4. RIVER MODELS FOR TRANSPORT OF MATTER AND HEAT

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4.1 General

Insufficient quality of water-supply may become the limiting factor for growth and development particularly in highly industrialized regions. A deterioration of water quality may result, aside from natural sources, from excessive municipal or industrial waste-water or cooling water discharges. Assessment of the environmental impact of such discharges requires adequate knowledge of the mixing and transport processes to which the introduced substances are subjected. Such phenomena are investigated in hydraulic models. A decisive distinction between mixing- and conventional models is the requirement to simulate turbulent transport processes correctly, which necessitates an exact reproduction of the local velocity distribution in the model. This results in more sophisticated requirements for model similarity.

The main task of mixing models including intake- or outlet structures is usually the determination of the effluent concentration field in the water body, which is a prerequisite for the evaluation of possible negative consequences on the river ecology and on other water users located downstream. The model experiment gives answers to the question of how changes in the design of the outlet structure can influence the mixing pattern. Such questions are primarily important for large rivers and reservoirs, where incomplete mixing and stratification are likely to occur. For small rivers or creeks, the main problem is longitudinal dispersion, since cross-sectional mixing is quickly achieved because of the large ratio of effluent- to river flow rate. Similarly, the effect of very small waste-water discharges is easily evaluated as long as they do not produce a noticeable disturbance of the river flow.

Further typical tasks of hydraulic mixing models concern e.g.:

- Lateral velocities, which are generated by the discharge. These velocities have to be kept below a certain limit (current practice in Germany: 0.3 m/s at the main channel boundary) in order to assure save navigation conditions.

- Recirculation ("short-circuiting") and warm-water wedges between outlet and intake. This question is particularly important in reservoirs and slowly flowing rivers, because stratification easily develops under such conditions. Here the model yields information about the arrangement and necessary minimum distance between intake and outlet structure in order to avoid such disturbances, which may significantly reduce the efficiency of power plants.

- Withdrawal of sediment - free water and prevention of sedimentation in the river due to diversion of a large part of the river discharge. Particularly on rivers carrying a large sediment load, the intake structure has to be designed in such a way as to withdraw as little sediment as possible. This requires, for example, arrangement of the inlet openings near the water surface, whereas for the prevention of recirculation the openings should be deeply submerged. Furthermore, the transport capacity of the river may be reduced considerably due to diversion of a large percentage of the river discharge, which may result in increased sedimentation between intake and outlet. On the other hand, a jet-like discharge may produce local erosion problems.

- Selection of representative locations for water quality monitoring. The continuous collection of water quality data at several points within a cross-section is usually not possible because of the high costs of continuously operating stations. Therefore, an average quality of the entire discharge has to be inferred from data at a single point only. If a monitoring station has to be situated e.g. some distance downstream from the confluence of two rivers of different water quality or of a large waste-water discharge, a correct interpretation of the data may require information from model experiments.

The largest water uses on rivers result from cooling water discharges from power plants or industry. Cooling water discharges produce density differences, which may lead to stratification and density-induced spreading and thereby alter the mixing process considerably. In the following, therefore, the more complicated case of mixing processes for heated water discharges will be discussed. An analogous methodology can be applied to the modelling of the dispersal of other constituents, for which under certain circumstances the decay, due to biological, chemical or physical exchange processes, has to be taken into account. They may follow different laws than the decay law for the heat transfer to the atmosphere, however. Such biological or chemical processes can rarely be reproduced correctly in the laboratory.

The water quality in large river systems cannot be investigated in hydraulic models because of the huge extent of the areas of interest. However, for such large-scale investigations it is usually permissible to assume complete cross-sectional mixing at the point of discharge, so that this kind of problem can best be treated with the help of numerical models.

4.2 Basic Concepts

4.2.1 Description and Parameters

For each of the above problem areas, different parameters have to be considered and different processes have to be modelled. For example, for investigations of sedimentation at intakes or in the river reach between intake and outlet, not only the flow field, but also the properties of the transported material have to be taken into account. Such processes are reproduced according to the rules described in Chapters 3, 7 and 10.

Other parameters have to be considered for the investigation of recirculation.

Warm water wedges develop mainly when cooling water is discharged into slowly flowing rivers. If a sufficient density difference exists between warm water and river water, the cooling water will move upstream near the water surface. In its equilibrium position, the upper less dense layer comes to rest, due to a balance between the buoyant force due to the density difference and the friction at the interface due to the river flow. Relevant parameters in this case are the geometry, relative density difference, river flow, water depth, friction coefficient at the interface and at the bed and possibly turbulent entrainment. In the twodimensional case a wedge develops only for densimetric Froude numbers of

$$Fr_d \leq 0.8 \tag{4.1}$$

whereas, for example, for (Fr_d = 0.2) the length of the wedge already approaches thousand times the water depth. A twodimensional analysis is justified only for complete mixing over the whole river width at the point of discharge, which is seldom the case. An experimental investigation of a wedge in a hydraulic model requires exact reproduction of the discharge and identical Froude numbers, densimetric Froude numbers and friction coefficients in model and prototype.

If a temperature or concentration field downstream of an outlet structure has to be determined in a model, conditions both of the discharge and of the river have to be taken into account. The parameters of primary importance are summarized in Fig. 4.1. Such discharges frequently occur as jets. Because of the velocity difference between jet and ambient flow, there exist high shear stresses at the jet boundaries, which produce turbulent eddies and thereby cause fast mixing of jet- and ambient fluid. Generally, a jet flow is characterized by a rapid reduction of the initial concentration or temperature difference. The same is true for lateral discharges for which the effluent velocity is smaller than the river velocity. If there exist density differences between effluent and ambient fluid, buoyancy forces may generate stratification in the river. Stratification will occur if buoyancy forces are large and turbulence intensities small, as for example in run-of-the-river reservoirs where flow velocities are small and water depths are large. The stratification is stable as long as the buoyancy forces are strong enough to damp the bed-generated turbulence. If turbulence predominates, the density interface will become unstable and will be finally destroyed.

