological research institute was founded in Germany at Plön in 1891 by Otto Zacharias (ref. Overbeck 1989). August Thienemann (1882–1960) became its director in 1917. He collaborated in the early 1920s on lake typology and regional limnology with the Swedish limnologist Einar Naumann (1891–1934). Combination of their disparate viewpoints resulted in a general system of classifying lakes that persists to this day (e.g. Thienemann 1931). In 1921 they founded the International Association of Theoretical and Applied Limnology (Societas Internationalis
Limnologiae, SIL), drafted its statutes, and organized the first international congress of limnology in 1922 (Wetzel 2001).

During the first half of the twentieth century, limnology remained essentially an observational science: knowledge gained was largely from sample collection and analysis of the resulting data rather than from controlled experiments. Many new limnological field stations were founded in 1920s and 1930s, a wealth of information on individual lakes were collected, and synthesized at the regional scale. Edward A. Birge (1851–1950) and Chancey Juday (1871–1944) rooted academic limnology in North America at the University of Wisconsin in Madison and its Trout Lake Limnological Station (Mortimer 1956, Frey 1963, Beckel 1987, Kitchell 1992, Juday 1915).

After them, Arthur D. Hasler (1908–2001) further developed limnology as an experimental science – in contrast to its origins as an observational science. He also put focus on lakes as open systems that receive inputs of water, solar energy, and chemical substances from terrestrial and atmospheric sources (Beckel 1987). His group was involved in several whole-lake manipulations during the 1950s and 1960s. Examples include experimental liming in 1950 (Hasler 1964), "paired manipulation" of a two-basin lake separated into two lakes by an earthen dike, the first whole-lake experimental acidification (Zicker 1955); aeration-induced destratification experiments on several eutrophic lakes; and the addition of short-lived radioisotopes to the water of stratified lakes to measure rates of water movement (e.g., Likens & Hasler 1960). His group also pioneered the use of small artificial ponds (wading pool size) treated in various ways to simulate lakes.

Already earlier, in 1930s, Juday had added fertilizers to a small pond to study their effects on plankton production and fish populations (Juday & Schloemer, 1938), and Einsele (1941) performed a similar experiment on a small lake in northern Germany. A whole-lake radiotracer experiment was done by G. Evelyn Hutchinson (1903–1991) at Yale University in June 1946. After addition of approximately 10 millicuries (0.37 GBq) of \(^{32}\)P-phosphate to a small lake, the distribution of radiophosphorus was determined in several strata of the water column and in littoral macrophytes on two dates over the following month (Hutchinson & Bowen, 1947).

The role of experimental limnology became more prominent in lake science during the late 1960s and 1970s, involving mainly three types of manipulations:
1. stress-response experiments, in which a lake (or a basin in a lake) is treated with a chemical or biological stressor (such as excess nutrients, acid, or a top predator) and the responses of the lake system are studied;

2. hydrologic, physical, chemical, and biological manipulations aimed at lake remediation or rehabilitation; and

3. tracer additions to measure rates of physical processes, such as use of radiotracers to follow water movement and noble gases (or sulfur hexafluoride) to monitor air-water gas exchange.

Simultaneously, experimental approaches at smaller scales using enclosures of one to a few meters in diameter – also called mesocosms, limnocorals, limnoenclosures, or limnotubes – that are installed in the lake have become popular in Europe and North America. These mesocosms, however, cannot duplicate the complicated ecosystems of whole-lakes and are especially inadequate to study populations of large fish over long periods. Because manipulations of whole aquatic ecosystems generally cannot be duplicated, sophisticated statistical methods have been developed to evaluate data from such unreplicated experiments (Carpenter et al. 1989; Rasmussen et al. 1993). Of special importance is the gathering of adequate baseline data prior to manipulation where paleolimnological techniques can help.

Since the early 1960s, limnology can be characterized by four related main trends:

1. increasing emphasis on research related to the effects of pollution on aquatic resources and on ways to restore and manage these resources;

2. increasing diversity in the disciplinary backgrounds of limnologists (from its earlier biological focus of zoology, botany or biology);

3. increasing variety in the types of lakes studied; and

4. increasing focus on other types of inland aquatic ecosystems (streams, wetlands, and reservoirs), broadening the field of limnology from its traditional focus on natural lakes.

George Evelyn Hutchinson brought a theoretical approach to aquatic ecology to complement its empirical underpinnings (Lewis et al. 1995). The scientific foundations in biogeochemistry included in his monumental Treatise on limnology in four volumes (Hutchinson 1957, 1967) demonstrated the possibilities to interpret and synthesize disparate information into meaningful concepts. Together with population dynamics these led to major contributions in evolutionary ecology.
Raymond L. Lindeman (1915–1942) developed the concept for synthesizing ecological principles based on energy flow through food chains. His trophic-dynamic concept, published posthumously in 1942, emphasized the importance of short-term nutritional functioning to an understanding of long-term changes in the dynamics of lake communities. Many of his trophic-dynamic ideas were melded into conceptual and mathematical treatments from Hutchinson's then-unpublished writings. Hutchinson also assisted the publication of Lindeman's synthesis paper (Lindeman 1942), which was rejected at first because of its theoretical nature.

Howard Thomas Odum (1924–2002) contributed to the development of several new disciplines—particularly systems ecology, ecological economics, and ecological engineering (coined in 1962)—that relate ecology to other sciences in analyzing major environmental problems. He advanced experimental ecology through work on mesocosms and by refining the diurnal oxygen method for measuring primary production. He directed several large-scale experiments in a tropical rain forest in Puerto Rico and presented a computer language and modelling technique to describe energy flow through ecosystems. Thereafter, his work in aquatic ecology has focused on experimental wetland ecology, including the use of wetlands as natural treatment systems for wastewaters, and continued to promote the development of university curricula to produce ecological engineers (Mitsch 1994, Odum 1956, 1957, 1994).

The language and modelling approach became the tool of a group of followers who modelled energy flows associated with the movement of commodities in both natural ecosystems and human-dominated systems (Jörgensen 1986a, b). This work led to the concept of "embodied energy," since termed "emergy," which accounts for the direct and indirect energy flows (those from "free environmental services" and those supplied by the economy) required to produce a substance. In turn, this led to efforts to conduct economic analyses in terms of energy units.

3.2 Progress into modelling

The set of partial differential equations governing the (large scale) geophysical behavior of atmosphere and water bodies was presented by Norwegian Vilhelm Bjerknes (1862–1951). For their solution he proposed a "graphical calculus" based on weather maps. The method was used and developed until 1950'ies. In Stockholm (1895–1907) he also advised and urged Vang Ekman (1874–1954) for mathematical solution of the phenomenon observed by Fridtjof Nansen (1861–
1930) in Arctic expeditions aboard the research vessel Fram (1893–1896) that icebergs were not drifted in the direction of the wind but at an angle to the right (Nebeker 1995, Nansen 1898, Aspley 1922, Ekman 1905).

Attempts for numerical solution of the geophysical equations were presented 1910 by Lewis Fry Richardson (1881–1953) who earlier had worked for development of the graphical solution techniques (Richardson 1910). In 1920'ies he scheduled a stadium of 64'000 people needed for coordinated calculation of weather forecasts (Richardson 1922, Bjerknes & Richardson 1921). In the Netherlands 1919–1928, Hendrik Antoon Lorenz (1853–1928) calculated the movements of seawater expected during and after the reclamation of the Zuyderzee. Concerning one of the greatest works of all times in hydraulic engineering, the results were confirmed in actual practice in a most striking manner (ref. Nobel Lectures, Physics 1967, Leendertse 1967).

Bio-geo-chemical influences were calculated in the U.S.A. by Harold W.Streeter and Earle B. Phelps (1925) for the oxygen in the Ohio River, and almost 40 years later by Robert V. Thomann (1963) for the Delaware river and estuary. Further components of water quality indicators were included in the longitudinal 1DL model systems until 1970's (e.g. Texas Water Development Board 1971, Roesner et al.1973). At the same times attention was directed also to fully integrated 0D mass balances of lakes (e.g. Vollenweider 1969, 1975, Dillon & Rigler 1974, Kirchner & Dillon 1975) and to the vertical 1Dv structure of deep places of reservoirs and lakes (Gaume & Duke 1975).

The mathematical justification of numerical solution of partial differential equations was specified by the stability criteria of Courant, Friedrichs and Lewy (1928). In fluid dynamics, numerical methods were used for solution of viscous fluid flows by Thom 1933 (ref Roache 1974). The first digital computer ENIAC was used by John von Neumann (1903 Budapest–1957) for simulations of nuclear explosions, for shock waves with help of artificial viscosity, and for weather calculations (Neumann 1949, Neumann & Richtmeyer 1950, Charney et al. 1950, Platzman 1979).

In 1950 the weather model of North America consisted of 270 nodes in one layer with horizontal resolution of 700 km and time step of 3 hours. Regular computations of weather forecasts were started at SMHI in Sweden under the lead of Carl-Gustaf Rossby (1898–1957) with the Swedish BESK computer three times a week in December 1954, and in Suitland, Maryland, USA, under George Cressman in May 1955 (University of Stockholm 1954; Bergthorsson et al. 1955; Nebeker 1955).
The use of numerical methods for solution of water currents was suggested in 1938 by Walter Hansen (1909–1991) and realized in his "Hydraulisch-Numerisch(en)" HN-model in 1956 (Hansen 1938, 1956; Laevastu 1974). Thereafter the use of models was quickly spread to several parts of the world, e.g. to North-America (Platzman 1958, Rao 1967, Leendertse 1967), the Netherlands (Lauwerier 1960), Finland (Uusitalo 1960), Sweden (Welander 1961), France (Preissmann & Cunge 1961), Japan (Miyazaki et al. 1961–62), and Soviet Union (Vasiliev & Godunov 1963) as well as Germany (Fischer 1959, Sündermann 1966), Belgium and the British Islands (Heaps 1971, Nihoul 1975). International cooperation and mobility of scientists accelerated the spreading and development of applications significantly.

3.3 Surveys of model use

Reviews and surveys of model use have been done and published at least since the middle of 1970's both in Finland and abroad. International reviews were collected e.g. by Hinwood and Wallis (1975a, b) and by Peter Shanahan annually since 1980's (e.g. Shanahan & Galya 1988; Shanahan 1991, Shanahan & Gaudet 2000). In Finland the main surveys of multidimensional model use have been carried out

- 1974–75/-77 for the subproject "Estimation of the applicability of mathematical models describing the dispersal of waste and cooling waters" of the Community Water and Environment (YVY-) Project of SITRA, The Finnish National Fund for Research and Development (Kuoppamäki et al. 1977);
- 1986–87/-89 for the Bothnian Bay Research Project (Koponen et al. 1992);
- 1992–96/-99 in connection of numerous EUREKA and EU Projects (e.g. Baumert et al. 1999; Heikkinen et al. 2000); and
- 2003–04/-06 at the Finnish Environment Institute (SYKE) for search of alternative 3D models (Huttula & Lehtinen 2003) and for EU Projects to collect tools to help the implementation of the Water Framework Directive (Kämäri et al. 2006, Hutchins et al. 2006).

Hinwood and Wallis (1975a, b) listed and classified 141 applications of coastal water quality models. Shanahan's main interest were in the transport and mixing models. The first Finnish review was based on relatively unique and invaluable set of original pioneering publications collected by the Finnish Institute of Marine Research (FIMR). Participation in international conferences and contacts created
in these meetings completed the survey. The main meetings included IAHS–AISH Conference in Helsinki, 1973 July 16–20 with Kuoppamäki, Kuusi, Virtanen; Hari; Solantie; Hyvärinen, Järvinen, Tuominen, Jaatinen, Lemmelä, Laikari, and Sarkkula as the 12 Finnish participants; IAEA Cooling water Conference in Oslo, 1974 August 26–30 with Ilus, Kovanen, Launiainen, Mikkola, Storå and Virtanen; and ICES Special Meeting in Copenhagen, 1974 September 26–27 with Mälkki and Virtanen as the Finnish delegation.

From this basis, the derivation and presentation of hydrodynamics for model solutions was preliminary based on description and evaluation of 35 references (Virtanen 1974a). Finally in 1977 the number of references analyzed and utilized was increased to 148, including 75 publications of the years 1975–77 (Virtanen 1977a).

A most comprehensive survey of model use was carried out in the Bothnian Bay research project with a questionnaire mailed to almost 200 institutes between September 1987 and September 1989, visits to numerous model centres in Europe and North-America 1987, 1989 and 1990 (Alasaarela, Koponen, Virtanen 28.9.–10.10.1987; Kinnunen, Koponen, Lehtinen, Malve, Myrberg, Virtanen 10.–15.9.1989; Alasaarela, Koponen, Virtanen 1.–13.9.1990), and versatile analysis of their results (Koponen et al. 1992). In response, descriptions of 105 models were received from 56 institutes in 17 countries, while almost 40 questionnaires were returned unfilled for the sake of changes in staff, activities or addresses.

In the answers, the total number of applications amounted to about 800 case studies, and the number of persons involved in surface water modelling to almost 250. More than 500 person work years (pwy's) were used for the development and application of the models. 65 of the 105 models were used for description of the water currents, 54 for transport and mixing, 42 for stratification and its development, and 33 for water quality indicators. All of the four outputs could be received from 8 models, water currents, transport and stratification from 13 models, and water currents alone from 26 models. Three-dimensional (3D) computation was possible with 34 models, 2D with 45, 1D with 20 and no space resolution (0D) in 3 models.

About 15 organizations were found to represent half of the pwy's done and more than 60 per cent of the staff involved. Many of these institutes were subject to considerable organizational changes at the beginning of 1990's (Koponen et al. 1992). Their role in the model applications was further focused after the Bothnian Bay project in numerous EU and EUREKA projects where many of them were also met as cooperative partners.
In 2003, the Finnish model review was based on a list of almost 50 models collected by Steve Baum at the Department of Oceanography in Texas A&M University (Baum 2004, preceded by quite comprehensive review of Wurbs 1994; Huttula & Lehtinen 2003). A questionnaire was mailed to 30 model groups. Detailed further information was received from 15 of these, while 10 models were evaluated by their developers less suitable for the purpose requested. The models of further information included the following acronyms with explanation of their background (in parenthesis) and mainly the first and a latest reference supplied:

- **BRIOS** (Bremerhaven Regional Ice-Ocean Simulations, by Alfred Wegener Institute, Germany) e.g. Beckmann *et al.* 1999, Timmermann *et al.* 2002;
- **COHERENS** (COupled Hydrodynamical–Ecological model for RegioNal Shelf seas, by Royal Belgian Institute of National Science Belgium, and Napier University, Proudman Oceanographic Laboratory and British Oceanographic Data Centre, UK) e.g. Luyten *et al.* 1999, 2003;
- **ELCOM-CAEDYM** (Estuary and Lake COMputer Model, by University of Western Australia, Australia) e.g. Hodges *et al.* 2000, Hodges & Imberger 2001;
- **GETM** (General Estuarine Transport Model, by Bolding og Burchard Hydrodynamics, Denmark, Baltic Sea Research Institute Warnemünde, Germany, and Inland and Marine Waters Unit at the Joint Research Centre Ispra, Italy) e.g. Burchard and Bolding 2002, Stips *et al.* 2002;
- **HIM** (Hallberg Isopycnal Model, by NOAA GFDL, USA) e.g. Hallberg 1997, Papadakis *et al.* 2003;
- **MICOM** (by Los Alamos National Laboratory, USA) e.g. Bleck 2002;
- **OPA** (by LODYC/ CNRS, France, with 16 user institutes in France and 23 abroad) e.g. Brossier *et al.* 1994, Caniaux and Planton 1998;
- **POP** (Parallel Ocean Program, by Los Alamos National Laboratory, USA) e.g. Fu and Smith 1996, Best *et al.* 1999;
- **RCO** (Rossby Centre Ocean model, by SMHI Rossby Centre, Sweden) e.g. Meier 2001, Meier and Kauker 2002;
- **ROMS/ TOMS** (Regional Ocean Model System, by Rutgers University IMCS, New Brunswick, USA, based on S-Coordinate Rutgers University Model SCRUM) e.g. Song and Haidvogel 1994;
A collection of models has been gathered and evaluated to River Basin manager's Toolbox (Kämäri et al. 2006, Hutchins et al. 2006) in three different research projects, viz.

- Benchmark Models for the Water Framework Directive: BMW,
- Tools and systems to extend and harmonize spatial planning on water courses in the Baltic Sea Region – WATERSKETCH, and
- Relationship between ecological and chemical status of surface waters: REBECCA, for the information and tools needed in the implementation of the Water Framework Directive (WFD) and for assistance to the River Basin managers in various steps of the WFD implementation process.

The collection includes descriptions of 72 models. Of these 7 are for socio-economic cost assessment, 31 for groundwater, wastewater and diffuse load estimates, and 34 for surface water influences. 21 models are informed to be suitable for river applications, 23 for lakes, and 10 for estuaries. Nine models of these are informed capable for 3D solutions, three for vertical 1Dv, ten for longitudinal 1DL, and seven for 0D compartment solutions. Among others, Norwegian, Swedish and French partners have supplied updated information of their methods and applications.

The Toolbox collection contains information also of the largest European water-related service companies, viz. WL Delft Hydraulics, the Netherlands, and Wallingford Centre for Ecology and Hydrology, U.K., as project partners, and DHI, Denmark indirectly, via users and descriptions of their models. Indication of their activity in publications is mainly concentrated on conference presentations. Including these, it is remarkable that only one clear 3D application of Delft (Kester et al. 2002) and one 2Dv vertical plane case of DHI (Dorostkar et al. 2006) is included in their lists of publications, each containing tens of items since 2000. Although in principle 3D models have been developed by and are usable at them,
neither in the publications nor in their commercial applications these are thus known being used almost at all.

Any survey, review or list of model applications can nowadays hardly embrace all of the existing and possible models developed. Further models include e.g. the objective oriented MOHID system, which has been recently integrated also with other type of models (Braunschweig et al. 2004, Neves 2007). Its developers and users at Instituto Superior Técnico Lisboa and Hidromod Lda co-worked 1990–2000 in EUREKA and EU Research & Development Projects OPMOD and OPCOM for operational modelling together with e.g. Hydromod GmbH, Germany, Sogreah, France, and EIA Ltd., Finland. In the recent literature, Chinese names seem to dominate the applications (e.g. Liu et al. 2007, Cai et al. 2007, Huang et al. 2008, Liu et al. 2008, Li et al. 2008, Shen et al. 2008). Single cases are reported also from other parts of the world (e.g. Kachiashvili et al. 2007, Fossati & Piedra-Cueva 2008).

3.4 Model efforts in Finland

In Finland, after the early application of the vertical average 2DH model for calculation of sea currents and water level elevations (Uusitalo 1960), the use and further development of hydro-dynamical models was continued in the middle of 1970's. Attention was directed then

– to the 2DH model of flows and water level elevations (Virtanen 1977b; Jokinen 1977),
– to its 2DH extension to transport and mixing to explain the radioisotope tracer results (Virtanen 1977a, b),
– to mainly 1Dss longitudinal self-similarity models for jets of cooling water discharges (Kämäräinen 1977, 1978, 1980), and
– to two profile-type 2Dp models to add the vertical structures onto the horizontal flow fields (Rämö 1976, 1977).

The profile type models adopted for application to Lake Asikkalanselkä in Central Finland were from Heaps (1971, Belgium and British Islands) and from Bengtsson (1973a, Sweden). When compared with the measured flow velocities, the 2Dp results seemed comparable with the 2DH results. An advantage of the vertical average 2DH currents, however, was their easy and more direct use for transport calculation, although quite soon it appeared that additional 2D+ approximations were needed for proper description of transport as single layer results (Virtanen
Almost at the same times, 1975–78 a research project for Reconstruction and Development of the early water quality models of U.S. origin was carried out at the National Board of Waters, funded by the World Bank. Thereafter the work was immediately continued as a co-operation between IBM and the National Board of Waters. The models implemented, used and developed included 0D mass balance, 1DL longitudinal, and 1Dv vertical resolutions (Kinnunen et al. 1978, National Board of Waters 1978, Frisk 1978, Kylä-Harakka 1979, Niemi 1979, Frisk & Kylä-Harakka 1980, Frisk et al. 1980, Kinnunen et al. 1982, Frisk 1989, Kylä-Harakka-Ruonala 1989).

Since the end of 1970's, selected components of water quality interactions started to be integrated to the 2DH and 2D+ transport models at the Reactor Laboratory of the Technical Research Centre of Finland (Juutilainen 1980) and permanently in its co-operation with the National Board of Waters (Rautalahti-Miettinen et al. 1981, Academy of Finland 1982). Nordic co-operation, especially the Special Course on the Physical Processes of Lakes in Lammi and Helsinki (1977 May 2–13 with Palosuo, Virta, Forsius, Hari, Hiltunen, Huttula, Jungner, Järvinen, Sarkkula and Virtanen from Finland), was utilized in the further development of the hydro-dynamical models (Bengtsson & Svensson 1977) and their interaction with the measurements. Co-operation with Hungary and the International Institute of Applied Systems Analysis IIASA at Laxenburg, Austria, also contributed to the development of the transport models (Virtanen 1978, Shanahan & Harleman 1982, Somlyódy & Virtanen 1982).

Already earlier K. Matti Lappalainen had presented original developments and applications of proper integration of transport influences on water quality predictions, including quite complex flow and stratification situations (Lappalainen 1971, 1972, 1974, 1975, 1978). These were based on analytical solution of water quality indicators with layer thickness and flow velocity estimates taken by expert evaluation and experience. As such their direct integration into the on-going computer model development remained limited. Quite much the same applied also to the prediction techniques of Granberg (e.g. 1977, Granberg & Lappalainen 1971) based on statistical relations and experience. Also recently (Malve 2007) contribution of statistical treatments has been presented for improvement of water quality predictions.

Simultaneous development of water quality models were carried out at the Helsinki University of Technology (HUT), Faculty of Civil Engineering and
Surveying, Laboratory of Hydrology and Water Resources Management (Karonen 1978, Karonen & Seppänen 1979, Kettunen 1981, Varis 1984, Varis & Kettunen 1990). Started with central attention often to the sediment interactions, the main interest was shifted to questions of sampling (Kettunen 1993), decision support (Varis 1991, 1998), and socio-economical aspects (Keskinen 2008, Varis 2008). These have recently been integrated with the 3D model results of hydro-physics, water quality and eco-systems productivity (Kummu et al. 2006, Kummu 2008).


From the common basis of 2DH hydro-dynamical models (Uusitalo 1960, Jokinen 1977, Virtanen 1977b) model efforts were continued also at the Finnish Institute of Marine Research (Häkkinen 1979). More recently it has included development and application of two-layer models (Myrberg 1991), their further developments (Myrberg 1999, Myrberg & Andrejev 2003), studies of non-hydrostatic calculations (Stipa 2002), and inclusion of networks of water quality indicators into the models (Tamsalu 1998, Andrejev et al. 2000), quite much in international but also in national co-operation (Inkala & Myrberg 2002, Myrberg et al. 2008). Research and application of vertical 1Dv hydro-physical and water quality models were continued at the National Board of Waters and in several Regional Environmental Centres (Lehtinen 1984, Niemi 1987). Focussed-layer 2D+ water quality models were also used by them quite much (e.g. Kallio 1986, Kotilainen et al. 1988, Koski 1989, Rautalahti-Miettinen et al. 1981, 1986, Rautalahti-Miettinen 1988) in co-operation with VTT as the predecessor of EIA Ltd.

Special steps in integration of influences of physics on bio-geo-chemical indicators and processes have included the first intermediate interpolation between the fully mixed 0D and longitudinal 1DL transport and mixing dynamics by Perttunen and Alasaarela (1981), and the ingenious presentation of the whole range of the dependence of kinetic rates on water temperature with the simple linear dependence of temperature correction factor on temperature by Frisk and
Nyholm (1980). Lakka (1982) used the 2D flow model results for eutrophication estimates in coastal waters. Recently information of water currents for the transport computation of water quality indicators has been also deduced without a flow model from the measurements (Frisk et al. 2008).

In addition to the EIA's models, 2D applications have been calculated with Hungarian flow models (e.g. Józsa & Gaspar 1992, Huttula et al. 1993) and with the original 3D model developments at the Pirkanmaa Regional Environment Centre (Podshedtsine & Huttula 1994, Podshedtsine et al. 1999). Case studies of these have been applied e.g. to Lake Pyhäjärvi in Säkylä, Lake Saimaa near Ruokolanti, Lake Lappajärvi, Lake Karhijärvi, Lake Längelmävesi; Lake Inari, Lake Tanganyika in Africa (Huttula 1997), and Lake Ladoga in Russia. Use of their results for water quality predictions (e.g. Malve et al. 1994) can have been done also with more integrated approaches. Longitudinal 1DL river models have been applied in the water administration and in several companies, e.g. Fortum Ltd., Vesi-Hydro Ltd., Reiter Ltd., and Vesirakentaja Ltd., sometimes also with further extension 2Dv or 2DH applications (e.g. Forsius 1981, Järvi 1988, Huokuna 1988, Laasonen 1997), these also including mutual co-operation (Forsius et al. 1983).

Special attention to the bottom interactions and sediment dynamics was incorporated to the models since 1981 (Virtanen et al. 1982, Huttula et al. 1990) and algal dynamics since 1982 (Koponen 1984, original publication VI) with the emergence of and final shift to full 3D applications. Later usage of the 3D applications at the Regional Environment Centres has been of central importance for the accumulation of most comprehensive experience of the model validity with versatile concern to the real life situations (Seppälä 1986, Luonsi 1991, Helminen et al. 1998, Kainua 2000, Karjalainen 2008). In close co-operation with the Regional Environment Centres and the Finnish Environment Institute further features of the food web dynamics and sediment interactions have been incorporated into the 3D model system (e.g. Inkala et al. 1993, Inkala 1993, 2001, Kiirikki et al. 2001, 2006).

Already in 1980's, the computational capabilities for hydrodynamics and spatial resolution were expanded so much, that illustrative visualization was needed for their proper presentation. These were developed in Finland since 1982 at first for off-line use where foreign examples were known (e.g. Simons 1974, seen by Mällki & Virtanen 26.–27.9.1974), soon followed by the pioneering on-line solution (Koponen 1984). This formed a central basis for combined European development of visualization techniques in 1990–93 in the EUREKA
project VISIMAR. For management of the expanded sets of the input data, output control, other selections and their growing complexity, fluent user-interfaces were developed and implemented for the 3D models since 1991 (Lauri 1993, Alasaarela et al. 1994, Lauri et al. 1998, Lauri & Virtanen 2002, Koponen et al. 2008a).

3.5 Own contributions to model applications

The numerical models of water bodies created, developed and maintained by the present author (at first mainly alone, since 1980's partly) have been applied since 1974, during the past 35 years, to more than 300 case studies in different parts of the world (Appendix I). The cumulative experience with applications is graphically illustrated in Fig. 2. In five years' periods the number of model types used in the applications has developed as follows:

<table>
<thead>
<tr>
<th>Period</th>
<th>2D</th>
<th>2D+</th>
<th>1D</th>
<th>3D</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1974–78</td>
<td>10</td>
<td>1</td>
<td>-</td>
<td>2</td>
<td>13</td>
</tr>
<tr>
<td>1979–83</td>
<td>2</td>
<td>17</td>
<td>5</td>
<td>3</td>
<td>27</td>
</tr>
<tr>
<td>1984–88</td>
<td>3</td>
<td>10</td>
<td>-</td>
<td>19</td>
<td>32</td>
</tr>
<tr>
<td>1989–93</td>
<td>2</td>
<td>2</td>
<td>5</td>
<td>38</td>
<td>47</td>
</tr>
<tr>
<td>1994–98</td>
<td>1</td>
<td>-</td>
<td>5</td>
<td>61</td>
<td>67</td>
</tr>
<tr>
<td>1999–03</td>
<td>-</td>
<td>-</td>
<td>7</td>
<td>59</td>
<td>66</td>
</tr>
<tr>
<td>2004–08</td>
<td>-</td>
<td>-</td>
<td>7</td>
<td>45</td>
<td>52</td>
</tr>
<tr>
<td>Altogether</td>
<td>18</td>
<td>30</td>
<td>29</td>
<td>227</td>
<td>304</td>
</tr>
</tbody>
</table>

At first the basic, vertical average 2D solutions dominated the applications. Within less than 10 years thereafter, the additional approximations (2D+) were replaced by the real vertical resolution of 3D models. Since 1984, these have totally dominated the applications. Most of the recent 1D applications are river networks calculated in connection with the watershed and drainage models (Lauri et al. 1998, Lauri & Virtanen 2002; Heikkinen et al. 2000, 2006). The 3D cases above include all variations of explicit vertical resolution, also the two profile type (2Dp) model applications in 1975 (Rämö 1976). The 2D columns exclude ten cases where 2D or 2D+ type models have been used for comparison with models of more advanced vertical resolution or approximations.
Fig. 2. The cumulative number of 3D (thick line below) and all (thin line above) model applications of the models of EIA Ltd. 1974–2008.

The reasons for the model efforts have included loading effects in 230 cases. In 61 cases the main attention has been in the effects of waste waters from pulp and paper industry, chemical, metal or other industries, or municipal sources. In 102 cases also other types of loading, e.g. internal loading from the bottom, deposition and remote transport effects from the air, non-point source loading from the watershed, or the effects of fish farming, dredging or dumping have been taken into account together with the waste water effects. In 67 cases these other types of loading have dominated the loading effects.

In 85 cases the purpose of the model application has included the effects of flow and discharge control, e.g. flow regulation, pumping, water level changes, or impoundment of reservoirs, almost always abreast of the loading effects. In 40 cases the effects of loading have been extended from flow velocities, water levels and chemical concentrations to biological indicators like algal biomass, zooplankton, and periphyton (e.g. V, VI, Inkala 2001, Kiirikki et al. 2001).

In 30 cases special attention has been directed to the effects of water temperature, changes of stratification, and ice cover (thickness, extension, freezing and melting). Most of these are done for power plants (plans, design, and change alternatives) and can include significant effects on water currents from the outlet and intake of cooling waters.
The effects of changes of bottom topography have been studied in 80 applications. In 48 cases the attention has been in the reduction or closing of the cross-sections (with embankments for roads, harbours, or breakwaters, artificial islands, dams, thresholds (bottom dams) or other structures). In 11 cases main attention has been in enlargement or opening of cross-sections (channels, passages, sand intake, maintenance dredging etc.). In 21 cases both type of changes have been calculated. Overlapping with cooling water effects appears in 16 cases, and overlapping with loading effects in 56 cases.

The water areas of the model applications have been lakes in 67 cases, rivers, river sections or river networks in 48 cases, and reservoirs, watersheds, wetlands or ponds in 31 cases, in almost 30 cases including overlapping with each other. General circulation, water level changes or substance distributions of wider sea areas have been studied in 25 cases, coastal areas separated from the sea with approximate boundary conditions in other 26 cases, and coastal areas fully surrounded and coupled with the wider sea areas in 135 cases.

The geographical locations of the application areas have distributed as follows:

<table>
<thead>
<tr>
<th>Sea cases</th>
<th>60 in Gulf of Finland and its coastal areas</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>48 Bothnian Bay and its coastal areas</td>
</tr>
<tr>
<td></td>
<td>38 Bothnian Sea, the whole Gulf of Bothnia and their coastal areas</td>
</tr>
<tr>
<td></td>
<td>28 other parts of the Baltic Sea (Archipelago Sea, the Baltic Proper)</td>
</tr>
<tr>
<td></td>
<td>14 other sea and coastal areas (Atlantic, Pacific and Indian Ocean, the Mediterranean Sea, Red Sea, Arab Gulfs, South-China Sea)</td>
</tr>
<tr>
<td></td>
<td>186 sea and coastal areas altogether</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Inland cases</th>
<th>22 in North Finland</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>18 East Finland</td>
</tr>
<tr>
<td></td>
<td>10 West Finland</td>
</tr>
<tr>
<td></td>
<td>17 Central Finland</td>
</tr>
<tr>
<td></td>
<td>12 South Finland</td>
</tr>
<tr>
<td></td>
<td>14 elsewhere in Europe</td>
</tr>
<tr>
<td></td>
<td>17 South-East Asia</td>
</tr>
<tr>
<td></td>
<td>8 elsewhere in the world (mainly other areas of Asia, and Africa)</td>
</tr>
<tr>
<td></td>
<td>118 inland areas altogether</td>
</tr>
</tbody>
</table>

3.6 Tracer studies as background to modelling

Artificial tracers are an appropriate means – often the most accurate or the most sensitive if not always the only ones – for detailed examination of transport and mixing in any kind of industrial or environmental systems. In surface waters their merits and possibilities have been recognized and intensively utilized decades ago
(e.g. Ljunggren et al. 1959, Likens & Hasler 1960, Harremoes 1966, Kuoppamäki & Kuusi 1973).

In line with the increased use and development of the tracer techniques the interpretation of tracer results developed as well, resulting in a considerable increase of understanding on the transport and mixing dynamics in the nature. The present section is aimed at summarizing the experience gained from the two–three decades of tracer studies, at evaluating its significance and at assessing the needs for further application of the tracer techniques. To illustrate the background of the present situation, the application history of tracer studies in Finland is at first briefly reviewed. Thereafter the conclusions and consequences of the tracer results are analyzed and finally the future prospects of tracer techniques are discussed.

The use of the tracer studies in Finland started in the beginning of 1970'ies for analyzing the effects of wastewater discharges and for predicting the effects of the new alternatives planned. Altogether more than 60 tracer studies with radioactive or activable isotopes have been carried out by the Reactor Laboratory at the Technical Research Centre of Finland (VTT). The demand and execution of tracer studies rapidly increased during the first half of 1970'ies but stabilized thereafter to 0–2 studies a year as appears in Fig. 3.

![Fig. 3. Number of annual radioisotope tracer studies of surface waters in Finland 1970–90 by Reactor Laboratory at the Technical Research Centre of Finland (VTT).](image)

The intensive but relatively short life-span of the tracer studies calls for closer analysis of the factors having contributed to the demand and to its decay. The urgent and apparent need for better knowledge of the waste water dilution and movements together with the availability of a most appropriate tool to meet these requirements were the main reasons for the rise of the tracer bloom in the
beginning of 1970'ies in Finland. The decrease of this demand, on the other hand, was contributed by a more complicated bunch of reasons.

As an immediate factor, the oil crisis in the middle of 1970'ies considerably reduced the industrial funding for environmental research. This was highly significant especially for tracer studies because they always had to be separately arranged and agreed, they were quite expensive and they were almost totally financed by the industry. As a co-effect of the oil crisis, the production of pulp and paper was temporarily decreased in some places resulting in reduced loading and consequently in changes of water quality in the recipients.

During the late 1970'ies legislation, administration practice and attitudes developed as well. Higher standards were put for waste water purification which permanently reduced the need of traditional applications of tracer studies by decreasing the relative importance of point sources and emphasizing the role of other types of loading, like the non-point sources, the atmospheric deposition, and the internal loading from the bottom. Regular water quality sampling at the recipients was started.

In addition to the regular water quality sampling (Heinonen 1983, Kettunen 1993), several other types of compensation or competitive measurement techniques have been emerged during the past decade. These include especially the flow velocity measurements with recording current meters and drogues, the satellite images and remote sensing data in general (Kuittinen et al. 1991a,b, Colpaert & Lauri 2000) and the several alternatives of radioisotope tracers, e.g. bacteriophages, temperature and salinity etc. as natural tracers, activable tracers and fluorescent dyes with improved detection sensitivity.