If water is discharged laterally into a quickly flowing stream, the jet is bend towards the shore and often reattachment occurs. The reason for this may be either the pressure difference, which results for discharges over the entire water depth (as long as the jet is not elevated due to buoyancy) from the fact that the ambient flow cannot reach the leeward side of the jet, or the reduction of lateral entrainment due to the existence of the side wall. Between the point of discharge and the point of reattachment, back flow develops if the exit velocity v_e exceeds 1.3-times the free stream velocity v_o (Gehrig, Jurisch and Lemmin, 1976). The length of the back flow zone L_b, relative to the width b_e of the outlet opening, is

$$L_b / b_e = (12 \ldots 125) \quad \text{for} \quad v_e / v_o = (1.3 \ldots 3) \tag{4.2}$$

	Near-field		Far-field	
	Zone 1	Zone 2	Zone 3	Zone 4
(I) Relevant parameters				
(A) Discharge parameters:				
Geometry of the outlet	+			
Geometry of the immediate outlet surroundings	+	+		
Momentum flux, F_I (magnitude and direction)	+	+	(+)	
Buoyancy flux, F_A, due to density difference between effluent and river water	+	+	+	
Mass flux, Q_e	+	+	(+)	+
Effluent concentration, c_e	+	+	+	+
(B) River parameters:				
Water depth, h		+	+	+
Discharge, Q, or flow velocity, v_o		+	+	+
Vertical stratification or horizontal density gradients in the river		+	+	
Turbulence from bed-generated shear		+	+	+
Lateral boundaries and alignment of the stream bed (groins, bends)			+	+
Ship traffic, sluice operation			+	
Wind				+
Exchange processes (e.g. chemical reactions, heat loss)			(+)	+
(II) Spreading mechanisms				
Jet spreading	←—	→		
Density-induced spreading	←	—→		
Convection by the river flow	←—	—	—	—→
Turbulent diffusion and dispersion		←	—	—→
Wind-induced transport		←	—	—→
Exchange processes			←—	—→
Typical extent (L: characteristic length of the outlet structure)	~ 10 L	~ 300 L	~ 1000 L	

Fig. 4.1: Relevant Parameters and Physical Phenomena Involved in Mixing Processes in Rivers

if the opening extends over the whole depth of flow. Accordingly, in those cases where the outlet velocity is limited to relatively small values, the back flow region has an appreciable extent only for discharges into slowly flowing streams. However, a disturbance of the free stream velocity profile is noticeable over much longer distances.

The shore-attached warm water plume often extends over many kilometers. Mixing with the river water takes place only very gradually. Contrary to the "active" mixing of jets due to large velocity differences and because of density-induced spreading, the mixing may be called "passive" at larger distances from the source. Besides to advection of particles, mixing occurs only due to turbulent diffusion (which is called "diffusion" in analogy to molecular diffusion, since the spreading due to turbulent velocity- and concentration fluctuations also is described by a gradient law) and dispersion, due to secondary currents and the threedimensional mean velocity distribution. The warm water is carried along by large eddies. The interface between warm water and ambient water remains rather distinct for long times but changes its position with time over wide lateral distances.

From the description of the mixing process it becomes apparent that not all parameters of Fig. 4.1 are of equal importance at every point of the flow field. There exist several zones, in which different parameters are dominant. In the immediate vicinity of the outlet structure (near-field), the velocity and the concentration field are governed by parameters of the discharge. The conditions in this area can therefore be influenced by the design of the outlet. On the other hand, the specific form of discharge has no dynamic influence any more on the conditions far from the point of discharge (far-field). Here the flow field is determined by parameters of the river, and mixing is "passive", i.e. comparatively slow. Near-field effects determine only the concentration or temperature distribution at the transition from near-field to far-field. The parameters of Fig. 4.1 are listed in about that order with which they loose importance with increasing distance from the point of discharge. All in all, four different zones can be distinguished:

- Zone 1 (immediate outlet area, extends to about 10 L, where L is a characteristic geometric measure of the outlet opening): Only parameters of the discharge and the geometry of the immediate outlet vicinity are of importance.
- Zone 2 (near-field, extends from about 10 L to 300 L): Besides momentum flux and buoyancy (and perhaps the mass flux) of the discharge, the water depth, river flow and possibly natural density gradients are of importance. Back flow regions and vertical density gradients can develop in this zone.
- Zone 3 (far-field): Bed friction and the form and alignment of the shore line determine the flow field and therefore the mixing process. Outlet parameters prescribe only the initial tracer distribution. Only lateral, no vertical concentration gradients exist.
- Zone 4: Large-scale region far from the point of discharge, where parameters

of the river and exchange processes such as heat loss to the atmosphere or wind stresses are controlling. Concentration gradients exists in longitudinal direction only.

Transitions from one zone to the other are fluent and not distinct. Therefore no unique criterion exists for the extent of the different zones. Generally it can be said that for the case common in Germany of small efflux velocities and relatively fast flowing rivers the near-field is restricted to a rather narrow area.

4.2.2 Model Similarity of Turbulence

Spreading of water contaminants is governed by advection and turbulent transport. Turbulence results from an interaction of viscosity and inertial reactions and is therefore characterized by the Reynolds number. In models, where the Reynolds number has the same value as in nature, the turbulent fluctuations are automatically reproduced correctly. Since, however, in Froude models the Reynolds number always is smaller than in nature, it is necessary to discuss how the turbulent mixing process may change and how any changes possibly influence the performance of a hydraulic model.

In order to evaluate this aspect, the interpretation of turbulence as a system of eddies of different magnitudes should be recalled. The main flow generates large eddies whose length scales are of the order of the main dimensions of the flow field (e.g. water depth for open channel flows). These large eddies usually are inertial eddies in which viscosity effects are negligible. The main flow conveys energy directly to them. Therefore they contain a large amount of energy. Due to the decay of these large eddies, energy is transferred to smaller and smaller eddies, until their size is finally so small that dissipation due to viscosity takes place.

This energy cascade may be described by the following length scales:

- a macro scale Λ_M,
- the Taylor micro scale, Λ_T, which is characteristic for the size of eddies where viscosity just begins to play a role,
- the Kolmogorov micro scale, Λ_K, which is characteristic for the size of eddies whose energy is completely dissipated by viscosity.

For a correct representation of turbulence in a hydraulic model first of all the large eddies have to be reproduced, because through them energy is extracted from the main flow. The same is true for turbulent transport: The large eddies are of primary importance. It is irrelevant, how the energy further cascades to the small eddies and whether the small "viscous" eddies, which dissipate the energy, are reproduced correctly, as long as the main flow is not altered.

Since the large eddies in a turbulent flow are proportional to the main dimension of the flow field ($\Lambda_{M,r} = L_r$), their correct simulation is always ensured in a geometrically similar model (Abraham, 1975). There is but one condition: The micro scale of turbulence, at which viscosity effects become important, has to be smaller than the macro scale in the model in order to avoid alteration of the large eddies due to viscosity.