One of the main factors responsible for the reduced demand of the tracer studies in surface waters, however, was an accomplishment, output and merit of the tracer studies themselves. The improved understanding of the nature processes and their dynamics, much boosted and gained by tracer experiences, appeared as the development of more and more detailed and comprehensive mathematical models. Their expanded use and demand, staff allocation, and the increased confidence on their results belonged to the main factors contributed to the cease of the use of tracers in the open environment.

As to the present possibilities to use radioisotope tracers in the environment, the legal and other written and explicit constraints have not changed considerably since 1950'ies (Suomen Laki 1957–2000: Radiation act 174/1957 vs. 592/1991, Radiation decree 328/1957 vs. 1512/1991, Decree of the Ministry of Social Affairs and Health 594/1968 vs. 423/2000; Nuclear energy act 990/1987, Nuclear energy
decree 161/1968). Public attitudes, however, may have changed since 1970's, and possibilities to transmit and distribute scientific and especially numerical facts via mass media presumably decreased or disappeared.

Since 1989 it has not been tested whether and how the changes of circumstances would appear in the administration practice of the supervising authorities. Special permits for releases would be needed in any case, now as in 1970's. The personal dose limits today, 50 mSv/ year/ person and 100 mSv/ person in 5 years, would restrict the number of tracer injections done by the same person to not more than 4–8 each year and to less than 20 in five years. Development of radiation protection, detection sensitivity or other arrangements would enhance the number of permitted contributions correspondingly.

Despite of the termination of the large scale mixing studies with radioisotope tracers in water bodies, their use in other type of applications has continued vividly without interruptions. In the industrial applications, the use of radioisotope tracers in flow and mixing studies has been partly supplemented with acoustic and electric techniques by the IndMeas Ltd. for Industrial Measurements having the same origin and background as EIA Ltd. for environmental modelling (e.g. Kuoppamäki 2000, 2003, 2006). In the most extensive use of isotopes as tracers in organic food webs, wetlands and water bodies, the stable isotopes have been applied very much in addition to the radioactive ones (e.g. Jones et al. 2004, Grey et al. 2004, Kværner & Kløve 2006, Ronkanen & Kløve 2007, 2008, Taipale et al. 2008). Also dyes have been used as tracers for decades (e.g. Hela & Voipio 1960, Kiirikki & Mykkänen 2008), and bacterophages in some cases (e.g. Niemelä & Kinnunen 1968).
4 Materials and methods

4.1 Application areas

The main area of application in Papers I–III is the Kemi River water course. The locations of planned and existing reservoirs there are shown in Fig. 4. Along the river, 17 hydropower stations produced electricity 4000 GWh/year, 7% of Finland's consumption in 1995. Vuotos would increase this yield with more than 350 GWh/year, almost with 10%. The main features of the three basins compare with each other as follows:

<table>
<thead>
<tr>
<th>Area</th>
<th>Lokka</th>
<th>Porttipahta</th>
<th>Planned Vuotos</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impounded since (date)</td>
<td>July 11, 1967</td>
<td>September 17, 1970</td>
<td>(not known)</td>
</tr>
<tr>
<td>Drainage area (km²)</td>
<td>2 280</td>
<td>2 573</td>
<td>9 406</td>
</tr>
<tr>
<td>Annual mean flow MQ (m³/s)</td>
<td>26.5</td>
<td>28</td>
<td>106</td>
</tr>
<tr>
<td>Mean low flow MNQ (m³/s)</td>
<td>7.8</td>
<td>8</td>
<td>27.5</td>
</tr>
<tr>
<td>Detention time under MQ (d)</td>
<td>218–901</td>
<td>62–559</td>
<td>16.5–144</td>
</tr>
<tr>
<td>Detention time under MNQ (d)</td>
<td>742–3070</td>
<td>217–1960</td>
<td>63.6–555</td>
</tr>
<tr>
<td>Regulation range (m a.s.l.)</td>
<td>240–245</td>
<td>234–245</td>
<td>158.5–166.5</td>
</tr>
<tr>
<td>Water volume (km³)</td>
<td>0.50–2.063</td>
<td>0.15–1.353</td>
<td>0.151–1.318</td>
</tr>
<tr>
<td>Surface area (km²)</td>
<td>216–417</td>
<td>34–214</td>
<td>55.0–236</td>
</tr>
<tr>
<td>Mean depth (m)</td>
<td>2.31–4.95</td>
<td>4.41–6.32</td>
<td>2.52–5.54</td>
</tr>
<tr>
<td>Maximum depth (m)</td>
<td>5–10</td>
<td>23.5–34.5</td>
<td>10.0–18</td>
</tr>
<tr>
<td>Bottom distribution</td>
<td>thick-peat bottoms (%)</td>
<td>56.4</td>
<td>31.2</td>
</tr>
<tr>
<td></td>
<td>thin-peat bottoms (%)</td>
<td>19.4</td>
<td>13.5</td>
</tr>
<tr>
<td></td>
<td>mineral bottoms (%)</td>
<td>21.0</td>
<td>54.9</td>
</tr>
<tr>
<td></td>
<td>old rivers and lakes (%)</td>
<td>3.3</td>
<td>0.4</td>
</tr>
</tbody>
</table>

The existing reservoirs, Lokka and Porttipahta, are interconnected with each other through a channel opened at November 20, 1981. Since then, more than 90% of the water has been discharged through the Porttipahta Reservoir and power station downstream to River Kitinen, about 140 km until the main stream of the Kemi River and the planned areas of the new reservoir. Therefrom, there is about 39 km till the main natural lake of the area, Lake Kemijärvi. From the lake to the sea there is about 216 km along the river. Approximative water volumes of the river sections are up to 0.06 km³ between Vuotos and Lake Kemijärvi and 0.6–0.8 km³ from the lake to the sea. These correspond to detention times of almost 3 and about 20 days for the upper level and the mean flow MQ.
Fig. 4. Locations of the areas of applications considered:
1 = Lokka reservoir (impounded since July 11, 1967)
2 = Porttipahta reservoir (impounded since 17 September, 1971)
3 = Vuotso channel (opened 20 November, 1981)
4 = planned reservoir
5 = Lake Kemijärvi (regulated since 1963)
6 = River Kemijoki (regulated from its mouth since 1948)
7 = Coastal area off Kemi
8 = Bothnian Bay
9 = Lake Haukivesi
10 = Lake Näsiselkä
11 = Kymi River
12 = Estuary off Kotka
13 = Gulf of Finland
14 = Bothnian Sea (8 + 14 = Gulf of Bothnia)
15 = Baltic Sea
Lake Kemijärvi has been regulated since 1963 and the Kemi River from its mouth since 1948. Main features of the lake and sea areas modelled are summarized as follows:

<table>
<thead>
<tr>
<th>Area</th>
<th>Lake Kemijärvi</th>
<th>Coastal zone off Kemi</th>
<th>Bothnian Bay</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drainage area (km²)</td>
<td>27 285</td>
<td>50 910 (Kemi River)</td>
<td>277 000 (30 rivers)</td>
</tr>
<tr>
<td>Annual mean flow MQ (m³/s)</td>
<td>302</td>
<td>530</td>
<td>3 200</td>
</tr>
<tr>
<td>Other water exchange (m³/s)</td>
<td>0</td>
<td>(5000–8000)</td>
<td>(10 000–13 000)</td>
</tr>
<tr>
<td>Approximative detention time (d)</td>
<td>8–50</td>
<td>about 7 (3–30)</td>
<td>1 100–1 300</td>
</tr>
<tr>
<td>Regulation range (m a.s.l.)</td>
<td>142–149</td>
<td>about 0 (natural)</td>
<td>about 0 (natural)</td>
</tr>
<tr>
<td>Water volume (km³)</td>
<td>0.22–1.29</td>
<td>(1.5)</td>
<td>1 490</td>
</tr>
<tr>
<td>Surface area (km²)</td>
<td>130–285</td>
<td>(200)</td>
<td>36 800</td>
</tr>
<tr>
<td>Length x width (km)</td>
<td>(30 x 35)</td>
<td>6–10 x 20–30</td>
<td>300 x 150</td>
</tr>
<tr>
<td>Mean depth (m)</td>
<td>1.70–4.3</td>
<td>&lt;10</td>
<td>40.5</td>
</tr>
<tr>
<td>Maximum depth (m)</td>
<td>14–21</td>
<td>15</td>
<td>147</td>
</tr>
<tr>
<td>Phosphorus loadings in 1980’s</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- from point sources (kg/d)</td>
<td>60</td>
<td>170</td>
<td>920</td>
</tr>
<tr>
<td>- from drainage area (kg/d)</td>
<td>(500–800)</td>
<td>1200 (Kemi River)</td>
<td>8900</td>
</tr>
<tr>
<td>- from air + surrounding sea (kg/d)</td>
<td>(&lt;10 + 0)</td>
<td>(&lt;10 + 5000)</td>
<td>1100 + 5500</td>
</tr>
</tbody>
</table>

The coastal zone is an integrated part of the Bothnian Bay as well as Bothnian Bay is connected to other parts of the Gulf of Bothnia and the Baltic Sea. Thus the borders, especially for the coastal zone are not sharp, and only vague estimates for its volume, surface area, water exchange through open boundaries (very much depending on wind and ice conditions) and detention times are presented, mainly for illustration of the orders of magnitude.

Pulp and paper industry discharged 97–99% of the point source loading to Lake Kemijärvi, 92–99% of that to the coastal zone and 50–60% of that to the wider sea area. The rest was mainly from municipal sources and in the sea less than 3% from fish farming.

The reservoirs are usually covered with ice from October till the beginning of May, Lake Kemijärvi for 200–210 days from the middle of November, and the sea for 4–5 months between December and May. Mean salinity of the Bothnian Bay is 3.5 per mill. In ice-free seasons the salinity is quite well mixed but below the ice cover sharply stratified off the river mouths. Thermocline varies between 10 and 25 m depending on the weather conditions especially during the ice-free period.

In the earlier model applications in the coastal area off Kemi (Paper IV), the model area included the same locations as above (in Paper III) but without the external sea areas. Water exchange across the open sea boundaries was estimated by approximate boundary conditions. Compared with the area of the finest resolution in 1990’s, the extensions of the earlier model applications were as follows:
For practical solution of the models, mainframe computers Univac 1108 in 1981 and Cyber 170 in 1983 were used at first, supercomputer Cray X-MP in 1990, and personal computers thereafter, PC 486 in 1992.

The extensions of the coastal areas of the other 40 applications until 1993 reviewed in IV were comparable with those of the coastal area off Kemi presented above. In 14 cases 3D models were used, in 20 cases 2D+ models focused to specific layer with extra assumptions, and in 9 cases vertical average 2DH models without assumptions for their vertical profiles.

Compared with the extensions of the Bothnian Bay above, the characteristic features of the other areas receiving waters from and surrounding the application areas, viz. Bothnian Sea and Gulf of Bothnia I–IV and VI, Gulf of Finland V, VII, and finally the Baltic Sea, varied as follows:

<table>
<thead>
<tr>
<th>Area</th>
<th>Bothnian Sea</th>
<th>Gulf of Bothnia</th>
<th>Gulf of Finland</th>
<th>Baltic Sea</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface area (km²)</td>
<td>66 000</td>
<td>115 500</td>
<td>29 600</td>
<td>415 300</td>
</tr>
<tr>
<td>Water volume (km³)</td>
<td>4 340</td>
<td>6 390</td>
<td>1 100</td>
<td>21 700</td>
</tr>
<tr>
<td>Mean depth (m)</td>
<td>62</td>
<td>55</td>
<td>37</td>
<td>52</td>
</tr>
<tr>
<td>Maximum depth (m)</td>
<td>230</td>
<td>230</td>
<td>123</td>
<td>459</td>
</tr>
<tr>
<td>Drainage area (km²)</td>
<td>221 000</td>
<td>490 000</td>
<td>413 000</td>
<td>1 720 000</td>
</tr>
<tr>
<td>River inflow MQ (km³/a)</td>
<td>83</td>
<td>185</td>
<td>114</td>
<td>480</td>
</tr>
<tr>
<td>Rivers in 2000 (km³/a)</td>
<td>128</td>
<td>283</td>
<td>107</td>
<td>584</td>
</tr>
</tbody>
</table>

When the water exchange between these subareas exceeds the river inflows typically with a factor of about three, hydrological detention times of about 3 years are received for the Bothnian Bay, Bothnian Sea and the Gulf of Finland, about 6 years for the Gulf of Bothnia and 12 years for the Baltic Sea.

The lake areas of Haukivesi V and Näsiselkä VI and the coastal area off Kotka VII are located in the middle course or in the estuary of the major South-Finnish
rivers, viz. the Vuoksi, Kokemäki River and Kymi River. Their hydrological properties are summarized as follows:

<table>
<thead>
<tr>
<th>Area</th>
<th>Haukivesi [V]</th>
<th>Näsiselkä [VI]</th>
<th>Estuary off Kotka [VII]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface area (km²)</td>
<td>370</td>
<td>92.6</td>
<td>105</td>
</tr>
<tr>
<td>Water volume (km³)</td>
<td>4.25</td>
<td>1.43</td>
<td>1.10</td>
</tr>
<tr>
<td>Mean depth (m)</td>
<td>11.5</td>
<td>15.4</td>
<td>10.5</td>
</tr>
<tr>
<td>Maximum depth (m)</td>
<td>55</td>
<td>61</td>
<td>33</td>
</tr>
<tr>
<td>River inflow MQ (m³/s)</td>
<td>540</td>
<td>64</td>
<td>145 (of 300)</td>
</tr>
<tr>
<td>Drainage area (km²)</td>
<td>50 600</td>
<td>7670</td>
<td>37 160/2.07</td>
</tr>
<tr>
<td>Lake percentage (%)</td>
<td>17.5</td>
<td>13.9</td>
<td>18.3</td>
</tr>
<tr>
<td>Width of the model area (km)</td>
<td>51.2</td>
<td>17</td>
<td>13.7</td>
</tr>
<tr>
<td>Length of the model area (km)</td>
<td>43.2</td>
<td>15</td>
<td>13.7</td>
</tr>
<tr>
<td>Horizontal resolution (m)</td>
<td>400</td>
<td>1000</td>
<td>720</td>
</tr>
<tr>
<td>Number of vertical layers</td>
<td>12</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>Horizontal grid boxes</td>
<td>128 x 108</td>
<td>17 x 15</td>
<td>19 x 19</td>
</tr>
<tr>
<td>Total number of grid boxes</td>
<td>165 888</td>
<td>1275</td>
<td>361</td>
</tr>
</tbody>
</table>

The mean flow rates MQ of river inflows above are those used in the model applications. For the estuary off Kotka, the mean flow estimates in 1984 were 155 m³/s to West outside the model area, and about 48, 2 and 95 m³/s to the three branches in the model area from West to East, viz. branches of Langinkoski, Huumanhaara and Korkeakoski. The last one of these is regulated by a hydropower plant and maintains the discharge 95 m³/s as long as possible. The corresponding mean flows of 1961–90 are 170 m³/s to West outside the model area and 160 m³/s to the model area. In both estimates the part of the drainage area discharged to the model area is the total drainage area divided by 2.07. For the lake Näsiselkä the mean flow of 1961–90 is 71 m³/s instead of the 64 m³/s of 1986. The flow statistics and distribution for the lake Haukivesi were calculated separately for the present study V.

The modelled river section leading to the estuary off Kotka VII was 75 km long, at the mean flow rate about 180 m wide and as an average 4.7 m deep. Its surface area is thus 13.5 km², water volume 0.06 km³ and hydrological residence time about 2.5 days at the mean flow rate.

### 4.2 Main models used

In most of the applications, the EIA 3D model system is used (Fig. 5). Detailed description of the mathematical relations between the model quantities and the numerical values of the model parameters are given in the Papers I and VI, and also e.g. by Koponen (1984), Virtanen et al. (1993b), and most recently by Koponen et al. (2008a,b).
The EIA 3D model system is a fully three-dimensional model based on combinations of rectilinear rectangular grids. The model system accommodates meteorological, hydrological, topographic, land use and infrastructure characteristics of any modelling area and produces 3D hydrodynamics and water quality. The modelling platform including data processing, model control, GIS, database control, model data products and visualization is de-coupled from the actual model engines. The model is able to describe the 3-dimensional characteristics of the flooding, flow, water quality, erosion and sedimentation in the lakes, reservoirs, river channels and floodplains, as well as in the coastal areas, seas and oceans.

The EIA 3D model is developed by Environmental Impact Assessment Centre of Finland Ltd (EIA Ltd.). The development work started 1974 when EIA Ltd. was still part of Technical Research Centre of Finland, the largest governmental research institute in Scandinavia. The EIA 3D model has two components: EIA 3D hydrodynamic model and EIA 3D water quality model. The main attention here is on the characteristics of the first one.

EIA 3D model is a three-dimensional baroclinic multilayer model (Simons 1973, 1980, 1988, Koponen 1984, Koponen et al. 1992). It is based on solving simplified Navier Stokes equations in rectangular model grid. The cell width can vary in x- and y-directions. It is possible to model whole domains with varying grid resolutions and couple them together. Hydrostatic assumption, Boussinesq approximation and incompressibility of water are used in the model formulation. The water mass is treated as vertical layers similarly to z-level models. Horizontally the model area is subdivided into rectangles with arbitrary mesh intervals in both directions.

The currents in the model are determined by the following factors:
- wind force (or ice friction) on the water surface,
- water level gradients (hydrostatic pressure),
- bottom friction on the bottom,
- atmospheric pressure at the surface,
- conservation, continuity and incompressibility of water,
- density differences (their effects on hydrostatic pressure),
- internal friction (vertical, and also longitudinal and transversal viscosity),
- Earth rotation (Coriolis effect),
- transport of velocity differences with water currents (advection),
– vegetation impacts (on friction).

The model is solved numerically using implicit finite difference method applied to control volumes. For computational purposes the calculation of the 3D currents is divided into integrated 2D external mode (surface level elevations, depth integrated currents) and to 1D internal mode (layer velocity differences). Model can also calculate directly the layer velocities. Eddy viscosity approximation of turbulence is used with constant coefficients, also mixing length and k-epsilon turbulence models are available. The advection of momentum has only minor effects on flows, when the flow velocities are small, and is therefore not always used.

An overview of the model facts is shown in Fig. 5.

<table>
<thead>
<tr>
<th>Name of software:</th>
<th>EIA 3D Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Developer:</td>
<td>Jorma Koponen, Markku Virtanen, Hannu Lauri, and Arto Inkala (of about 20 other developers)</td>
</tr>
<tr>
<td></td>
<td>Environmental Impact Assessment Centre of Finland Ltd. (EIA Ltd.)</td>
</tr>
<tr>
<td></td>
<td>Teknikantie 21 B, 02150 Espoo, Finland</td>
</tr>
<tr>
<td></td>
<td>Tel. +358-9-70018680, Fax. +358-9-70018682</td>
</tr>
<tr>
<td></td>
<td>E-mail: <a href="mailto:koponen@eia.fi">koponen@eia.fi</a> / <a href="mailto:virtanen@eia.fi">virtanen@eia.fi</a></td>
</tr>
<tr>
<td>First available:</td>
<td>first 2D version 1975, first 3D version 1983, last major revision in 2002</td>
</tr>
<tr>
<td>Hardware required:</td>
<td>can be run in all types of computers from PCs to supercomputers</td>
</tr>
<tr>
<td>Software required:</td>
<td>can be run on all platforms (most user friendly version requires Windows 2000 or XP)</td>
</tr>
<tr>
<td>Program language:</td>
<td>FORTRAN (model and basic graphics) and C++ (graphical user interface)</td>
</tr>
<tr>
<td>Program size:</td>
<td>Hydrodynamics and other physical modules 1 Mb.</td>
</tr>
<tr>
<td></td>
<td>Water quality and ecological modules 1.6 Mb.</td>
</tr>
<tr>
<td></td>
<td>Graphical user interface 0.7 Mb (sizes are for Windows NT)</td>
</tr>
<tr>
<td>Availability:</td>
<td>Available free within cooperative projects or as part of an application</td>
</tr>
<tr>
<td>More information</td>
<td><a href="http://www.eia.fi">www.eia.fi</a></td>
</tr>
</tbody>
</table>

Fig. 5. Overview of the main model facts.

Numerous alternative or optional features, possibilities or characteristics are directly included in the 3D model code, e.g.
- 6 vertical turbulence models (e.g. k-epsilon)
- 5 horizontal turbulence models (e.g. Smagorinsky)
- 2 integrated wave models (others in specialized applications)
- 2 wind fetch models for the wave characteristics and effects
- 3 erosion models
- 4 bottom friction models
- Vegetation friction in different water layers
- Surface friction (e.g. ice)
- Radiation and heat
- Hydraulic controls (dikes, gates, water intakes, outlet points etc.)
- Wetting and drying
- Morphological changes due to sedimentation and erosion
- Cohesive sediment simulation
- Bed load simulation
- Specialized 3D reservoir model
- Diagnostic calculation from irregular data
- 2 isopycnal modes for stratification
- Hybrid stratification calculation (combined normal and isopycnal modes)
- 6 momentum advection modes (e.g. TVD)
- 3 transport calculation modes (e.g. TVD and flux correction)
- Integrated statistical analysis
- Algorithmic and code optimization resulting in fast execution times
- Parallelization for multi-processor machines
- Flexible, fully coupled nesting for better local accuracy
- Transportable code (tested from supercomputers to PC’s)
- Code developed and tested over 20 years in over 200 applications
- Several models can be coupled to the hydrodynamics (hydrological models such as conceptual and distributed gridded watershed models; chemical processes e.g. evaporation, dissolution, emulsification on surface, in the water column and on bottom; several water quality and ecosystem models for oxygen, BOD, turbidity, nutrients, heavy metals, carbon, different phytoplankton groups, macrophytes, bacteria etc.; benthic processes)
Thus the model system forms an extremely versatile platform for a wide scope of applications.

Examples of special applications include
- flood modules for dam- and dike breaks,
- detention area simulation,
- flooding of floodplains;
- reservoir models for managing reservoir hydrodynamics,
- sedimentation and water quality;
- water resources management;
- oil- and chemical accidents;
- monitoring support;
- anoxia, eutrophication, algal blooms, filamentous algae, shore vegetation.

The model grid is based on the depths measured from the modelled area. Horizontal grid resolution depends on the application requirements. Typical grid box sizes are from 50m in the area of interest, up to tens of kilometres for large sea areas. Vertical resolution typically ranges from 0.5m on the surface to tens of meters in deeper areas.

In the horizontal direction model utilizes rectangular Arakawa E-grid (Arakawa 1966). In Arakawa E-grid both velocity components are defined in the middle of the grid cells as opposed to the usual C-grid arrangement where the components are defined on separate grid boundaries. In E-grid the vertical velocities are defined on the corners of the velocity grid cells. E-grid avoids stagnation points in 3D applications because water can circulate in the cells even if they are surrounded by land on each side. Model uses finite volume method to solve equations. Because of this the grid width can vary in x-, y- and z-directions.

In the vertical direction z-grid is used. This means that the layer depth remains constant over the whole model area except on the bottom where it varies freely. In the EIA model it is possible to couple different models with different resolutions together. In this way a large area can be modelled with very high resolution for critical areas. The nested models are fully coupled, in other words the high resolution model affects the coarse one.

As the boundary conditions, the following types are most usual:
- discharge boundaries (typically upstream river boundary)
- rating curve discharges: h-Q curve points, simple equation, steep bank, mild bank
water level boundaries (downstream or tidal boundaries)
- wind stress including wind fetch and wave action effects
- bottom friction.

Vegetation stresses are internal stresses created by vegetation in different water layers. Vegetation and structures impact on model parameters, for instance wind stress is diminished when submerged vegetation reaches over the water surface.

In addition to the boundary conditions, hydrological control structures can be located in the middle of grid cells. They don’t change grid cell volume, that is it is assumed that the control structure dimensions are small compared to the grid cell size. If the volume change needs to be accommodated, the model grid has to be changed accordingly. At the moment the treatment of four possible control structure types is implemented and included in the 3D model, viz. dike (weir flow), water level gate, time gate, and dam or dike break. Overflow for each dike can be restricted to the direction of one horizontal co-ordinate axis or allowed for both axis directions. The model input, data and processing structures have been devised in a way that allows easy implementation of any new required structure in addition to those four mentioned above.

When GIS-data on dikes is available, it can given to the model in BIL (Binary Inter-Leaved) format. The resolution of the BIL-file has to be the same as in the model. If nested models are used there must be a separate BIL-file for each nested grid. Existence of a dike is expressed in the raster data with a specific numerical value. Other numbers mean no dike. The raster can be created by GIS-software such as ArcGis with appropriate spatial extensions. After GIS-processing the raster layer has to be checked and corrected by hand in order the dikes to be continuous and not block river channels.

Dikes (or embankments in general) and gates can be defined through a map and control structure table editor. After user has pointed out the area and specified the type for the structure, the user interface asks secondary data such as dike orientation, dike height and gate flow.

Specific inputs for floodplain and lake modelling are:
- topography (DEM, digital elevation map)
- vegetation (roughness and friction)
- inflows and outflows
- inflow concentrations
- possible loadings
Grid generation programs read GIS-generated DEMs or other elevation data and produce the model grid. The data is read separately for each nested grid with different resolution. Based on the tributaries data model calculates the average width and depth of the tributary in each model grid cell.

Model outputs that can be taken out from the hydrodynamic part of the system include

- water depths
- water level elevations
- flow velocity components
- flood durations
- flood arrival times.

Other quantities that can be selected for outputs are e.g. concentrations, bottom heights especially in morphological studies, vertically averaged velocities, viscosity and other parameters connected to turbulence. Model output files for GIS contain co-ordinate system and format specifications. The names of the files signify the output date and time, variable, layer and nested model. Model output resolution is user defined and is usually higher than calculation resolution. Interpolation and tributaries masking is used in the output. Output files are read directly into the GIS and are used e.g. for damage analysis and evacuation planning.

The GIS-format selected for the data exchange between the GIS and modelling software is BIL (Band Interleaved by Line). This format is open so that it can be accessed directly from the modelling software and is relatively efficient in storing data. The main BIL-data files are accompanied by auxiliary files that define the binary format and coordinate system of the data.

The model input data consists of model grid and model forcing data, e.g. wind and boundary flows. Output is 3-dimensional time-dependent flow field, which can be further used to compute, for example, transport of substances, water exchange, and sedimentation processes. Visualization of the flow data can be done with animations, and information of computed variables from single sites can be obtained as time series.

As a summary the features of the input data for the flow model include

- bathymetric data for model grid, either as shorelines, point depth data and depth isolines, or as a digital elevation model.
– wind measurements from modelled area for wind forcing computation, wind speed (m/s) and direction (degrees) with 3-6h or better time resolution
– boundary flows (m³/s) including rivers and open boundaries (daily values)
– flow and/or water level measurements for model calibration, flow is often measured in cm/s for every ten minutes, for surface height the time resolution depends on the modelled area and may vary from 10 minutes to one day.
– temperature and salinity initial and boundary values (if computed).
– sources, initial and boundary values of transported substances (if computed).

As a summary the computed results can include (with any time resolution, with any time step)
– computed 3D time-dependent flow field for the modelled area
– time series of flow speed, direction and water level
– time-dependent fields of other computed variables (temperature, salinity, suspended sediments etc.)
– time series computed variables
– animations of flow and computed variables
– The flow model parameters can be divided to several categories including:
  – model setup parameters (calculation type selection related parameters)
  – numerical parameters (computation time steps, etc.)
  – physical parameters (e.g. turbulence coefficients, wind drag coefficient)

In addition to above model related parameters there are options for setting up the input and output data.

The basis of the water quality modelling is transport and dispersion of substances. Dispersion is modelled using advection-diffusion equation. It states that a concentration is advecting (moving) with a given flow, and diffusing (spreading) with given diffusion speed. The model equations and numerics are presented in detail in the Papers I and VI, and also e.g. by Koponen (1984), Virtanen et al. (1993b), and most recently by Koponen et al. (2008a). A general scheme of the stages in application, common to both flow and water quality model, is outlined in Fig. 6.
To compute the water quality first the water flows must be computed using a flow model. Flows can be provided in three different ways (as a selection of the main alternatives of Chapter 2.4.):

1. Flow is computed together with the water quality
2. The flow is computed dynamically using the flow model and stored periodically – the water quality model then uses these stored flow fields.
3. The flows can be assumed to be linearly dependent on the boundary and wind forcing and linearly combinable, so that a number of pre-computed static flow fields can be combined to create a flow field for given boundary flows and wind direction.
The disadvantage of using stored dynamic flow fields is that they necessarily have to be averages over rather long time periods, at least a few hours. This is not a problem for transport, but for erosion the method tends to even out important flow peaks.

The model requires flow computed by the flow model, either as static flow fields or as a dynamic flow field. In the case of static flows, weather and boundary conditions are needed to run the model, if dynamic flow is used this data is already included into the flow field. In addition to flow related data point loads and initial concentrations of computed variables are needed.

As a brief summary, the input data for water quality computation include

- flow fields (static or dynamic)
- wind and boundary flow data, if static flow fields used
- point load data
- boundary concentration data
- initial concentration data
- water quality measurements for model calibration and verification.

As a summary, its computed results can include (with any time resolution, with any time step):

- computed 3D time-dependent concentration fields of the modelled variables
- time series of computed variables
- animations of computed variables.

The water quality model parameters can be divided to several categories including

- model setup parameters (calculation type selection related parameters)
- numerical parameters (computation time steps, etc.)
- physical parameters (settling parameters, diffusion coefficient).

In addition to these model related parameters there are options for setting up the input and output data. The model parameters are explained more carefully in the model documentation and user interface help files (Koponen et al. 2008b).

As a recent extension of the model system, an ecosystem productivity component is implemented (Lamberts & Koponen 2008). It is based on the fact that flow alterations affect the hydrological characteristics of the ecosystem. A question of paramount importance is what the impact of these changes will be for the productivity of the ecosystem and hence the livelihoods it supports.
The productivity of the ecosystem is a complex combination of aquatic and terrestrial production. The dynamic interactions between these two are often at the basis of the high productivity. The interactions between all the elements of the ecosystem are intense and very dynamic, and, overall, little specific knowledge exists. Judging by the livelihoods that are sustained by the natural resources of the ecosystem, the production is very large, and the system is resilient to natural inter-annual variation in the flood cycle. Fish catches are very large, albeit that the knowledge about their size suffers from inadequate data and very large uncertainties.

Fish are at the end of the production webs of the ecosystem. With the current lack of specific knowledge and basic data, it is practically impossible to forecast the impact of alterations on fish catches both quantitatively or even qualitatively. The same applies to the other natural resources such as wood and non-wood forest products. Still, the natural productivity of the ecosystem is of high importance in decision making.

While there is an unquantified amount of organic matter that enters the ecosystem with the flood and drainage waters, most of the productivity is believed to be based on primary production inside the ecosystem. In this respect, the autochthonous primary production is the limiting factor for secondary production and, given the high efficiency of energy and nutrient use in tropical flood-pulsed ecosystems, loss of primary production potential inside the ecosystem will affect the overall productivity.

Contrary to the complex production pathways for secondary producers such as fish, the primary producers and their characteristics can be modelled in a robust way. Crucial data can be collected in a short period of time and by means of sampling.

The model module on (primary) production potential has identified the main groups of primary producers (phytoplankton, periphyton, terrestrial macrophytes and floating aquatic vegetation) in the ecosystem and modelled their primary production dynamics in function of selected environmental parameters. The environmental parameters have been selected based on their adequacy in explaining primary production potential. Data availability has been considered, as well as methods for filling any critical knowledge gaps.

The model allows to quantitatively calculate the changes in primary production potential of the ecosystem in function of changing hydrological conditions. Where data from the are inadequate for the modelling purposes, data have been used from literature on similar ecosystems. One of the most crucial
parameters is the depth to which photosynthetically active light can penetrate in the water column, known as the euphotic depth. The hydrodynamic model contributes this information with a high degree of spatial and temporal detail, allowing for accurate simulations of the impact of different scenarios (Lamberts & Koponen 2008).

The primary production module thus provides a tool to assess the impacts of flow changes and alterations on the productivity of the ecosystem.

In addition to the 3D model system, the 1DL models used in the Papers III and VII are briefly described in these papers and more comprehensively by Rautiainen and Virtanen (1986). A most detailed analysis of the stability conditions of a 1DL model system is presented by Somlyody and Virtanen (1982).

The 2DH and 2D+ model systems used in several applications of the Paper IV and in Paper VII utilize the Arakawa C-grid and are briefly explained in the papers. Their details are described by Virtanen (1977, 1978), Rautalahti-Miettinen et al. (1986), and Koponen et al. (2008a). The most detailed and comprehensive analysis of their formal accuracy and truncation errors are presented in Virtanen (1978) and Koponen et al. (2008a).

### 4.3 Steps of model applications

The applications of flow and water quality models are almost entirely made for solving some practical problem(s). This can be a planned or already done action or intervention, the effects of which on the water environment need to be known. Information can be needed e.g. for prevention or mitigation of drawbacks and disadvantages, saving in costs, optimum efficiency, design and dimensioning of the plan, selection between alternatives, fair distribution of benefits and costs, or evaluation and certification of the acceptability of the work. From this basis the model application proceeds ideally, in most comprehensive extent, as follows, starting with calculation of water currents (Fig. 7).

At first, the results of earlier observations are collected. These are completed with the information of the history of water use, loading and their changes, river flows, water level changes, periods of ice cover, winds especially of ice-free periods, wave action, tidal cycles and other factors which may have had influence on the water currents.

Historical data can be further supplemented with measurements of flow velocities. In analysis of their results, attention is directed especially to their correlation and time lags with winds, river flows and water level changes.
The numerical treatment of the area (the actual "model work") is started with specification of the extensions of the model area and its horizontal resolution(s) inside that area, i.e. its division into very small computational grid checks (in 2D) or boxes (3D). This division then determines how detailed results can be received as the computation of flows and transport is mainly concentrated on the differences between the adjacent grid boxes.

The locations of land areas and cost line(s), and the depths of each water point need then to be identified. For this, additional measurements can also be used. At the same, information on more detailed bottom and land shapes, finer than resolution, can be supplied for the model, to be taken into account as further possibilities or restrictions for water exchange. These supplements can concern e.g. narrow channels, passages, or deeps, sounds, capes, islands, isthmuses, necks of land, breakwaters, and embankments. With refined resolution, however, the need and use of these extra supplies has recently reduced very much. (Virtanen, Vepsä & Koponen 1993, Virtanen et al. 1979)

Flow velocities between the grid boxes are computed with the flow model, and compared with the measured values at measuring points. If serious disagreements are observed, the reasons for these are looked for. From the modelling side, this can mean e.g. more detailed or revised attention to the water depths, stratification conditions, or discharges. From the measured results, it is evaluated how certain, representative, and how closely correlated with ("explained by") the external conditions they are (Sarkkula & Virtanen 1978, Virtanen et al. 1979).

For more comprehensive or more detailed comparisons, tracers or drifters can be released, their movements observed, computed with the transport model, and the results compared with each other. Sensitivity tests analyze the dependence of model output on model inputs, parameter values and their changes. They help and advice to direct main attention to the factors most crucially affecting the model results, because their accuracy and accordance with nature are most central for the reliability of the model results. From this basis the flow fields (as such or as readiness for their calculation) are ready for usage for computation of further impacts as follows (Fig. 8).
Fig. 7. Steps of a model application, part 1: Beginning of the work until completed validity tests.
Fig. 8. Steps of a model application, part 2: From completed validity tests to practical decisions.

The bio-geo-chemical properties of water – and occasionally also its interfaces – have been measured mainly from water and sediment samples. Results of these earlier observations are acquired and connected with the information of loading,
water and weather conditions. When needed, further measurements and also field tests and laboratory experiments can be made. All results are analyzed with respect to the background, history and changes of external conditions.