From dimensional analysis, for a Froude model the micro scales increase according to the following relation (Abraham, 1975):

$$\Lambda_{T,r} = L_r^{-1/4} \quad ; \qquad \Lambda_{K,r} = L_r^{-1/8} \tag{4.3}$$

Therefore the ratio of micro scale to macro scale is

$$\begin{aligned} (\Lambda_T / \Lambda_M)_r &= L_r^{-5/4} \\ (\Lambda_K / \Lambda_M)_r &= L_r^{-9/8} \end{aligned} \tag{4.4}$$

These considerations lead to the conclusion that the characteristic dimension of viscosity-dominated eddies is increased in a small scale Froude model. This is illustrated in Fig. 4.2, which was derived from flow visualization experiments with turbulent jets.

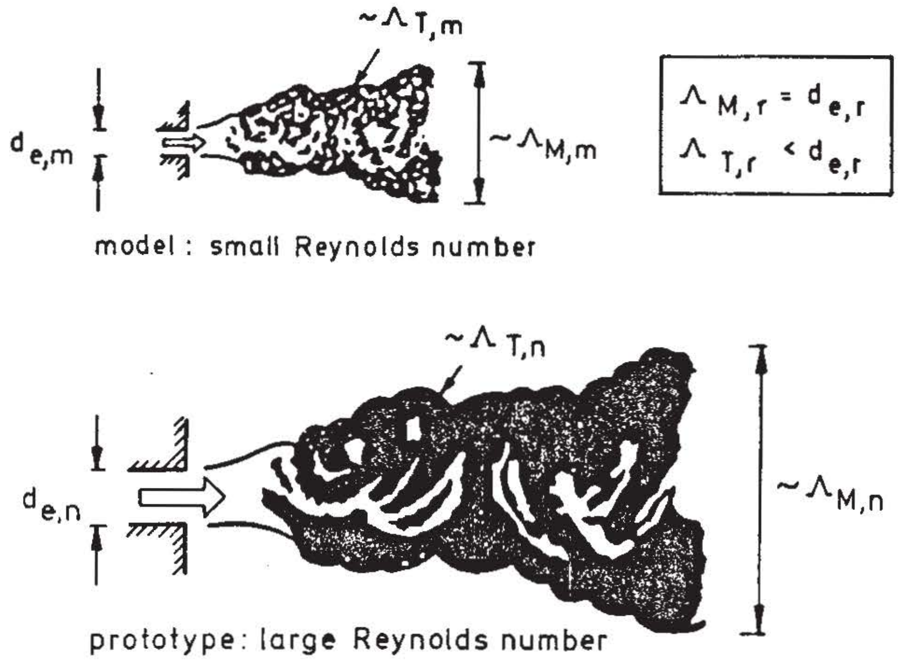

Fig. 4.2: Turbulence Structure of a Jet in Model and Prototype (Abraham, 1975)

Different Reynolds numbers in model and prototype hence cause a modification of the fine structure of turbulence which, however, does not act back upon the rough structure and thereby on the main flow as long as a critical value of the Reynolds number is exceeded. In other words, in Froude models turbulent transport processes are simulated correctly as long as the main flow remains turbulent. The critical value of the Reynolds number is approximately

$$Re_{kr} = \begin{cases} \dfrac{v_e \cdot d_e}{\nu_w} \approx 2000 & \text{for jets} \\[2ex] \dfrac{v_o \cdot 4 r_{hy}}{\nu_w} \approx 3000 & \text{for open channel flows} \end{cases} \qquad (4.5)$$

The question remains, how geometric roughness elements as they are frequently used in hydraulic models influence the turbulence pattern and thereby possibly enhance mixing. In Chapters 1 and 2 it has been shown that the correct simulation of bed friction always requires a smaller relative roughness in undistorted models than in nature. Because of technical difficulties to produce such smooth surfaces - which imposes an upper limit to the choice of length ratios - it often becomes necessary to use distorted models with correspondingly larger relative roughness (see Chap. 2). This may result in a modification of the structure of turbulence and thereby of turbulent mixing.

With respect to the question of whether it is possible to reproduce turbulent mixing in distorted river models too, it can be shown (Kobus, 1974):

- that the near-field, which is influenced by momentum flux and buoyancy, can be reproduced correctly in undistorted models only (Chap. 1);
- that lateral mixing is overestimated and vertical mixing is underestimated in distorted models. If the turbulent diffusion coefficients E are assumed to be proportional to water depth h and shear velocity v_* , it can be shown that for a distorted model there is

$$\frac{\text{actual model value of } E_{\text{horizontal}}}{\text{for similarity required } E_{\text{horizontal}}} = n^{3/2}$$

$$\frac{\text{actual model value of } E_{\text{vertical}}}{\text{for similarity required } E_{\text{vertical}}} = n^{-1/2} \qquad (4.6)$$

In very wide, shallow rivers (for width-depth-ratios in the model of $(b_{wsp}/h)_m \geqslant 40$) even a distorted model could yield similar spreading (see Chap. 8). In these cases, the lateral turbulent mixing seems to be better correlated with the width of the river than with the depth. However, the assumption of a very wide channel usually is not satisfied for river models, as for instance, for the model-prototype comparisons by Holley and Karelse (1973). The investigation of threedimensional mixing processes in river models therefore usually requires undistorted models.

4.2.3 Model Laws and Types of Model Application

For a correct simulation of river flows, the similarity requirements which have already been discussed in Chapters 1 and 2 have to be satisfied. As has been shown there, the maximum possible length scale is given by geometric considerations and limitations due to surface tension and viscosity (as a rule at most a few hundred for undistorted and approximately 1000 for distorted models). For an appropriate representation of gravity effects, the Froude law has to be satisfied. That fixes the velocity scale number and assures that the distribution of mean velocities corresponds to those in nature. Furthermore - in accordance with the above considerations - mixing models generally have to be undistorted, i.e. geometrically similar, because mixing phenomena are influenced not only by advective transport but also by turbulent diffusion.

For the investigation of spreading processes some additional similarity requirements which are summarized in Fig. 4.3 have to be obeyed. The densimetric Froude number has to be equal in model and nature, if buoyancy forces have to be taken into account. For a Froude model, this implies identical density difference in model and prototype. This condition can be relaxed for very slowly flowing rivers or reservoirs, where gravity effects may be neglected ($Fr \approx 0$) in the presence of a non-moving level water surface. In this case the velocity scale is determined by the densimetric Froude number.

In density-stratified flows, the interfacial friction has also to be modelled correctly. Apparently this is realized for a wide range of Reynolds numbers with sufficient accuracy, if bed friction is represented correctly, because the ratio of both friction coefficients varies from 0.32 to 0.42 only for $Re = 10^3$ to 10^5 (Abraham and Eysink, 1971). For smaller Reynolds numbers a distortion may become necessary.