The set of model variables is selected. This means specification of the indicators of water quality and other properties to be computed and used to show the influences and impacts. Abreast of this, also the periods and conditions for model application and comparison of the effects are specified. These can include both real periods with varying conditions and sets of constant or presumed worst sequences of conditions to show the extreme effects hardly ever approached.

The model validity is put under the most demanding and severest test with conditions varying as widely as possible. Therefore periods of dry and rainy weather, cold and warm temperatures, and high and low loading are preferred to include in applications. For comparisons between effects of different alternatives, the average low flow (MNQ) and mean flow (MQ) conditions are often especially preferred.

The transport and inherent changes (reaction kinetics, e.g. settling, sedimentation, buoyancy, degradation, decay, re-aeration, leaching etc.) of the water quality indicators are computed with the coupled transport and water quality models. The model results are compared with those of the field observations, and the reasons for possible discrepancies clarified. In comparison also the opinions of local experts and experiences of boatmen, fishermen and inhabitants are taken into account.

Possibilities to adjust the distributions of 3D model results by changing the values of kinetic rates or velocities – or their dependencies e.g. on temperature or concentrations – are quite limited. Their effect, however, can be tested, also as a part of sensitivity analysis, especially as there seldom are any direct measurements of or even possibilities to measure the rates and their dependencies.

Deeper and more thorough changes to 3D model results can be obtained by changes of flow model (mainly revision of depth data or closer attention to stratification), check of loading data and locations, or by refined subdivision of the model variables. E.g. suspended sediments can be divided by grain size and settling velocity, biological oxygen demand (BOD) by degradation rate, nutrients (phosphorus and nitrogen) by their chemical form and usability for algae, and algae and plankton by function or size, etc.

In comparison between the model and field results, the different nature of both has to be kept in mind. The model results are representative for grid box volumes, with typical extensions of 1–100 hectares and 0.5–5 meters, while field samples
are typically a few liters taken in a few seconds. In nature, concentrations can move in separate spots, patches or pulses, narrow wedges, and very thin layers, or accumulate in very small volumes at the bottom deeps. In the model their appearance is rounded off or smoothed down by grid resolution, unfortunately often also by numerical diffusion (non-physical mixing caused by the numerical approximations used in the solution of advective transport), and especially by the limited frequency (and sparse density) of the data of driving forces available and supplied for the model input.

Differences can be particularly striking between the external conditions supplied for model input and those having appeared and affected in the nature. Winds can vary very irregularly by time and space above the real water surface. The model results are typically computed with 3-hourly observations of one place (or their half-daily or daily averages, without space differences), often locating on land and sometimes even quite far, at 10–20 km distance, from the model area. River and wastewater discharges can vary within a day but can be supplied for model input as monthly averages.

Discharge and other inflow concentrations can also vary within a day but may be measured once a month which value is then supplied for model input. Universal, constant and simple approximations are also preferred in the kinetic rates, their dependencies and other model coefficients although the nature of flow, bottom roughness, vegetation and other factors can considerably vary in the nature. For these reasons, exact agreement between the model and field results can not be expected nor required – although quite close agreements in the Finnish applications are not exceptional.

After comparison with measurements (Fig.7), the effects of planning alternatives are computed with the transport – water quality model (Fig. 8). Differences between the alternatives can be illustrated as time-series, horizontal distributions (map plots of selected layers or vertical averages), vertical cross-sections, extreme and average values or other numbers. Development and variation of distributions can also be illustrated as animations on the screen. Visual illustration of the results is important, since the number of single values in model output can be enormous. E.g. in a grid of 200 x 300 horizontal points in 20 layers hourly output of each variable means more than 10 billion values per year.

In comparison between the effects of alternatives, one has to remember that they all are computed exactly under the same conditions. Thus the differences between them do not suffer from the main reasons of differences from field results. Also the sensitivity of difference between alternatives on changes of kinetic rates
and other model coefficients is usually much weaker than the sensitivity of the model results themselves. Therefore smaller and more fine-grained differences can be meaningful between the alternatives than were the differences between model and field results. This can be taken into account in interpretation of the model results and their meaning, and in evaluation of confidence in them for conclusion and recommendations.

4.4 Practice of isotope tracer studies

Tracer studies in general need selection the tracer, its preparation or purchase, selection of the place, way and arrangements of injection, measurement plan and facilities for measurements, injection of the tracer into the water, measurement of the tracer concentrations, and interpretation of results. For radioactive tracers, strict permissions and protection against radiation are also needed.

Mostly short-living radioisotope tracers (e.g. Br-82 as KBr or Na-24 as NaOH solutions) were used in the tracer studies in Finland (Kuoppamäki & Kuusi 1973, Virtanen & Kuoppamäki 1980, the Paper VII, Rautiainen & Virtanen 1986). Their main advantages include their easy and sensitive detection directly from water without any sampling, and their natural decay in water without any problems of long-term contamination.

At the times of measurements, detection limit for radiation in water was below 1 Bq/l, while recommendations for drinking water were below 37 Bq/l, and legally accepted for waste waters without any kind of permits 11 000 Bq/l. Present recommendation for drinking water is 20 Bq/l, except for radon 300 Bq/l and radon in private wells 1000 Bq/l. Present upper limit for free discharge of Br-82 into public drainage network is 100 GBq per year or 50 MBq instantly, e.g. 14'000 Bq/l in one hour if water flow is one litre/s (Suomen Laki 1957/-2000, Anttila 1990, STUK 1999).

Despite of the extremely sensitive detection, the activities and concentrations in injection usually exceeded the upper limit for free regular releases, and needed a special permit from the national Radiation Protection Agency (the present Radiation and Nuclear Safety Authority STUK). In the widest lake and sea areas the highest activities released were 400–650 GBq. Their release during 0.5–4 hours into waste water discharge of 0.05–3 m³/s resulted in typical discharge concentrations 0.1–0.5 MBq/l, i.e. 10–50 times those allowed without the permit.

Strong special protection against direct radiation was needed during the transportation and injection, especially. Supervision of water use was needed
further in the field at a distance where the radioactivity could exceed the permit
limit and until the concentration was diluted below the level recommended for the
public drinking water. At most in practice this was about hundred metres for less
than two – three hours.

In addition to dilution, concentrations – and the integrated radioactivity as a
whole – was decreased by radioactive decay. The half-life of Br-82, about 36
hours, reduced the tracer amount to half every 1.5 days, to one thousandth (1/
1000) part of the origin in 2 weeks (15 days, 360 hours) and to one millionth (1/
million) part in a month (30 days, 720 hours). This restricted the time during which
concentrations could be measured to not more than 3–4 days in coastal waters and
to less than 2 weeks in almost any conditions.

For Na-24 the half-life is 15 hours, and decay to 1/1000 takes place in less
than 1 week (150 hours), to 1/million in 12.5 days (300 hours). It was mainly used
for relatively closed and concise water areas, and also for wastewater treatment
ponds.

As the opposite extreme, Fe-59 with half-life of 45 days was tested in one case
study for offshore discharge. Unique arrangements for its treatment were needed,
developed and used. Injection was done as Fe(II)SO₄ with ascorbine acid (to
ascertain its solvability) every 8 hours for 16 days. Total radioactivity was not
more than 77 GBq, 1.6 GBq each 8 hours. Average discharge concentration in
wastewater was 500 Bq/l. After dilution its direct detection in the sea was not
possible. Sampling was arranged by pumping 10–20 m³ water in 6–12 hours
through a filter, and measuring the radiation of filter in laboratory.

The main disadvantages of short-living radioisotopes, viz. need of strong
protection against radiation risks, and short period of measurements, could be
avoided – at the cost of sampling and laboratory work – by using inactive,
sensitively activable tracers, e.g. lantanides as complex compounds. Based on a
literature survey, laboratory tests and cost analyses, natural stable Indium
(including 95.72% In-115 and 4.28% In-113) as DTPA complex was selected and
used in four field studies (Kuoppamäki & Muurinen 1976).

The amounts of Indium released in 10–30 days varied from 0.1 to 0.4 kg.
Natural background concentrations of Indium in sea and lake waters appeared to
be less than 0.3 ng/l. Its detection sensitivity as a tracer was then estimated to 1
ng/l. This corresponded approximately to extreme dilution ratio below 1:5000
compared to its discharge concentration in wastewater outlet. In addition to
sampling labour, also the measurement of sample concentrations by neutron
activation analysis was laborious and slow, restricted to 6 samples per person-work-day.

Abreast of one radioisotope tracer study, the use of a dye (Rhodamine-A) as an inactive tracer was tested for comparison. In another case, 800 kg salt was pumped as a solution into river together with the radioisotope tracer (Virtanen & Kuoppamäki 1980). In a couple of tracer studies, drogues were used to approximate the movement of the tracer cloud. A few studies were further accompanied with recording of water currents with Aleksejev type recording current meters.

Short-living radioisotope tracers were prepared by irradiating them for several (6–10) hours in the neutron flux \((10^{13} \text{ neutrons/cm}^2/\text{s})\) of the Triga Mark II type (250 kW) nuclear research reactor FiR-1 of Reactor Laboratory in Otaniemi, Espoo. The reactor and the laboratory were belonging to the Helsinki University of Technology until the end of 1971 and thereafter to the Technical Research Centre of Finland VTT. The tracer compound (usually pure potassium bromide KBr) was packed for irradiation in three capsules, 50 g each. After a waiting time (of 10 – 16 hours, for decay of the most short-living (side-) products of irradiation), the capsules were taken out from the reactor core, sealed in heavy lead containers, and transported in these to the discharge site. There the tracer powder was initially dissolved into (60–150 litres of) water in a barrel behind thick concrete walls, and pumped (injected) therefrom into the target water system.

Radioisotope tracer injection was most preferably done at wastewater treatment plants or hydropower plants where the concrete structures give protection against the direct radiation and where the tracer is effectively mixed into bigger water volumes in the turbulent flows. More complex arrangements were needed for transport and dilution studies of offshore areas, e.g. scheduled discharge sites without existing water releases. The radioactive tracer was at first mixed into a tank (of about 1–2 m\(^3\)), hauled to the off-shore place using a long rope (of about 15–20 m, to keep the radiation dose attenuated by distance), and remotely opening the bottom valve of the tank there.

After release, the tracer concentrations in water were measured, recorded or surveyed in three ways, viz.

– at a few fixed locations with automatic recording units (to observe the local time-series),
– at fixed depth(s) across the tracer cloud by moving the detector(s) with continuous counting and (usually automatic) recording of the count rates (to
observe the horizontal tracer distributions; not applicable during the ice
cover), and
– at several points in the area with manual logging of concentrations at several
depths (to observe the local vertical distributions and stratification).

Radiation was detected with scintillation counters (Ljungren et al. 1959, Kuusi et
al. 1971). In the field measurements these were NaI(Tl) detectors, usually 1 inch
by 1 inch in size. They detected the typical background radiation of natural water,
0.5 Bq/l, with a count rate of 1/(3s) (one count in three seconds). With practical
counting periods of 30 seconds, the tracer concentrations 0, 0.5 an 1 Bq/l result in
10, 20 and 30 counts, respectively, as an average. The statistical variation is square
root of counts, i.e. 3–5.5 counts in 30 seconds, about half of the difference between
the counts of tracer concentrations 0 and 0.5 Bq/l.

The electronic pulses from scintillation detectors were received and analyzed
at the beginning by a set of relatively massive laboratory analyzers, pulse rate
meters and scalers, and recorded by plotters and punched paper tape perforations.
Point logging results could also be punched direct onto the computer cards. The
count rate recordings were often supplemented with temperature and seldom with
salinity measurements as well. In the second half of 1970’ies, a special portable
analyzer and recorder called TRACER was developed. It was of suitcase dimensions
(47,3 cm x 29,4 cm x 13 cm, 6,5 kg) and recorded results on magnetic tape with a
small cassette recorder. The equipment was manufactured by the Finnish company
Outokumpu Ltd.

4.5 Elaboration and presentation of tracer results

The count rates G detected in each point at each time $t_m$ are converted to the
correspond the tracer concentration $C_0$ injected at time $t_0$ by multiplying them with
the detector efficiency $E$ (about 1.85 (Bq/l)/(counts/s)) and the radioactive decay
correction $\exp\{+(\ln 2) (t_m - t_0)/T_{1/2}\}$, i.e.

$$c = G \cdot E \cdot \exp\{+(\ln 2) (t_m - t_0)/T_{1/2}\}. \quad (1)$$

Thereafter the three main types of measurements resulted for analysis and
interpretation of tracer recordings in presentations of their own, respectively as
follows:
– showing the horizontal distributions $c(x,y,z_m; t_m)$ of tracer concentrations $c$, or relative tracer concentrations $c/C_0$ at selected depth $z_m$ and time $t_m$;

– showing the vertical profiles $c(x_m,y_m,z; t_m)$ of tracer concentrations $c$ or relative tracer concentrations $c/C_0$ (and water temperatures and salinities if measured) at selected points $(x_m, y_m)$ and time $t_m$;

– showing the time variations $c(x_m,y_m,z_m; t)$ of tracer concentrations $c$ or relative tracer concentrations $c/C_0$ at selected points $(x_m, y_m)$ and depth $z_m$.

In these forms a lot of invaluable information was given for practical decisions concerning the effects of waste waters, the selection of better discharge points, specifying the compensations charged for environmental pollution and predicting the requirements for further purification of waste waters. The same forms for illustrative presentation of results are continuously used also in connection with the numerical models. (Koponen et al. 1992, 2008a, b, Virtanen 1989)

In addition to these case- and site-specific practical results and conclusions, general experience of the real conditions in the water systems was gained and accumulated all the time. Abreast with them also more specific and scientifically oriented information was analyzed and gathered from the results (Virtanen 1973, Paper VII). These included

– long-term dilution estimates for the conditions prevailed during the tracer study,

– estimates for dilution areas of several dilution ratios,

– comparisons of dilution areas with basin characteristics and case conditions,

– estimates for dilution lengths of several dilution ratios,

– comparisons of dilution lengths with basin characteristics and case conditions,

– advection and transport velocity estimates,

– quantitative measures for horizontal spreading,

– use of the theory of turbulent mixing for their analysis and interpretation,

– estimates for turbulent dispersion coefficients and length scales,

– mutual relations between dispersion coefficients and length scales,

– estimates for transversal dispersion coefficients in longitudinal flows,

– comparisons of transversal dispersion with flow and bed characteristics,

– statistics for vertical dispersion and stratification
In each of the tracer studies the dilution ratios $R_i$ were calculated for fixed points in the area by comparing the concentration integrals at the point in question $i$ to those at the discharge point $o$, i.e. (e.g. Harremoes 1966)

$$R_i = \frac{\int c_i(t) \, dt}{\int c_o(t) \, dt} \quad (2)$$

or

$$R_i = \frac{\int c_i(t) \, dt}{A_o/Q}, \quad (3)$$

where $A_o$ = the total amount of tracer released, and $Q$ = the waste water discharge (real or planned) for which the dilution is estimated.

The dilution ratios relate the discharge concentration with the steady-state concentration that had been reached from a continuous constant discharge under the external conditions – winds, stratification, through-flow and weather – prevailing or dominating during the experiment. Repeated measurements with reasonable intervals at fixed points $i$ are needed for calculation of the dilution ratios. The most accurate results are obtained from the automatic recording of time-series but useful estimates can be received from repeated surveys of horizontal distributions and repeated measurements of the vertical concentration profiles, too.

When located on a map, the dilution ratios indicated areas of more or less equal concentration levels which could be distinguished from each other by equiconcentration lines. The areas within each of these contour lines were calculated as the dilution areas of the dilution ratios concerned.

Several attempts were made to correlate the dilution areas of different experiments to the bathymetric characteristics of the area and to the external conditions of the experiment. The research areas and conditions, however, varied to such an extent that no clear correlation between them and the dilution areas was found in the 60 studies carried out.

In addition to the integrated dilution ratios and the corresponding dilution areas, several other indicators of dilution were analyzed as well. The dilution lengths needed for 99% (1:100) dilution and their dependence on the river flow and on the river bed dimensions were quite similar in an international review (Cole 1974) and in the border between Sweden and Finland (Virtanen and Kuoppamäki 1980).
The total amount of tracer reached in the surveys and its average location, center of gravity, were integrated for approximations of each day or of 3 – 6 hours' periods as follows:

\[ A = \iiint c(x,y,z; t_m) \, dx \, dy \, dz \]  
\[ x_c = \iiint x \, c(x,y,z; t_m) \, dx \, dy \, dz / A \]  
\[ y_c = \iiint y \, c(x,y,z; t_m) \, dx \, dy \, dz / A. \]

Comparison of the reached tracer amount \( A \) with that originally released \( A_o \) reveals most strictly and untouchably how comprehensive the survey has been. The average flow velocity components in the recipient are calculated as the changes and movement of the average location of the tracer cloud between consecutive moments of integration \( t_k \) and \( t_{k+1} \):

\[ u = dx_c/dt = (x_c(t_{k+1}) - x_c(t_k)) / (t_{k+1} - t_k) \]  
\[ v = dy_c/dt = (y_c(t_{k+1}) - y_c(t_k)) / (t_{k+1} - t_k). \]

The clear but complicated dependence of the water movements on winds during the open water period was one of the main outputs of the tracer studies. During the ice-covered period the tracer studies clearly indicated the transport of the waste water along the bottom slopes to the deepest parts of the recipient. In the estuaries and coastal areas the waste waters in winter could be stratified for a while as a separate layer between the fresh and cold river water above and the saline sea water below.

The horizontal spreading of the tracer cloud is calculated as the variances \( S^2 \) around the average locations \((x_c, y_c)\):

\[ S_x^2 = \iiint (x - x_c)^2 \, c(x,y,z; t_m) \, dx \, dy \, dz / A \]  
\[ S_y^2 = \iiint (y - y_c)^2 \, c(x,y,z; t_m) \, dx \, dy \, dz / A \]  
\[ S^2 = S_x^2 + S_y^2. \]

The directions of x- and y-axis can be selected according to the deformation of the tracer cloud as longitudinal (maximum variance) and transversal (minimum variance) ones, or according to compass to East and North. Usually values for both sets have been calculated. The value of the combined variance (11) is independent
of the directions x and y, as far as these are perpendicular to each other (Virtanen 1973).

The horizontal mixing coefficients K and length-scales L are calculated on the basis of the variances $S^2$ and the time $t_m - t_o$ elapsed since the tracer release in almost 20 of the case studies as follows (e.g. Kitaigorodsky 1971, Virtanen 1973, Murthy 1973):

$$K = \frac{S^2}{4(t_m - t_o)} \quad (12)$$
$$L = 3 \sqrt{(S^2)} \quad (13)$$

The dependence between the dispersion coefficient and the length-scale was observed to follow approximately the "4/3 -power law"

$$K = K_o \left(\frac{L}{L_o}\right)^m \quad (14)$$

with $m \sim 1.33$ (1.26 ... 1.34) and $K_o \sim 1 \text{ m}^2/\text{s}$ (0.51 ... 1.14 m$^2$/s) for $L_o = 1 \text{ km}$

This was in close accordance with Okubo's ocean results ($m = 1.33$, $K_o = 4.64 \text{ m}^2/\text{s}$, Okubo 1971) and with Murthy's results in the Great Lakes of America ($m = 1.27 ... 1.36$, $K_o = 1.13 ... 1.25 \text{ m}^2/\text{s}$, Murthy 1973) and with their extended combination (Murthy & Okubo 1977). An example of the dependence observed in Finland is shown in Fig. 9 (Virtanen 1973).

![Fig. 9. Least squares’ fit (thick line) for the measured pairs of L and K (square dots) compared with the theoretical dependence of eq. (11), $y = (4/3) \cdot \log(L/\text{km})$ (thin line).](image)

The difference between the longitudinal and lateral (transversal) dispersion coefficients is particularly clear in rivers. The longitudinal dispersion coefficient $K_L$ seemed to increase with river depth and flow velocity (e.g. Hess & White 1975, Paper VII)

$$K_L = a \ H \ u \ ( = a \ Q/\text{B}), \quad (15)$$
where $a = \text{constant} \sim 20$,
$H = \text{depth}$,
$u = \text{flow velocity}$,
$Q = \text{river discharge}$ and
$B = \text{river width}$.

Calculation of the transversal dispersion in rivers according to Holley et al. (1972)

$$K_P = \frac{1}{2} u_{\text{max}} dS \frac{d^2}{dx}$$

resulted in close agreement with the approximation (Elder 1959, e.g. Ward 1974, Somlyódy 1977, Virtanen & Kuoppamäki 1980)

$$K_y = bH \sqrt{(gI H)}$$

with $b \sim 0.63$,
$H = \text{the hydraulic radius}$,
$g = \text{the gravity acceleration}$, and
$I = \text{the surface slope}$.

Comprehensive calculation of estimates for vertical dispersion coefficients was restricted to a few tracer studies. Main obstacles to these were the lack of horizontal coverage of the vertical concentration profiles and the considerable distance of 2 to 5 metres between the survey depths of horizontal distributions. Also the boundary conditions at the water surface and bottom were more important to interpretation of the results than in the horizontal case. The orders of magnitude of the vertical dispersion coefficients, however, could be estimated to vary usually between 5 and 15 cm$^2$/s.

Despite of the limited number of exact estimates for the numerical values of the vertical dispersion coefficients, both general and detailed information about the reality of the vertical mixing was found in the measurements. The vertical profiles of tracer concentrations indicated indisputably that the thermal stratification in the shallow lakes in Finland during the summer was not constant. Down till 20 metres and more the water column could be well mixed by winds without any sign of stratification at least for weeks.

This observation was going to be of crucial importance for the start of the numerical modelling of water currents, justifying the neglecting of the vertical dimension in the beginning of the model development when the computers were slow and their memories restricted. The significance of this step for the early accumulation of model experience can hardly be overestimated.
5 Results and conclusion

5.1 Cumulative model development as illustrated by the original publications

The Papers I–VII are principally written for, and concentrate their attention directly on, their practical results, i.e. the effects, acceptability and evaluation of the planned or performed construction or control measures or their changes or alternatives. In addition, each of the publications also has a role in the cumulative accumulation of model experience, practice and further development.

Publication VII (Virtanen 1984) specifies the most important roles of tracer studies to modelling to be
- support to and selection of model structure,
- estimation of the model parameters, and
- most detailed tests of the model validity.

The models, on their side, are most appropriate for
- explanation of the reasons for the tracer results (also under unsteady conditions),
- generalization of the tracer results to other weather and flow conditions,
- prediction of the effects of planned changes of discharge rates, places and bottom geometry etc., and
- extension of the results from plain transport and dilution ratios to quantities that directly indicate the water quality and usability of water.

The utmost sensitivity of tracer results for comparison with the model results and for testing the model validity is presented and compared with comparisons of the flow velocity recordings and water quality indicators. The influence of flow fluctuations in the sea area and the storage of water in a side lake at high flow rates in the river can be seen only in comparisons with the tracer results. Their effects are missing from the model results because neither the geometry of the side lake nor the factors giving rise to the fluctuations were supplied for computation as model inputs. In the estuary, the paper presents a most complicated formulation of extra assumptions in a 2D+ focused layer model. Soon afterward these were superseded by full 3D solutions. A later example of the comparison of the flow velocity components of a 3D model (Virtanen 2006) with their measured values is shown in Fig. 10.
Fig. 10. Location of the output and observation points (A, B) in a recent model application of the Kotka estuary (upper left, fig. 10A, finest horizontal resolution 150 m surrounded with 900 m and 4.5 km grid areas, vertical layers 1.5 m until a depth of 9 m and below that 3, 4, 4 and at most 30 m thick, total number of grid boxes 325 x 123 x 10 = 399 750, Virtanen 2006). Comparison of the observed estimate (based on one measurement at the centre of cross-section) and model discharges to East trough strait A (upper right, 10B) and the vertical profiles to North at strait B (below, 10C–E) at three situations. The flow velocities caused by the river flow to the model area without wind (Q=87 m$^3$/s, calm, 10C) with 5 m/s wind from South-West (Q + SW, 10D), and from South-East (Q + SE, 10E) respectively.
A more comprehensive review of the available means to test the model validity was collected and presented in Publication II (Koponen, Virtanen & Itkonen 1998). The possibilities of comparisons stated and used there include

- drogues for flow measurements in ice covered waters,
- flow recordings with recording current meters (used elsewhere),
- flow measurements with acoustic Doppler current profilers (used elsewhere),
- flow tracing with drifters (used elsewhere),
- tracer experiments (used elsewhere),
- direct measurements of water temperature, conductivity, transparency or turbidity, and a few indicators of water quality, e.g. oxygen concentrations,
- sampling for laboratory analysis of wider set of water quality indicators,
- oxygen consumption tests in isolated vertical tubes in the field,
- compression tests for bottom releases in the field,
- immersion and inundation tests of soil samples in laboratory,
- expert evaluations and estimates, and
- analytical solutions of several basic cases.

Possibilities of remote sensing for model comparisons were suggested and tested earlier in a separate study (Kuittinen et al. 1991a, b) and was further developed at a later date (Colpaert & Lauri 2000). For the Northern reservoirs II they were less appropriate and were not mentioned because the water surface there was covered with ice and snow for long periods of time, while in ice-free seasons large parts were covered with peat floats.

Further examples of comparisons of the model results with the measured values up to the biological indicators of algal biomass are presented in Publications VI (Virtanen, Koponen, Dahlbo & Sarkkula 1986) and V (Virtanen & Manninen 2000). Publication VI describes in detail the 3D model structure and presents the first 3D model application of this type in Finland. The demand for a proper description of the algal dynamics was the central reason that forced the shift towards a 3D solution. The necessity of both horizontal and vertical resolutions is separately tested and shown by Koponen (1985).

Publication V updates the model application with much finer space resolution, more direct control quantity (phosphate phosphorus instead of total phosphorus as the basis for limiting the growth rates of algae), and with most comprehensive data sets for four years 1990 to 1993. In both cases of V and VI a very close agreement
between the model and observed values for the indicators of algal biomass has been received. Furthermore, the loading changes in Näsiselkä VI have later taken place according to the plans that were included in the computations, and the observed changes of water quality have corresponded very closely with those predicted by the model (Luonsi 1991).

Publication I (Virtanen, Koponen, Hellsten, Nenonen & Kinnunen 1994) updates the detailed description of the 3D model system and extends it to include wide variations of water levels, water volumes and surface areas, conservation of matter under rapidly changing conditions like spring floods, and descriptions for the complex development, dependence and influence of the bottom sediments. The seasonal dynamics of water level changes, internal loading and the water movements to both directions in the channel connecting the two reservoirs express most clearly the features of the flood pulse system as presented by Kinnunen (1982) and Junk et al. (1989).

Comparison between the development of the observed and modelled indicators of water quality for the first 15 years since impoundment from 1971–1986 shows a relatively close agreement especially near the water surface and in mixed waters behind the power plant but also near the bottom. Here the deepest observations are measured just above the bottom at 35, 26 and 23 meters down from the uppermost level of regulation. When these are compared with the model results of the bottom layers between 20–30, 20–21 and 15–17 m respectively, the observations do not represent the same water masses as the model results.

A recent application of the model system to the later development of the Lokka and Porttipahta reservoirs (Karjalainen 2008) between the years 2000 and 2006 further confirms the validity of the model system presented in Publication I. The comparison is very rigorous as the specification of model parameters is based on data taken over a period of 1967–1986 and the model system was fixed and published between the years 1993–1998.

Publication III (Virtanen, Koponen & Nenonen 1998) combines the effects of a planned and two existing reservoirs to their influences on the downstream river sections, a regulated lake, and on the coastal area and sea. Simple methods for an approximate calculation of the influences of confluence tributaries and transport along the river are explicitly presented while a more detailed method for transport and mixing computation for rivers was described in VII.

Publication IV continues with the presentation of the coastal application which was briefly touched upon in III with a comparison between earlier model applications of the same area and with a review of other applications of the sea.
area. The increase of grid points in solutions with time is also illustrated by comparing the horizontal flow patterns of two reservoir models taken in 1978 and 1993 (Fig. 11). The list of coastal applications, on its side, has been the basis for attempts to present, describe and classify the applications in Chapter 3.5. The coastal applications of 1977 to 1993 included 29 vertical averaged 2D, 20 focussed layer 2D+, and 14 full 3D model cases.

![Fig. 11. Examples of flow fields of two reservoirs, viz. the Kisköre reservoir in Hungary (left, 12 x 8 x 1 = 96 grid boxes, resolution 2.5 km, Virtanen 1978) and a planned reservoir in North Finland (right, 64 x 95 x 11 = 66 880 grid boxes, resolution 0.333 km, Virtanen et al. 1993b).](image)

### 5.2 Repeated general model results and experiences

In the model applications carried out, several common features have repetitively appeared in the model results. The appearance of most of these is quite natural, and often the reasons for their appearance can be proved and demonstrated in simple cases and regular geometry with analytical mathematical solutions.

1. Almost always in solutions, the vertically integrated 2D flow in the shallow areas is directed by the wind whereas in deeper areas a return flow opposite to this is generated. At steady state the water surface is inclined more or less
against the wind with a minor modification by the Coriolis effect. As a result, in 3D solutions the flow with the wind on the surface is increased in all areas, while the return flow is emerged below the surface.

Density stratification further affects the distribution of flow velocities. Furthermore, factors determining the density (mainly temperature, salinity and the strongest wastewater concentrations) are redistributed by their mixing and the transport determined by the flow velocities. This makes the combined computation of flow, water levels and density factors necessary.

Shelter of the wind by forests, rocks, buildings or other formations as well as differences of the free distance of wind sweep and wave generation can change the flow patterns from those computed with uniform winds.

2. For parallel passages, flow routes or channels (separated by islands or walls) the minimum cross-section area of each route is most important for the distribution of flow between the routes. Enlarging or narrowing of the narrowest cross-section is thus the most direct way to influence the flow distributions. Rules for approximation of bottom depths for grid boxes including different depth records can be derived from further analysis of these effects.

3. The transversal and vertical distribution of slow boundary velocities has influenced the flow only in the immediate vicinity of that border. The fast boundary flows, on their side, can extend their jet influence for longer distances mainly by means of the non-linear advection effect (transport of velocity differences with water flow). In areas locating further from the open boundaries the flow is also quite sensitive to the fixed given transversal distributions of water level elevations and the density (temperature, salinity) distributions at the boundary.

The changes of water levels with time (tides and other water level variations depending on air pressure and winds for example) appear in and can be supplied to the model as slow boundary velocities. In the Baltic Sea and especially off the coast of Finland the influence of tides is negligible. Other water level changes are often correlated with the winds. This is seen in the analysis of the flow velocity recordings (e.g. Sarkkula 1989, Sarkkula and Virtanen 1978, 1983), where the water level variations have very seldom had a separate role in explaining the recording results after the influence of winds has been taken into account.
4. Changes of water level elevations are accompanied by changes of water volumes to which the loading effects are diluted. Simultaneously they also change the detention (or residence) time of the water exchange. For the factors or water level indicators directly discharged from point sources, the influences of these opposite effects compensate each other as an average, although net changes are locally possible. For factors (e.g. oxygen consumption and algal growth) depending on or determined by direct indicators (BOD and nutrient concentrations respectively) the chain of influences is more complex but the compensation of reduced initial dilution with faster water exchange, or vice versa, remains dominant also here. For loading types depending on the water area (internal loading from the bottom; remote transport, deposition, rainfall and melting onto the surface) the total amounts of loading are also changed as the area changes with the changing water level.

Influence of water exchange is also important in cases where transport of loading effects from point sources is reduced by restricting the water flow to sensitive areas. The concentrations of direct load indicators can thus be reduced, but during longer residence time their effects on oxygen consumption (or algal growth) may not be reduced by much if at all.

5. The algal biomass received as the model result is centrally determined by the availability of the usable limiting nutrient. When all concentrations of the usable liming nutrient is taken up by the algae, further growth is ceased. This is a typical situation that occurs during the growth season. The rate of approach to this balance situation can be solved analytically in a simple case. The solutions of both the steady state biomass and the approach rate show their attenuated sensitivity on values of the half-saturation level, maximum growth rate, decay rate and thus also on their temperature dependencies.

6. To a large extent the differences between the measured and model results are caused by

a) differences in shore lines and bottom topography (which can be caused both by the finite resolution of the model grid and by a deficit or inexact transfer of information from the field to the maps or from field or maps to model input),

b) unrepresentative locations of sampling, recording or other measurements or observations (caused mainly by the finite resolution of the model grid, typically 100 m x 100 m x 1 (– 10) m boxes, while the differences in
nature can appear as narrow wedges, thin layers, separate clouds or as other forms of patches), and

c) differences between the external conditions prevailed in nature and those supplied for the model input (caused mainly by deficit information from nature, for example winds are typically recorded every three hours at a more or less distant location, wastewater and river concentrations perhaps once a month, river flows monthly averages etc).

An example of the appearance of the directly less representative comparison (6b) is illustrated in Fig. 12. In the transversal West–East cross-section just north of the Porttipahta dam, the lowest model layer between 215 and 225 m a.s.l. can include measurements at 210.5, 215 and 220 m a.s.l. A proper value for the comparison of the model results would be the water volume weighted average of observations within this layer. As this is not always available, the less representative bottom value is used for comparison when it has been the only available deep level location where samples have been taken from.

The differences between the available model inputs and variable field conditions (6c) seem to be the most significant reasons for the differences. They are also the most difficult or impossible to eliminate or substantiate. Sometimes certain factors, features or aspects can also be purposely left out of the model if changes of these do not include nor significantly affect the differences between the planned alternatives the effects of which are the aim of these studies. In these cases, when the model applications are reduced on purpose, the validity of the reductions can also be proved with further comparative computations.

The tests with the reduced model applications and the above deduction indicate that the comparison between the measured and model results includes many differences which do not affect nor harm comparison between the effects of different planning alternatives. The effects of each alternative are computed under the same conditions with exactly the same input data as all the others. Much finer differences between them can then be reliably and accurately resolved than has been the agreement between the measured and model results.
Fig. 12. West–East cross-section of bottom depths (left) through the sampling point P1 in Porttipahta reservoir, north of the power plant, and the vertical profile of total phosphorus concentrations measured (right). With computational layer limits at 1, 2, 3, 4, 5, 6, 8, 11, 15 and 20 m depth from the uppermost limit of regulation the deepest observations are not directly the most representative for comparison with the bottom layer model results.

Despite the difficulty or impossibility of perfect completion of the forcing data and the rare possibility of technical errors in field data, the differences between the measured and model results are always an important, invaluable and most welcome stimulus for further development of the models. It also calls for further analysis of the properties and possible defects of the models. In any case the avoidance of contradictions or discrepancies against the field results is a most central and highly ranked aspect in the model work.

5.3 Process analysis and evaluation of the flow influences

In addition to their contribution to the development of model systems and applications (Chapter 5.1), and to their illustrative presentation of the general features of the universal laws of nature which are the basis of model systems (Chapter 5.2), much detailed information about the role of specific processes, factors and terms have been identified and analyzed by model tests and comparisons. In many cases, models and calculations can be the only way for these analyses as all processes cannot be easily controlled or eliminated from nature. Explicit
identification and presentations of the process influences have often been central to the early stages of model adaptations (e.g. Leendertse 1967, 1970, Leendertse et al. 1973, Leendertse & Liu 1975, Virtanen 1977a, 102–111, Virtanen 1980, Rautalahti-Miettinen et al. 1982) but recently interesting aspects and discoveries have also been found in practical applications.

The wind shear on the water surface is the most central direct factor for the generation of free-surface water currents (e.g. Bengtsson 1973b, Bengtsson & Svensson 1977). The gradients and changes of air pressure give additional forcing to water currents and the movements of water masses. Under free-surface conditions their direct influence is small compared with their indirect influence as the reason for winds and via wind shear. Their independent influence can be distinguished mainly under the cover of ice, sometimes resulting in interpretation of observations as the effect of the wind affecting the currents below a fixed ice lid.