A simulation of physical, chemical or biological exchange processes requires the coincidence of the time scale for flow and exchange process. For a simple reaction of the first kind, i.e. an exponential decay law, as it is often used for heat loss to the atmosphere, the similarity requirement is

$$\left(\frac{K \cdot L}{\rho_w \, c_p \, h \, v} \right)_r = 1 \qquad (4.7)$$

Usually this condition can be fulfilled by a distortion of the model only. However, the distortion factor from equation (4.7) will not agree with the distortion factor due to the simulation of friction. This emphasizes the fact that a simultaneous correct reproduction of all mentioned effects is very rarely possible

Physical process	Characteristic parameter	Similarity requirement	Model law for Froude model	Resulting modelling rules
Gravity-driven open channel flow	Geometry, $Fr = \frac{v}{\sqrt{g\,h}}$	$Fr_r = 1$	$v_r = h_r^{1/2}$	Dictates velocity scale (see Chap. 1 and 2)
Bed friction	Friction coefficient $\lambda = f\,(Re, k/4h)$	$\left(\lambda \frac{L}{h}\right)_r = 1$	$\lambda_r = h_r / L_r$	Dictates model roughness, resp. vertical distortion factor (n_1) (see Chap. 1 and 2)
Turbulent diffusion	Diffusion coefficients E_x, E_y, E_z	Horizontal $(E_{x,y}\,L / L^2 v)_r = 1$ Vertical $(E_z\,L/h^2 v)_r = 1$	$(E_{x,y})_r = L_r h_r^{1/2}$ $(E_z)_r = h_r^{5/2} / L_r$	Prohibits model distortion if both directions have to be considered $(L_r = h_r)$
Buoyancy	Densimetric Froude number $Fr_d = \frac{v}{\sqrt{(\Delta\rho_w/\rho_w)\,g\,h}}$	$(Fr_d)_r = 1$	$(\Delta\rho/\rho)_r = 1$	Dictates density ratio
Density stratification	Interfacial friction coefficient λ_i	$(\lambda_i \frac{L}{h})_r = 1$	$(\lambda_i / \lambda)_r = 1$	Approximately satisfied for $10^3 \leq Re \leq 10^5$ (Abraham and Eysink, 1971)
Decay processes, heat loss	Exponent of first order decay laws, e.g. heat loss : $K\,L / (\rho_w c_p h v)$	$(\frac{K\,L}{h\,v})_r = 1$ with $(\rho_w c_p)_r = 1$	$K_r = h_r^{3/2} L_r^{-1}$	Dictates a vertical distortion factor (n_2). From experience: without reproduction of atmospheric condition, there is $K_r \approx 4/3$

Fig. 4.3: Similarity Laws for Mixing Processes in Froude Models

in just one model. Frequently recourse must be taken to a number of detail models.

Hydraulic models are especially suited for the investigation of the usually rather complicated flow situation in the near-field. When using an undistorted model, mixing due to momentum and buoyancy of the discharge can be represented correctly, as long as bed friction and exchange processes (e.g. heat loss) are of secondary importance within the model area. Typical near-field models for mixing investigations will be described in Section 4.3.

The extent of near-field models has to cover at least the area of "active" mixing due to momentum flux and buoyancy. It does not have to extend to the end of the intermediate region where there is complete cross-sectional mixing: Usually this is also not possible. Normally it should be attempted to cover the whole extent of density stratification in order to have complete vertical mixing along the outer boundary of the model. Such a fixation of the model boundaries in advance is difficult to achieve, but it is somewhat facilitated by the fact that there is no feedback between far- and near-field in rapidly flowing rivers. In any case, it has to be assessed at which distance the flow in the river will again be undisturbed.

Mixing in a river outside the near-field can be investigated in distorted models, if the water constituents or the heat are already distributed evenly over the water depth (which is achieved rather quickly for the type of discharges common in Germany) and if the mixing is dominated by horizontal velocities. In this case it is unimportant that the vertical mixing in the model is less intensive than in nature. Near-field mixing can also be investigated approximately in distorted models, if the flow is essentially twodimensional, as e.g. for discharges over the whole water depth or a long row of diffusers at the river bed (Abraham, 1975).

Because of the considerable economic advantages of a distorted model, Liong (1977) developed a correction procedure for reproduction of jet spreading in models with up to a fourfold vertical distortion. It uses a modification of the geometry of the outlet structure in order to compensate the deviation of jet spreading in a distorted model, which is possible for certain conditions (high exit velocities) with the aid of his experimental results.

Far-field mixing in rivers can be predicted for simple geometric and hydraulic conditions by means of numerical models. The combination of an undistorted hydraulic near-field model with a numerical far-field model offers a reliable method for dealing with mixing problems in rivers, especially since rather simple far-field models permit relatively exact predictions already and because in a river there are well-defined conditions with no feedback at the interfaces between far- and near-field (which correspond to the upstream and downstream model end). On the other hand, for the near-field still no universally valid numerical model exists, which could replace laboratory experiments, in spite of intensive research efforts.

Simple numerical models are also advantageous if only the heat loss in the far-field is of interest. Here lateral temperature gradients are unimportant if mixing in the vertical is complete (Kobus, 1975).

Particular attention should be paid in the future to the verification of model results by extended field tests, because the similarity relationships as derived for hydraulic mixing models are not without problems. Although there are a number of investigations (e.g. Stolzenbach, 1976), which show the reliability of model results, a systematic and comprehensive comparison of a larger number of case studies is still needed.

4.2.4 Modelling Technique

The choice of the model length scale follows the rules given in Chap. 2 for river models. The model discharge has to exhibit the same concentration or density difference as the prototype (identical Fr_d).

The effluent has to be labelled. Tracer material used should be easily measurable, conservative, cheap and safe. Chemical substances can be used in very minute concentrations as tracers for neutrally buoyant discharges (Smart and Laidlaw, 1977). Dyes like Uranin or Rhodamin can be used for visualization of the effluent. Optical procedures (fluorescence, absorption measurements) are the best method for quantitative investigations (Barczewski, 1975).

Buoyant discharges are produced either by addition of salt or by an increase in temperature. Salt concentrations may be detected with conductivity meters of sufficient accuracy, and thermistors or thermoelements may be used as temperature sensors.

In any case, the injection of the tracer has to take place with as little disturbance as possible. Usually it is advantageous to mix the effluent outside the model in a separate container until it has the desired concentration. Sometimes it is possible to achieve the necessary pre-mixing in the feeder pipes of the model.