Further direct reasons for water movements, much similar to those of air pressure differences, are throughflows across the model boundaries, inflows from upstream rivers and outflows to downstream water bodies, and gravity forcing of the moon and sun appearing as tidal fluctuations. The effects of these all are conveyed further into the water body much through their indirect effect appearing as the surface slope and changes of water level elevations. As pressure gradients through gravity forcing and water density, these contribute to the water currents. After changes of primary direct forcing conditions, the indirect effects caused by them continue their influence. Seiche fluctuations after wind changes are an example of these effects.

In addition to the direct and indirect forcing factors or processes giving rise to the water currents, there are processes which modify the currents once generated by the forcing factors. Main components of these modifying processes include the effect of Earth rotation appearing as the Coriolis phenomenon, the internal friction called viscosity, the bottom and ice friction at the boundaries of a water body, and advection, i.e. transport of velocity differences with water currents.

Furthermore, water currents are also significantly modified by the density differences and stratification of water which also control the strength of turbulence and viscosity. As a direct forcing process these derive their origins from heat exchange through the water surface, sometimes through bottom and also from temperature differences in discharges. Coupled with the specific temperature dependence of water density, the gravity forcing makes denser water to sink downwards as a convective motion. As their indirect effect density currents, up-welling and down-welling are generated in cases where the isobars, interfaces of equal
pressure, are not parallel with the isoclines which are interfaces of equal density. Further density effects are caused by the dependence of water density on differences in salinity and sometimes the densest of waste water concentrations, too.

The influence of different factors or processes on water currents have tested in numerous applications with relatively uniform and consistent general features for the main factors in comparable type of water areas (e.g. Virtanen 1977a). In closed areas (lakes, reservoirs and ponds) the flow velocities are increased almost in proportion to wind shear, and decreased with bottom friction and horizontal and vertical viscosities. With open boundaries (coastal areas, bay extracts) these dependences are slightly smoothed. The effects of transversal distribution of flow velocities as fixed boundary values at open boundaries are generally not penetrated very far from the boundary whereas the influence of transversal inclination of surface level elevations as fixed boundary values can be seen much further in the model area.

For uniform infinite lanes the influence of several type of vertical viscosities on the form and values of the flow velocities can also be solved analytically (e.g. Koponen 1984) in close agreement with the comparable model results. The analytically solvable types of vertical viscosity profiles include for example constant and stepwise stratified values, and viscosities changing linearly with depth. Special attention has been paid to the effects of the quadratic advection terms and their treatment (e.g. Virtanen 1980). As the main conclusion, these are found to be of most importance with fast flow velocities and in cases of large relative depth differences. Beside their effect on flow velocities, the stability properties of the solution are also affected by them.

In addition to the effects and processes appearing as separate terms in the equations of motion, influences of numerous other factors and dependences are included in the model system. These include for example the effects of wind fetch and shading of wind forcing behind obstacles, generation of and interaction with waves, and several alternatives for turbulence closure to estimate the time and space dependence of viscosities in more detail. A recent example of the relative importance of some of these factors is available from Lake Kallavesi, in East Finland (ref. Heitto 2009). With the observed westerly winds of 5 – 16 m/s and with estimated through flow close to the high flow MHQ, the model tracer distributions agreed very closely with the observed results (Kiirikki and Mykkänen 2008). The accordance between the model and field results concerned both vertical and horizontal distribution, maximum values and extensions of concentrations, time behaviour of tracer spreading, slow movement and little dilution at the
beginning of spreading, long stay near the place of injection, the direction and speed thereafter, and even the patchiness of the tracer distribution.

The effects of different factors were compared and analyzed under a western wind of 9 m/s as the average condition during the experiment (Fig. 13). Removal of the effect of wind fetch as the first step (from 13a to 13b) caused a little more transversal spreading to the tracer cloud. Here the time and space dependent vertical viscosities were calculated using the coupling between the turbulent kinetic energy of eddies (k) and their dissipation rate (epsilon) through the k-epsilon scheme. Their replacement with constant viscosities (from 13b to 13c) changed drastically the flow field and consequently the pattern, shape and location of concentration distribution. Replacement of direct calculation of vertical layer velocities (Fig. 13c) which essentially helped the k-epsilon solution (Fig. 13b) with computationally more efficient calculation of vertically average current and the velocity difference between adjacent layers (Fig. 13d) did not change the results at all.

An increase of the vertical viscosities from 1.5 to 15 cm²/s and the horizontal values from 0.01 to 1 m²/s (from 13d to 13e) appeared as an increase in dilution at both sides of the tracer distribution: near the injection shore the last parts of the tail were diluted below the detection limit, and at the opposite shore the values were spread to a wider area with decreased peak concentration that is not resolved in the distribution plot. Finally, the elimination of the advection terms (from 13e to 13f) further modified the flow field and the distribution pattern. A reduction of the directed motion allowed a wider transversal spreading and made the last parts of the tracer cloud to disappear when diluted below the detection limit of the plot. Vertical circulation was also increased by a small amount resulting in the appearance of minor tracer concentrations at the upstream and upwind areas in the West, behind the main tracer cloud.

At the high flow rate MHQ the fast flow velocities in the bridge openings have increased the relative importance of the quadratic advection terms. Also in general, the inclusion and utilization of the advection terms and the k-epsilon turbulence scheme was found to be essential for a proper description of the flow and transport effects in cases of fast flow velocities. In particular this applies to cooling water discharges of large thermal power plants where the buoyancy properties of the discharge further emphasize the need of stratified 3D solutions.
Fig. 13. Influence of flow factors on surface tracer distributions (ng/l) three hours after release at NE corner of the central bridge opening at MHQ flow rate and wind 9 m/s from West. Effects of wind fetch (from b to a), k-epsilon turbulence (c to b), way of calculation the layer velocities (d to c), decrease of vertical viscosities from 15 to 1.5 cm²/s and the horizontal ones from 1 to 0.01 m²/s (from e to d), and the quadratic advection of the flow velocity differences (from f to e). Velocity scale 10 cm/s for 180 m = distance between the arrow centres, every 6th arrow plotted. Concentration scale: black > 90 ng/l, dark gray 50–90 ng/l, medium gray 10–50 ng/l, light gray < 10 ng/l.
The nature of flow structure determines very much which dimensions are required to be resolved in the model solution. When vertical differences are less pronounced such as under homogeneous conditions in shallow waters, they can be disregarded. One can then concentrate solutions to vertical averages or to approximations of a specific layer. In the opposite case the vertical resolution is taken into account, sometimes even as the only dimension resolved. The omission of a horizontal resolution is best suitable for cases where loading is equally distributed throughout the model area, when horizontal mixing by the virtue of eddies or flow fluctuations is efficient, or when horizontal differences are otherwise not interesting. Solution can then be directed straight to the horizontal average or to a specific place without horizontal resolution. Reciprocally, when interest is directed to horizontal differences, for example between the loading places and sensitive, protected or other specific areas, or when the nature phenomena are aimed at being described with their time and space variations as in nature, then horizontal resolution is taken into account.

In a general case with irregular bottom topography, numerical methods are needed for a multidimensional solution of water currents. In principle, an intermediate alternative between detailed solution of multidimensional flow field and plain horizontal average could be found as the solution of a pure mixing equation, by approximating the effect of fluctuating currents as increased mixing. In practice, however, its use has been relatively limited, mainly because the shape of the analytical solution as multidimensional Gaussian function is not very convenient, and the boundary conditions make it even more inconvenient. The staff forces which could be interested in these kinds of solutions have mostly directed their efforts directly to more general numerical approaches.

Thus the acquaintance and preferences of the user have also had influence on the selection of the model type and dimensions resolved, abreast of the real physical characteristics of the water body. When a 3D model is developed, made available and learnt, it can be easily used for cases where vertical or horizontal differences are not the main target of interest and where a more integrated solution would be possible. As a side-advantage, the system can also be directly usable for more general cases and no further attention is needed to the possible influence of wider integration on parameter values. With proper arrangement the solution of 3D model can be made almost as fast as those of more integrated systems. In practice there are examples of 3D models which are even faster than some other 2D or 1D models with comparable resolutions.
5.4 Water quality processes and parameter estimates

Movements of water quality indicators are determined by the advective motion with water currents and by dispersive mixing. These are both analogous to the respective flow processes. Advection of water quality indicators with water currents is in principle the same as that of flow velocity differences. For water quality indicators, however, this is the central or only driving factor for movements from place to place, and it is not quadratic (as velocities multiplied by velocity differences) but linearly depending on concentration differences (multiplied by velocities). Therefore its inclusion in distributed model systems is a normal standard, far less optional than for the flow velocity components.

Dispersion as mixing of water quality indicators is analogous to viscosity which causes mixing of momentum and flow velocities. Both types of mixing are contributed by molecular diffusion or viscosity, by irregular eddies and fluctuations as eddy diffusion or viscosity, and by velocity gradients as shear-dispersion. In calculations with finite resolution, further dispersion can be artificially brought about as numerical dispersion by the numerical methods used for the solution. For its reduction or elimination, a relatively wide set of elaborated techniques have been developed and implemented as options in the model systems (Koponen et al. 2008a).

In addition to movements, the values of water quality indicators are changed by numerous inherent reactions specific to each indicator. The reaction types include a downwards settling within the water by gravity or an upwards lift by buoyancy, sedimentation onto the bottom, adsorption onto and desorption from fixed boundaries, direct influence of bottom, surface and other boundaries (e.g. sediment oxygen demand, reaeration through the surface), decay with time, radioactive decay as one of its special type, biological respiration as another one, mutual decay forced by coupled indicators of water quality (e.g. oxygen by biological oxygen demand), biological growth also controlled by coupled indicators (e.g. algae by nutrients or their specific fractions), and many types of chemical reactions.

Internal loading, erosion, leaching and release from the bottom compare well with the direct influences of the bottom. This comparability includes their possible dependence on the state and conditions of water body near the bottom, e.g. on the flow velocities, waves, several concentrations, temperature, light and turbidity. Other types of loading, from point sources, with inflows from rivers and other open boundaries, from surface as atmospheric deposition and ice melting, and
from the shore as non-point source or diffuse loading including natural leaching – are mainly external determined sources for transport. As a matter of fact, loading from inflows at the water boundaries is equivalent with advection inside the model area. The same also applies to point sources when the discharge of water volume is taken into account in the flow fields. For discharges which are considered insignificant for the flow fields and therefore not included in the computation of flow, care must be taken that the loading is not placed to stagnant deadlocks without any currents and water exchange in any conditions.

The relative importance of different processes can be tested by totally eliminating their effects (as in Fig. 13 for flow processes) or by changing the values of their rate or other control parameters e.g. with 25%. Reported results of these (for example Rautalahti-Miettinen et al. 1982) indicate that the dependence of results on parameter values is relatively smooth. Within this range the differences between the effects of different loading levels are not changed considerably by the parameter values although in comparison with measured values the effects of a 5–10% independent change in the single parameters can be seen (summary e.g. Virtanen 1992).

These kinds of sensitivity tests have consistently been used in practical applications. Usually they are done at the preparatory stage of an application to ensure that there are no steep dependences on parameter selections which would require focussed attention to specific processes and their non-linearity. After the application of the model system with a fixed set of parameter values to compare the effects of different planning alternatives the sensitivity tests are usually not repeated as the clients are seldom interested in their outputs. Therefore their explicit inclusion in reports is quite exceptional (examples are however e.g. Koponen et al. 2003). Most often their meaning is restricted to a less formal accumulation of experience as general impressions.

Further possibilities to compare the relative importance of different processes are analytical solutions of simplified model systems, and direct comparisons between the orders of magnitude of the time scales of each process. Comparable time scales can include (as examples, in time units)

1/ (decay rate)
1/ (growth rate)

depth/ (settling velocity)
depth/ (sedimentation velocity)
depth/ (reaeration velocity)
water volume/ (water exchange)
In distributed model systems the main attention is usually directed to areas of the main concentration gradients. With refined space resolution in these areas, the time scales of physical flow effects can become very fast, for example 1000 s for 100 m / (10 cm/s), or 50 s for 50 m grid resolution and discharge velocity of 1 m/s. Compared with typical time scales of biological process 0.1 to 1 day or more, i.e. at least 10 000 s, or 1 to 100 days for typical settling and sedimentation velocities of nutrients (0.06 m/d), clay (0.6 m/d) and silt (6 m/d) in 5 m thick water layers, this can create the illusion of sole dominance of the water movements alone. Although this biased comparison is not generally valid nor is it the whole truth, it properly illustrates the central importance of the physical flow and transport effects in these cases. With attention to wider water areas and bigger water volumes, the relative importance of bio-geo-chemical processes in comparison of time scales is respectively increased.

For non-moving components of the bottom storage, the concept of easily removable (volatile), slowly removable and permanent fractions (Publication I, Virtanen, Koponen, Hellsten, Nenonen & Kinnunen 1994) could not be strictly confirmed or specified with field data. Differences in the total amounts of quantities at the bottom of the two reservoirs in 25 years were not significant enough to be distinguished by measurements. The dynamics of the easily removable component, however, could be and was specified by comparisons with the measurements, with help of the laboratory and field tests, quite consistently for the two reservoirs, for different type of bottom material, and for different indicators of water quality.

In general the loading fluxes from the bottom to water are much stabilized during the first 8 to 12 years of impoundment. Successful simulations of the reservoir water quality with an age of 30 to 40 years (Karjalainen 2008) with the same fluxes specified for the bottoms 15 years earlier is a clear indication of this stability. Although the initial values for each of the hypothetical fractions of bottom storage could not be identified in the reservoirs by measurement, the concept of limited resources for immediate release has proved useful in other applications as well. These include for example erosion simulations of a fixed amount of sand on the bottom, and leaching calculations of known amounts of more immediately soluble or degradable materials from the bottom.
The stability of the loading fluxes in reservoirs with time seems to suggest to a large extent a balance between the release and new sedimentation, within the limits distinguishable by measurements. A comparable balance is also observed in several other areas of pulsing dynamics (Koponen et al. 2003, 2008a, Kummu 2008, Lamberts & Koponen 2008, Junk 1997). In general the results of most water quality indicators are also contributed by pairs of opposite reactions much balancing the effects of each other (e.g. growth – decay, erosion – sedimentation, aeration – oxygen consumption, and also for flow velocities surface shear – bottom friction). Without specific measurements many combinations of them can lead to much similar results. Fortunately, for many cases more direct or more strictly controlled measurements are available at least for some of the processes to fix the parameter combination to correspond those affecting in nature. Of particular importance here is the consistency and compatibility of the settling and sedimentation velocities of suspended solids and their dependence of grain size according to Stoke's rule in many different experiments and literature sources (Seuna & Vehviläinen 1986, Huttula et al. 1990, Alasaarela & Virtanen 1987).

Concerning the parameter values of flow processes, the acceleration due to gravity, dependences of water density, the Earth’s rotation and the Coriolis factor are known from direct measurements much more accurately than could ever be specified by model comparisons. At the interfaces of a water body, the values of wind shear, ice friction and bottom friction and their dependences also belong to those which have been measured and determined quite consistently for direct usage in the flow model. In field and laboratory tests, interpretation of detailed experiments for the dependences of parameter effects on their control quantities have often resulted in fractional exponents. In distributed model systems their description is often replaced with a combination of integer exponents at both sides from the suggested fraction.

Fixed standard values have been used for the parameters in the set of equations for turbulence (their kinetic energy k), its dissipation rate (epsilon) and their effect on viscosity. The numerical values of the vertical eddy viscosities which are thus obtained or otherwise given, are crucially determining the vertical structure of 3D flow. In the applications its values have typically varied from 5–15 cm²/s for ice-free conditions above the pycnocline to 0.01 cm²/s below the ice lid at the pycnocline. In k-epsilon -solutions the ranges of momentary local values have often spread beyond these average extremes.

In comparison of the orders of magnitude of different factors affecting the horizontal flow velocities in shallow water areas, almost all factors can be of comparable importance. With coarse resolution of 1 km or more, the relative
importance of horizontal viscosity is reduced to the level of percents. Reciprocally
with very thin layers of 1 m or less, the role of vertical viscosity is emphasized. For
the vertical velocities, the effects of gravity and hydrostatic pressure determined
by water level elevation are estimated to be $10^6$ times stronger than those of the
Coriolis factor and at least $10^8$ times stronger than other components (details in
Virtanen 1977a, pp. 15–16) which seem to justify the use of the hydrostatic
approximation. Furthermore, the relative variations of flow velocities are
estimated to be $10^3$ times bigger than the relative variations of water density which
seems to justify the neglection of the density differences when multiplied with
flow velocity variations.

The time scales of flow variations are centrally determined by the speed of the
gravity waves, about 2 m/s for waters up to 20 m in depth, changing proportionally
to the square root of the maximum depth of the model area. Its brevity is inversely
proportional to the speed which explains the advantage of using separate
calculations for flow velocities and the transport of water quality indicators
whenever possible.

Further aspects to the estimation of parameter values and to the selection of
the model structure are illustrated by looking at the special role of tracer
experience for the start of the present model efforts.

5.5 Summary and meaning of the tracer results

As a summary, the most general discoveries of the tracer studies in surface waters
proved
1. The variability of stratification during the summer, with considerable periods
   of homogeneous mixing down to 20 metres or more;
2. Regularity of the dispersion coefficients, with invariant relations valid for
   highly variable areas and conditions;
3. Complicated dependence of the dilution areas upon the site and conditions;
4. Crucial dependence of transport upon winds during the open-water period;
   and
5. Quite regular transport of waste water along the bottom of deep water in
   winter.

These relatively simple conclusions laid the foundation to and urged the
development of model tools and applications. To explain the complex variations of
transport and dilution (4, 3), mathematical models had to be developed. Thanks to
the observed existence of the homogeneous situations in nature (1), the two-dimensional (2DH) vertical-average models were sufficient at the beginning. This helped to gain the basic experience, reliance and confidence on the modelling, and to introduce, apply and add proper techniques and approximations to computation.