Hydraulic models are usually operated with closed circuits. Therefore care has to be taken not to increase the background level during the experiment due to continuous tracer or heat addition. This dictates a maximum duration for a single experiment, which is determined by the model discharge and the storage capacity of the system:

$$\text{max. duration of experiment} \approx \frac{\text{total volume of system}}{\text{model discharge}} \qquad (4.8)$$

The maximum duration can obviously be increased by enlarging the storage capacity of the pump-sump system, but after passage of the time defined by Eq. (4.8) the background level will increase, which has to be compensated by appropriate measures. In any case, control measurements have to be performed continuously at the model inlet.

Particular attention is necessary for modelling decay processes, which can be done in some cases, but usually requires an extraordinary effort. For example, modelling the heat loss to the atmosphere requires a distorted model (see Fig. 4.3) and the simulation of air temperature, humidity and wind conditions at least on the average. This requirement causes a considerable effort and usually cannot be fulfilled.

For the conversion of model results to prototype data one therefore usually has to be content to account for decay processes only approximately. Often the measured temperature profiles are corrected such that the total heat flux remains constant in all consecutive cross-sections. This corresponds to the case of a conservative tracer, resp. to the situation of no net heat loss in the model. If the decay law is known for natural conditions, the measured concentration- or temperature profiles can be corrected analytically. To this end the time dependance has to be converted into a function of distance from the point of discharge by means of the average flow velocity.

4.3 Case Studies

4.3.1 Cooling-Water Discharge into a Non-Impounded River

One of the first model investigations of mixing processes in Germany dealt with the consequences of a nuclear power plant intended for the BASF industrial complex on the river Rhine near Ludwigshafen (Naudascher and Zimmermann, 1972). This power plant was designed for a cooling water demand of 40 m^3/s, which was to be withdrawn at river kilometer 428.49 and discharged at km 428.76 with a temperature difference of 9 K. The mixing with the river flow had to be investigated for various discharges, and the influence of outlet structure design, discharge angle and temperature rise had to be evaluated. Also, the question of recirculation had to be dealt with, and magnitude and distribution of the discharge-induced lateral velocities had to be determined. The purpose of the investagation was to design the outlet structure such as to keep the cooling water plume within a narrow near-shore zone and to limit the discharge-induced lateral velocities to a maximum value of 0.3 m/s.

A fixed bed, undistorted model of the river reach from km 428.0 to km 431.0 was built in the Theodor-Rehbock-Laboratory of the University of Karlsruhe with a length scale of 1 : 70 (Fig. 4.4). Consequently, the mouth of the right side tributary Neckar was within the model boundaries. The model was operated according to Froude's law. In order to represent density effects correctly, the densimetric Froude numbers also had to be identical - i.e. the temperature rise in the model had to be the same as in nature. Meteorological conditions were

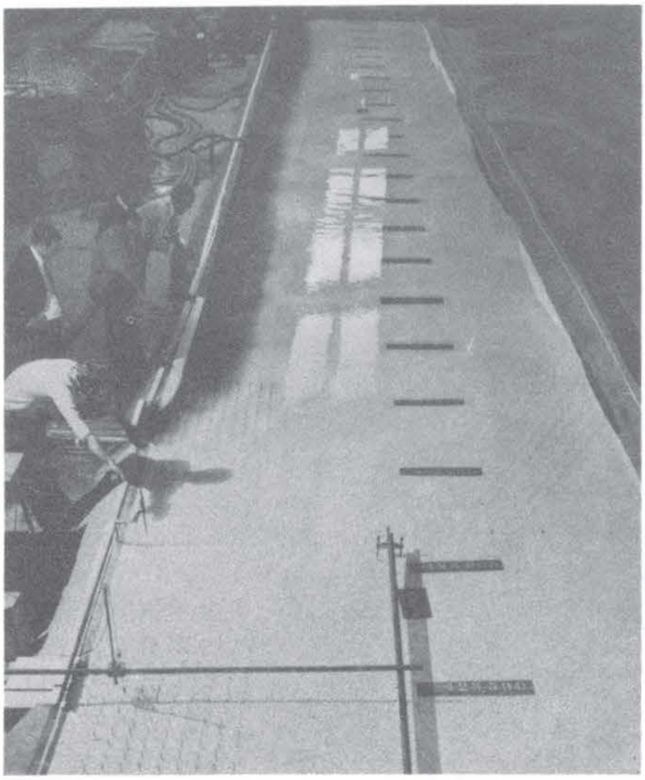

Fig. 4.4: Visualization of a Warm Water Plume in the Model (Rhine near Ludwigshafen)

not modelled since mainly the near-field mixing was of interest. During calibration of the model, velocity measurements in the river and the model were compared for a number of river discharges. As a result, the addition of roughness elements to the model surface was judged to be unnecessary. The stratification which was observed later in the experiments may possibly have been promoted by an unrealistically smooth bed, however. This emphasizes the importance of modelling the bed roughness exactly (see Fig. 4.10). The simulation of the many water intakes and outlets of the BASF along the left-hand shore required a distribution station with discharge measuring devices for each individual outlet. For simplicity, the same temperature rise was adopted for all outlets.

Velocity- and temperature sensors were mounted on a movable bridge. Velocities were measured with laboratory propeller meters and temperatures with thermoelements made of copper-constantan (diameter: 0.25 mm, thermo-electric voltage ratio: 0.043 mV/K).

From the temperature measurements a relatively modest mixing was observed within the immediate outlet area. The initially uniform distribution over the depth was altered due to buoyancy effects and a partly rather pronounced stratification developed at approximately 200 m downstream from the point of discharge. Thereafter the stratification was broken up due to the bed-generated turbulence. The plume remained near the shore and mixing with the ambient flow was rather slow. The maximum temperature in a cross section seldom occured at distances greater than 50 m from the shore.

Only at low river discharges could the mixing be influenced by variation of discharge angle and design of the outlet structure. The main influence on the position of the isotherms resulted from the ratio of cooling-water- to river discharge, whereas a twofold increase of the discharge velocity only resulted in a 1.2-fold increase in plume width. On the other hand, the variation of the temperature rise produced a fundamentally different behaviour of the plume

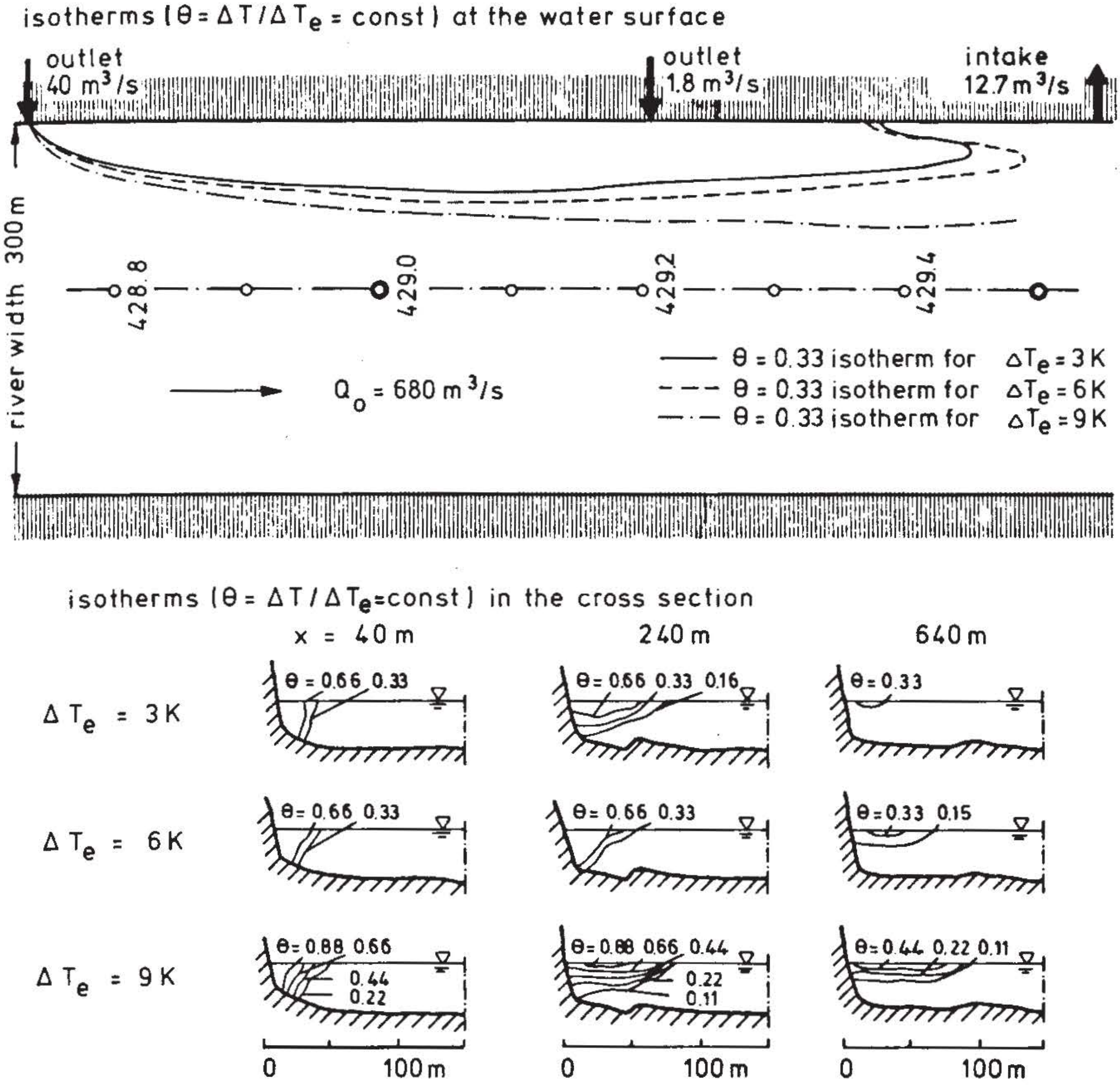

Fig. 4.5: Spreading in a River as Function of Initial Temperature Rise (According to Naudascher and Zimmermann, 1972)

(Fig. 4.5). The plume stayed closer to the shore and vertical temperature gradients were very mild for a temperature rise ΔT_e = 3 K, whereas strong stratification occured for ΔT_e = 9 K, which was broken up only very slowly.

The distribution of lateral velocities can also be determined quickly and easily in a hydraulic model. As an example, the lines of equal lateral velocity are shown in Fig. 4.6 as a function of the discharge angle α. From the model measurements an influence of α could be observed in a limited area very close to the outlet structure only. The influence of the buoyancy forces, however, could be detected up to several hundred meters downstream from the

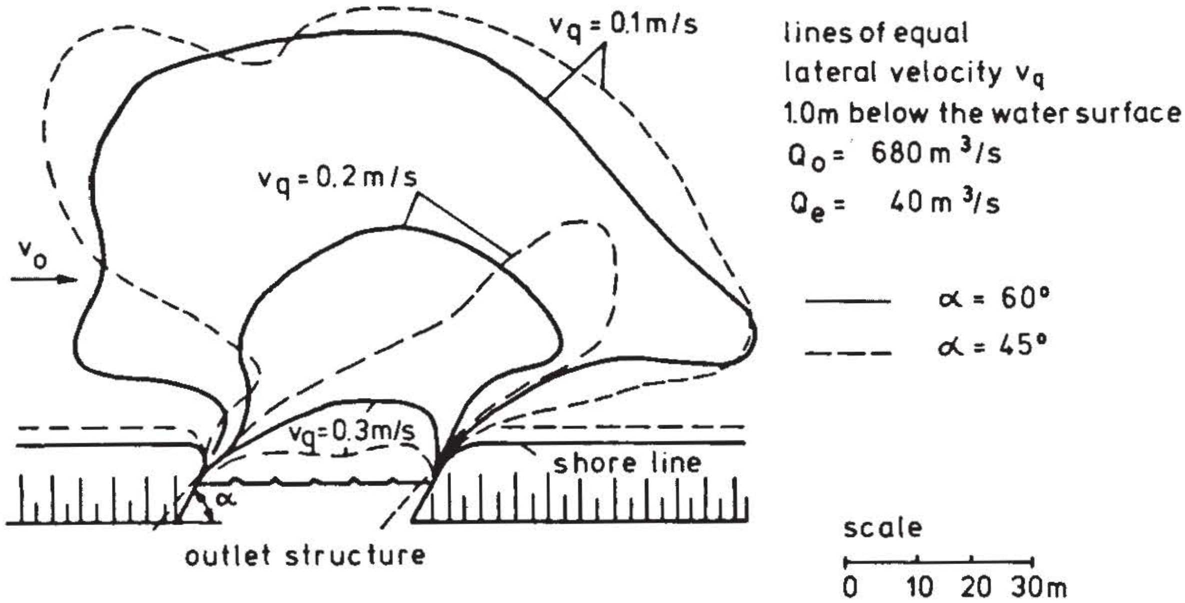

Fig. 4.6: Distribution of Lateral Velocites in the Outlet Region at Mean Low Water (According to Mosonyi [1])

point of discharge. Again, the most important influence for the development of the warm water plume was the ratio between cooling-water- and river discharge. The relatively unproblematic use of a hydraulic model even for complicated boundary conditions (numerous additional intakes and outlets) is demonstrated by this example.