With comprehensive and detailed knowledge of dispersion in the real field conditions (2), attention could and had to be directed to interactions and factors determining the flow and transport. This was obviously an advantage for a wider applicability of model development. Nevertheless, the feedback from the waste water densities to water currents (5) was included into the numerical model solution (Koponen & Virtanen 1986) only after the 3D models had replaced the dominance of the 2DH solutions (Koponen 1984, Publication VI). Conceptually the same behaviour (5) was recognized, taken into account and implemented for analytical solution by Lappalainen (1978) with layer thickness and flow velocity estimates taken by expert evaluation and experience.

5.6 Meaning and need of the measurements

Field data and observations have been and are of central importance for the original creation and for continuous further development of the model systems. Vice versa, the needs of the models are rather commonly declared as a central pretence for extensive field campaigns, often independently of the real needs of any model. In fact, the amount of data itself is usually less important for model tests. To some extent, however, excess amount and redundancy of data is welcome as it increases the possibilities for improved quality, focus and representativeness of data. The best benefits for models would be obtained from special arrangements of controlled experiments, preferably focussed on detailed information of the effects of specific processes, as pointed out several times previously.

Of special importance to model use is the proper analysis, interpretation, explanations and understanding of the reasons for field records. These can be done interactively with the models but for many type of measurements there are possibilities for analysis, explanation, compression, absorption, coupling, combining, filtering or crystallizing of results by their own techniques as well (e.g. Chapter 4.5). The internal couplings within the 3D model system make the model most suitable and detailed for interactive analysis of the field results. Simultaneously the causal relations included in the system make it impossible to adjust the model results artificially to agree with field data at one point or one
moment without changes to other locations too. This means that a relatively limited amount of data can be sufficient for exposing and meaningful validity test of a 3D model application.

Development of measuring techniques for easy and automatic collection of vast amounts of field data have strongly emerged and increased considerably the number of recordings from the environment. These techniques include automatic algae detectors in regular route ships, other recordings based on fast impact of radiating, acoustic, optical or electromagnetic responses and signals, acoustic Doppler current profilers, and remote sensing. Problems in strict interpretation of their results, in addition to the huge amounts of data, are caused for example by their momentary and moving nature in dynamically evolving and varying systems, by their most detailed space resolution emphasizing these variations, and by lack of comparable information of forcing data, such as time and space variation of winds, rains and clouds, air temperature and irradiation.

The results of vast surveys and moving data collections have their own justification and merits for example as descriptive presentations of the general views of data distributions, or in analysis of sub-grid scale structures and variations below the finest resolutions of the present models, and in many other possible ways. Accordingly, their comparisons with model results have remained mainly qualitative, without development of more quantitative procedures for comparison, in contrast for example with the standard practices available and used for comparison of the time series data of fixed points. The most meaningful comparisons with the results of moving acoustic Doppler current profilers have been obtained when the currents along the same line have been measured repeatedly for 4 to 5 times under relatively constant conditions.

In the collection of field data for model comparison, the purpose of the model application should be taken into account. For model application intended for the prediction of the effects of external cooling water discharges, field data of the variations of water temperatures under varying weather conditions without the discharge are of little or no value for model comparison, although for several other purposes the field data are very useful. Explanation of the natural variations of water temperatures with the model will considerably expand and shift the requirements of the model focus and its forcing data needs beyond their original schedule and purposes.

In spite of the very close agreement with observations in hundreds of model applications, the validity of any model can not be universally proved by any agreement between the model results and field data (Orestes et al. 1994). Neither
the possibility of some other model systems being equally successful can ever be totally eliminated. Nevertheless the comparisons between the model and field results are found to be most useful and have been utilized as extensively, comprehensively and frequently as possible in each of the case studies. On one hand the comparisons are used to accumulate reliance and credibility upon the model results while on the other hand they have been most interesting and rewarding. Finally, central discrepancies between the model and field results have been the key stimulus and adviser for further development of the model system.

It is indeed extremely important that the model results, when sincere and honest, are exposed most openly to the possibility of falsification (e.g. Popper 1943). All differences between the model and field results, however, do not mean falsification or inadequacy of the model system. There can be numerous natural and acceptable reasons for the differences, and it is important to understand these reasons and their meaning. As an extreme example, when flow fields are computed with the density effects of the present waste water loading, the transport of concentrations calculated with these flow fields are neither expected nor can be requested to agree with the concentrations measured at much stronger and denser loading before the implementation of the new treatment process and plant.

The multiple correlation coefficient squared is quite regularly used in Finland to indicate and quantify the degree of agreement between the measured and model time-series and distributions. Especially for comparison of flow velocity vectors it is a very demanding measure and reading which is not frequently used elsewhere. Its values can vary from minus infinity to plus one. Within this range the values of the closest agreements obtained in the Finnish applications, above 0.8, are remarkable. For sample size of 90 or more, already values of 0.15 are statistically very significant. In extensive comparisons in the Great Lakes, the use of flow and transport models was found to be most useful even with agreements varying at both sides of zero, thanks to the internal causal relations properly included in the models (Allender 1976, 1977, Allender & Saylor 1979).

5.7 Benefits of the model studies

The practical advantages and benefits of the model applications derive their origin from the possibility for justified and easily repeated predictions of the expected effects in advance without expensive and even hazardous trials or construction works. On one side the acceptability of the scheduled changes or interventions can be clearly seen, and on the other side unnecessary spending of resources like
money or time on the investments of harmful or zero effects can be avoided. The certainty of the acceptability of effects also means relief and savings later when the recipient or other resources remain usable, and compensation or remedial requests need not to be expected.

For the effects of scheduled changes or interventions, the possibility of exact comparison of the effects of different, exactly specified alternatives is an advantage. Its interactive use along with the course of the technical design and planning process can further help the selection of the most advantageous alternatives. In cases of confrontations and conflicting interests, the importance of models can be further emphasized. Proper understanding and illustration of the reasons for the effects, identification of the most influential factors and their distinction from the less important ones can help to find a commonly accepted basis for debates and further deductions (Virtanen et al. 1996). Their influence can be further supported with an illustration of the effects of alternative suggestions in policy planning, design, administrative selections and political or managerial decisions. In these kinds of cases the possibilities of model support could be significant although in real life these have seldom been utilized to their full extent.

The main types of the changes and interventions usually considered can be seen in the classification of the purposes or causes of the model applications in Appendix 1 and in the Paper IV. These include

- effects of changes in bottom topography and shore lines: embankments for roads, harbours, or breakwaters, artificial islands, bottom dams; opening, deepening or widening of channels, passages and other water areas etc.
- effects of loading changes: rates and locations of waste water releases from forest, chemical, metal and other industries and municipal sources; internal, airborne, and watershed loads, other non-point loading, fish farming, dumping and dredging releases etc.
- interest in temperature effects: cooling water circulation, outlet jets, intake suctions, extent, duration and thickness of ice cover, stratification changes etc.
- influences on higher trophical levels: biology, algae, zoo-plankton, periphyton, food webs, plants, fish, bio-accumulation, sediment processes, socio-economy, climate change consequences etc.
- effects of flow changes: regulation, flow and discharge control, water level changes, reservoirs, pumping etc.
- interest in flow velocities directly: drift and tracing studies, support to oil and chemical combating and sea rescue etc.

In particular the effects of embankments, opening of channels, or a change of wastewater discharge points need spatial resolution and use of flow models for
proper estimate and presentation of their effects. The discharge of cooling waters, changes in stratification, temperature and salinity conditions, on their side need vertical resolution and in practice the use of 3D models.

Fast response of model runs, clear user-interface and fluent availability of input data are of crucial importance for the applicability of the models for immediate use for operational services and as tools to support urgent needs. The operational applications of models are developed and tested to guide vessels and facilities directly to optimal places to combat oil or other chemicals or to help the rescue of lives in accidents (Koponen et al. 1994, Lauri 2004). Fast and effective execution of the model runs is also an advantage in all applications, because it makes the model use much more effective. Faster runs will allow earlier fixing of the optimal run selections, more versatile, careful and detailed comparisons with observations, and the effects or more alternatives or scenarios to be compared with each other. In this respect the EIA 3D model system (Chapter 4.2, Papers VI and I, Koponen et al. 2008a) with its ingenious solution algorithm and execution times comparable to 2D models have shown its excellence and superiority.

5.8 Conclusion

The combined use of numerical models of hydrodynamics and bio-geo-chemical indicators of water quality has appeared most successful in all of the applications. Their firm basis on, and continuously close contacts and comparisons with, field observations have further established their position as a central tool in understanding and support for solution of environmental issues. In particular, the 3D model system has appeared most useful because of its true space resolution. This makes strict tests for the model validity easier or possible as comparison can be achieved with less integration of observations.

The 3D model results can not be artificially adjusted to correspond with single observations at different moments at different depths and at all sides of the area because they are coupled with each other through the water currents, bio-geo-chemical reactions and mixing. In fact validity tests of a 3D model solution require fewer measurements or are more exposing than corresponding comparisons with more integrated solutions.

As a further advantage, the 3D solutions can use equations and dependencies as these are theoretically derived and as the forces and interactions are affecting in reality. For example the model parameters can be specified to depend on model variables (e.g. flow velocities, water temperature, other indicators of water quality) more directly than in integrated solutions. It is possible, although not proved until
now, that the values of model parameters can converge to more universal constants when proper descriptions for their dependence are learnt and taken into account.

The combined solution of hydrodynamics and bio-geo-chemistry makes the solution truly predictive and suitable for all kinds of measures planned to change the conditions in nature. In particular this applies to cases where the changes of water quality are caused by the changes of water currents, such as the construction of embankments, dams, bottom dams, or the opening of new channels, widening of passages, or by changing the shore line and bottom depths with dredging or dumping. The effects of changing discharge points, densities, amounts and rates can also be directly computed with the combined 3D model system.

In the nested grid system the focus areas can be surrounded with areas of coarser resolutions with full coupling of interactions to both directions across the resolution boundaries. Thus the model area can be extended in all directions to land areas or narrow cross-sections of remote sounds. This especially helps and provides more reliable computations of coastal areas, bays and creeks.
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Appendix 1. Flow and water quality model applications.

Made by EIA Ltd. (until 1989/90 part of Technical Research Centre of Finland VTT) Cases until 2006 (the most recent cases of 2007–2008 not listed in detail because of high share of confidential areas and purposes)

<table>
<thead>
<tr>
<th>nr.</th>
<th>start year</th>
<th>Area</th>
<th>model type(s)</th>
<th>purpose</th>
<th>water area(s)</th>
<th>geogr. location</th>
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<tr>
<td>283</td>
<td>2006</td>
<td>Hietanen Harbour, Kotka, Gulf of Finland</td>
<td>3D</td>
<td>w,x</td>
<td>L, S</td>
<td>GoF</td>
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<td>2006</td>
<td>Usuthu watershed, Swaziland</td>
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<td>w,u</td>
<td>R, W</td>
<td>Afr</td>
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<td>2006</td>
<td>Pongola watershed, South-Africa</td>
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<td>w,u</td>
<td>R, W</td>
<td>Afr</td>
</tr>
<tr>
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<td>2006</td>
<td>Pyhämää Fish Farming, Bothnian Sea</td>
<td>3D</td>
<td>w</td>
<td>C, S</td>
<td>BS</td>
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<td>278</td>
<td>2006</td>
<td>Lokka - Porttipahta user interface update</td>
<td>3D</td>
<td>w,u</td>
<td>I</td>
<td>GoF</td>
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<td>277</td>
<td>2006</td>
<td>Mussalo Harbour off Kotka, Gulf of Finland</td>
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<td>w,x,z</td>
<td>C, S</td>
<td>GoF</td>
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<td>276</td>
<td>2006</td>
<td>Navigation Plan, Chaktomuk, Cambodia</td>
<td>3D</td>
<td>w,x</td>
<td>R</td>
<td>SEA</td>
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<td>2006</td>
<td>Built Structures, Mekong, World Fish/ADB</td>
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<td>w,x,u</td>
<td>L, R, W</td>
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<td>R, W, L</td>
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<td>w,z</td>
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<td>3D+</td>
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<td>S</td>
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<td>Plain of Reeds, Vietnam</td>
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<td>TanTieu saline intrusion, Vietnam</td>
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<td>2005</td>
<td>Tan Chau erosion and WQ model, Vietnam</td>
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<td>R, W</td>
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<td>2005</td>
<td>Chaktomuk 3D erosion, Cambodia</td>
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<td>Nam Songkhram 3D flood, Thailand</td>
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<td>Nam Songkrham watershed, Thailand</td>
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<td>Vientiane – Nong Khai 3D erosion, Laos</td>
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<td>2005</td>
<td>Operational oil combating and sea rescue</td>
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<td>v</td>
<td>C, S</td>
<td>GoF</td>
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<td>2004</td>
<td>Jedzelewo - Elk Lakes/Elk River, Poland</td>
<td>3D, 1D</td>
<td>w,u</td>
<td>R, L</td>
<td>Eur</td>
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<td>261</td>
<td>2004</td>
<td>intumak mercury in Nura River, Kazakhstan</td>
<td>1D</td>
<td>w,z,u</td>
<td>I, R</td>
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<tr>
<td>260</td>
<td>2004</td>
<td>Vuosaari refined for dumping effects</td>
<td>3D</td>
<td>w</td>
<td>C, S</td>
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<td>2004</td>
<td>Sofia - Black Sea watershed, Bulgaria</td>
<td>1D - 2D, WS</td>
<td>w,u</td>
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<td>Archipelago Sea ecosystem</td>
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<td>w,z</td>
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<td>Coastal area off Jakobstad in Bothnian Bay</td>
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<td>Tonle Sap, 10 sub-catchments, Cambodia</td>
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<td>Kalbandagrin drift tests, Gulf of Finland</td>
<td>3D</td>
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<td>GoF</td>
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<td>2003</td>
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<td>w,x</td>
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Model Types

3D = 3D with horizontal layer interfaces
3Di = 3D with impermeable layer interfaces (isolated layers)
3D− = selected 2D layers extracted from 3D flow fields
3D+ = 3D with sediment process details or other extra aspects
3/2/1D = (most recent combined-dimension applications, Koponen et al. (2008))
3Dva = (3D with vertical accelerations, full equations of motion)
2D–3D = combination of 2D wave models with 3D models for concentrations
2Dp = vertical profile approximations as weighted sum of elementary profiles for 3D currents according to Bengtsson (1973)\(^B\) and Heaps (1974)\(^H\)
2D+ = 2D focussed-layer model with extra assumptions for the selected layer
2Dss = (given self-similarity profile approximation for 3D currents)
2D = 2D vertical average
2Dv = 2D vertical plane (one chain extracted from 3D grid)
2Da = 2D one-layer with analytical solution of mixing
1D–2D = river networks and lakes in watershed (WS) models
1D = longitudinal 1D
1Da = longitudinal 1D with analytical, pulse response or double-sweep solutions
1Dv = vertical 1D
WS = watershed models for hydrology including subsurface waters

Types of Purposes

v = interest in flow velocities directly: drift and tracing studies, support to oil and chemical combattting and sea rescue etc.
\(v\) = effects of flow changes: regulation, flow and discharge control, water level changes, reservoirs, pumping etc.
x = effects of changes in bottom topography and shore lines: embankments for roads, harbours, or breakwaters, artificial islands, bottom dams; opening, deepening or widening of channels, passages and other water areas etc.
w = effects of loading changes: rates and locations of waste water releases from forest, chemical, metal and other industries and municipal sources; internal, airborne, and watershed loads, other non-point loading, fish farming, dumping and dredging releases etc.
t = interest in temperature effects: cooling water circulation, outlet jets, intake suctions, extent, duration and thickness of ice cover, stratification changes etc.
z = influences on higher trophical levels: biology, algae, zoo-plankton, periphyton, food webs, plants, fish, bio-accumulation, sediment processes, socio-economy, climate change consequences etc.

Water area Types

C = coastal area
L = lake
I = artificial lake, impoundment
P = pond (mainly for waste water treatment)
R = river
S = sea or ocean
W = wetland or watershed
**Geographical locations**

Baltic Sea with Finnish coastlines

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**other seas and oceans**

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**inland waters in Finland**

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**inland and coastal waters elsewhere**

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Included publications


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<td>320</td>
<td>Komulainen, Mikko</td>
<td>Bandwidth enhanced antennas for mobile terminals and multilayer ceramic packages</td>
<td>2009</td>
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<td>321</td>
<td>Ronkanen, Anna-Kaisa</td>
<td>Hydrologic and hydraulic processes in northern treatment peatlands and the significance for phosphorus and nitrogen removal</td>
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<td>Liedes, Toni</td>
<td>Improving the performance of the semi-active tuned mass damper</td>
<td>2009</td>
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<td>323</td>
<td>Marina Tyunina &amp; Orest Vendik (Eds.)</td>
<td>Proceedings of the 16th International Student Seminar “Microwave and optical applications of novel phenomena and technologies”, June 8–9, Oulu, Finland</td>
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<td>Belt, Pekka</td>
<td>Improving verification and validation activities in ICT companies—product development management approach</td>
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<td>326</td>
<td>Selek, István</td>
<td>Novel evolutionary methods in engineering optimization—towards robustness and efficiency</td>
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<td>Optical spectra analysis of turbid liquids</td>
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<td>Ketsunen, Juha</td>
<td>Essays on strategic management and quality assurance</td>
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<td>Safety, health and productivity of cold work. A management model, implementation and effects</td>
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<td>Liljatainen, Henrikki</td>
<td>Interactions between fibres, fines and fillers in papermaking. Influence on dewatering and retention of pulp suspensions</td>
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<td>Intelligent medium access control for the future wireless networks</td>
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Markku Virtanen

MATHEMATICAL MODELLING OF FLOW AND TRANSPORT AS LINK TO IMPACTS IN MULTI-DISCIPLINE ENVIRONMENTS