4.3.2 Cooling-Water Discharge into an Impounded River

In 1976, the Bundesanstalt für Wasserbau (BAW) in Karlsruhe conducted a model investigation for the planned nuclear power plant Wyhl. Because this power plant is situated within the backwater region of a river dam, withdrawal and discharge take place into a flow with a very low velocity. Therefore navigation problems due to high lateral velocities and the occurence of stratification may be anticipated. Additionally, the Weisweil bight, which is ecologically an exceptionally sensitive area located only 1.5 km downstream from the power plant, might be particularly endangered by a warm water inflow.

The hydrothermal situation in the river Rhine in connection with this warm water discharge was observed in an undistorted, fixed bed model with a scale of 1 : 75 (Fig. 4.7). The model was operated according to Froude's law and

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1) Mosonyi, E.: "Die wasserbaulichen Auswirkungen eines Kernkraftwerkes der BASF auf den Rhein bei Ludwigshafen". Teil II, Gutachten der Wasserbauinstitute I und II der Universität Karlsruhe, 1971 (unpublished)

with identical densimetric Froude numbers (i.e. identical temperature rise) as in the prototype. Again, meteorological conditions were not simulated. In order to obtain the appropriate bed friction, additional roughness elements had to be distributed along the river bed (see Fig. 4.7). The model enclosed a river stretch of approximately 3 kilometers up to the next downstream river dam.

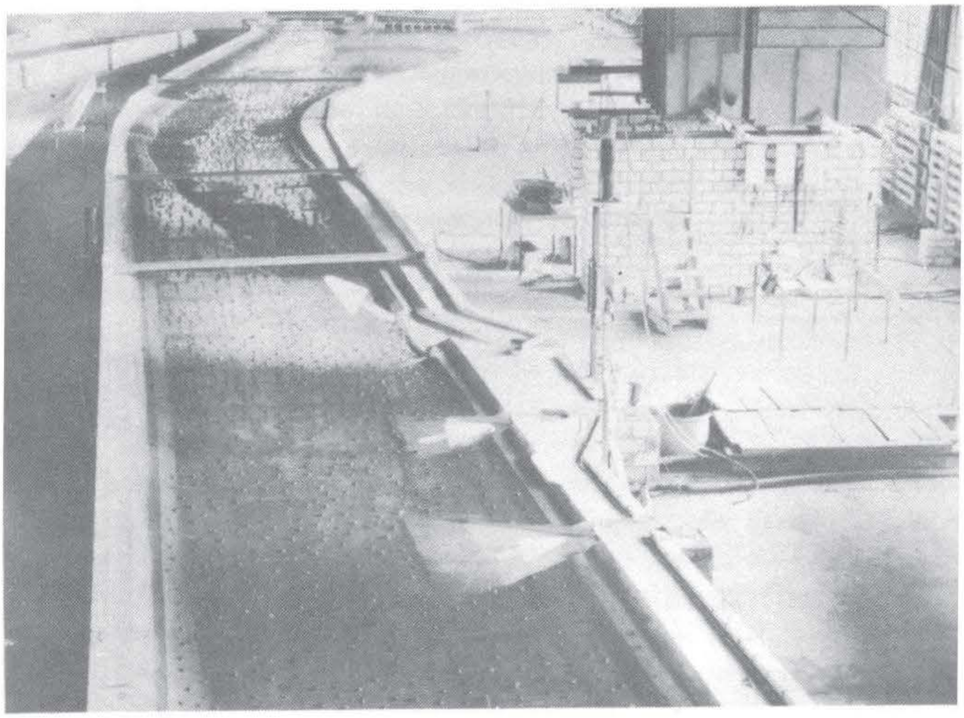

Fig. 4.7: Intake and Outlet Structure on a River Model (Rhine near Wyhl-Weisweil)

The experimental equipment in principle resembled the one described for the preceding example.

Measurements indicated strongly augmented mixing with the ambient flow for increasing river discharge. In this case it was possible to influence the spreading over a larger range by modification of the outlet structure. Whereas with the original design of the outlet a clearly defined jet with steep lateral and vertical temperature gradients crossed the river near its surface and struck the opposite shore, the plume stayed on the side of the outlet in a modified version which was designed mainly to reduce the lateral exit velocities (see Fig. 4.8). However, in the second version, improved with respect to navigation requirements, a larger area remained subjected to high excess temperatures and strong vertical temperature gradients (up to 3 K/m). In addition, the ecologically important shore region was influenced more strongly and higher temperatures as well as vertical temperature gradients occured in the Weisweil bight upstream of the weir, which is operated such as to divert only a very small portion of the river flow most of the time and thereby produces nearly stagnant water in the bight. In this case, the thermal situation at a distance as large as

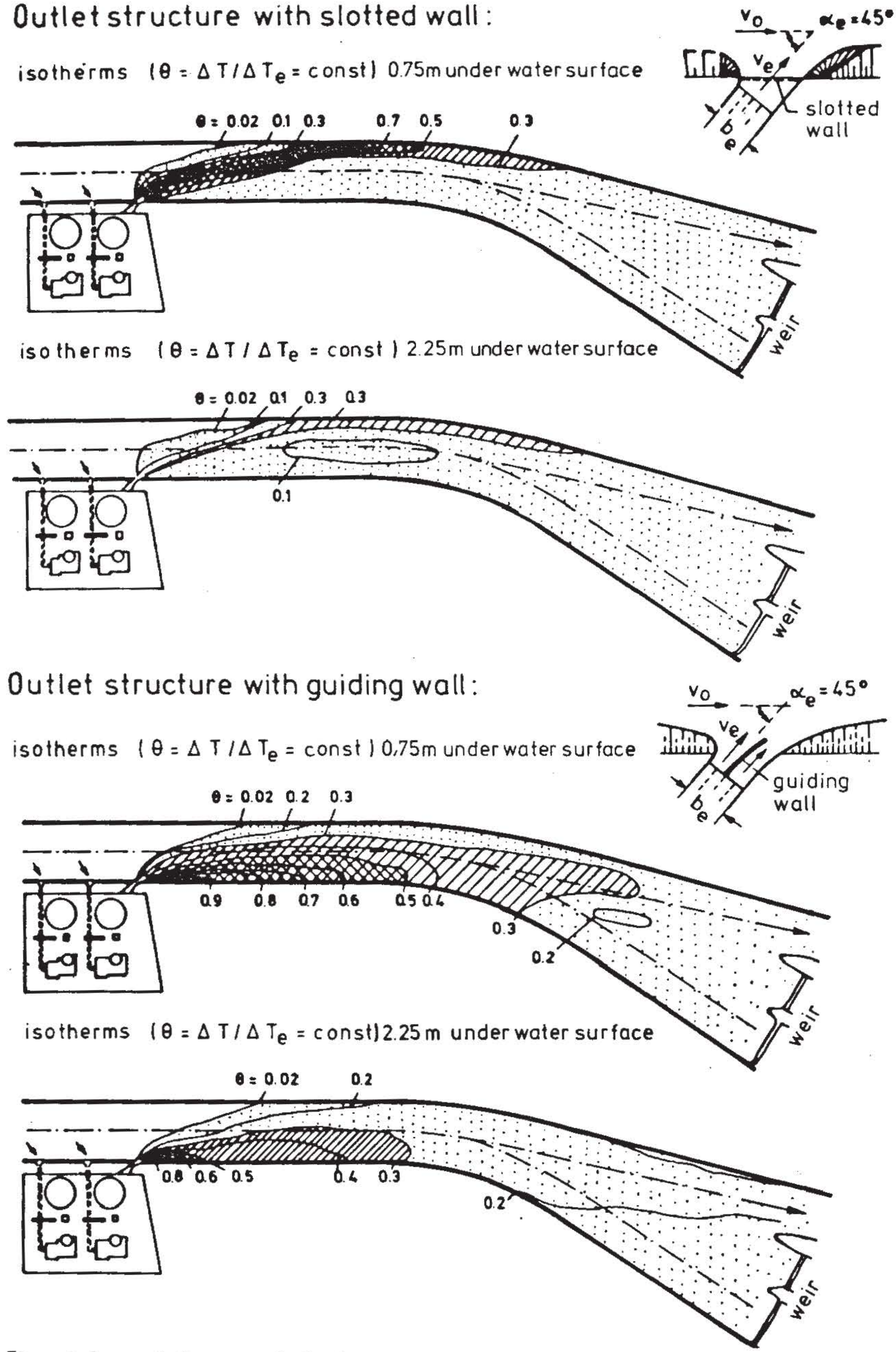

Fig. 4.8: Influence of Outlet Structure Design upon Plume Spreading under Otherwise Identical Flow Conditions (Planned Nuclear Power Plant Wyhl, Q_o = 1000 m^3/s, Q_e = 130 m^3/s, ΔT_e = 10 K)

3 km downstream from the outlet was markedly influenced by the design of the outlet structure.

4.3.3 Systematic Investigations on Lateral Discharges into Rivers

Outlet structures built so far in Germany may be classified according to certain design features (Geldner and Zimmermann, 1976). Therefore a systematic investigation of mixing processes in hydraulic models with a simplified geometry appears useful at least for that region where flow conditions caused by large scale topographic features of the river do not play an important role. The relative importance of different parameters for the behaviour of the warm water plume may be assessed by a systematic variation of these parameters. Such investigations have already been performed for some time at the Sonderforschungsbereich 80 at the University of Karlsruhe. They are not to be considered a true reproduction of a certain case in nature, but rather as a small-scale prototype on which mathematical models can be developed and verified.

Fig. 4.9 shows, as an example, the influence of the velocity ratio v_e/v_o on the shape of the jet boundaries within the near-field (according to Gehrig, Jurisch and Lemmin, 1976). Remarkable is the formation of a back flow region for a discharge over the whole depth of flow and velocity ratios of ($v_e/v_o \approx$ 1.3). The depth of penetration of the jet into the main flow and the length of the back flow region grow for increasing velocity ratios.

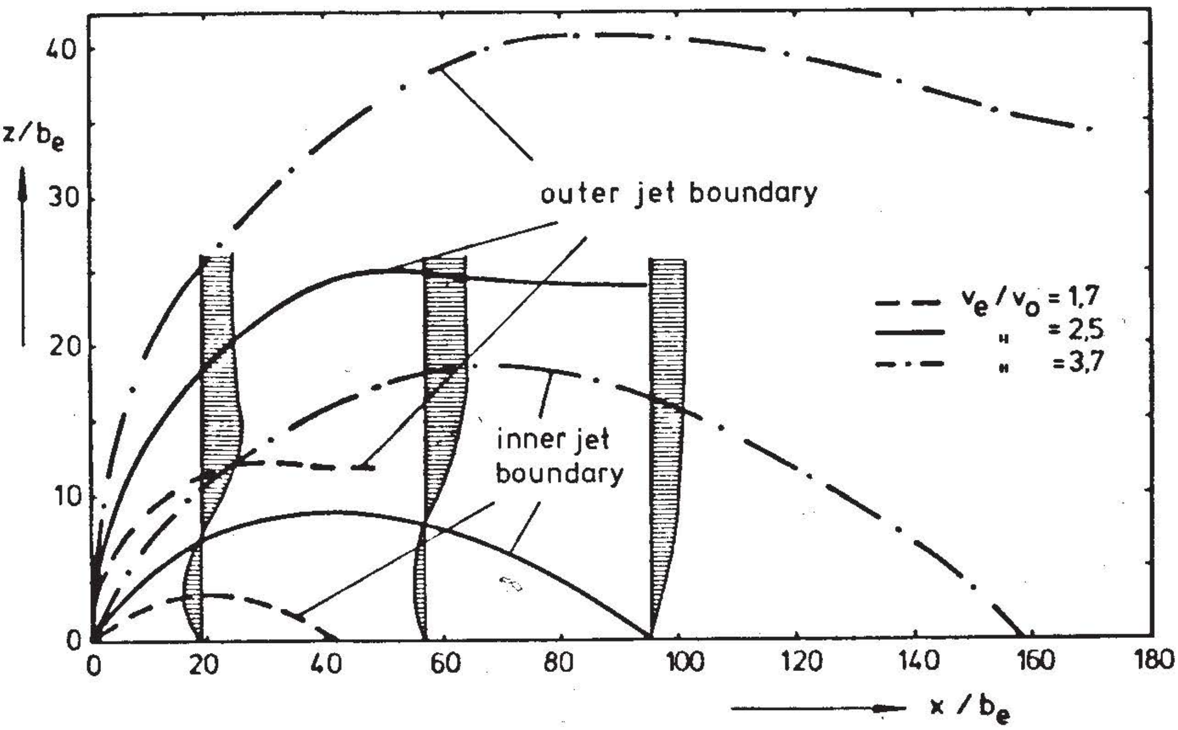

Fig. 4.9: Influence of the Velocity Ratio v_e/v_o on the Shape of the Jet Boundaries (Gehrig, Jurisch and Lemmin, 1976)

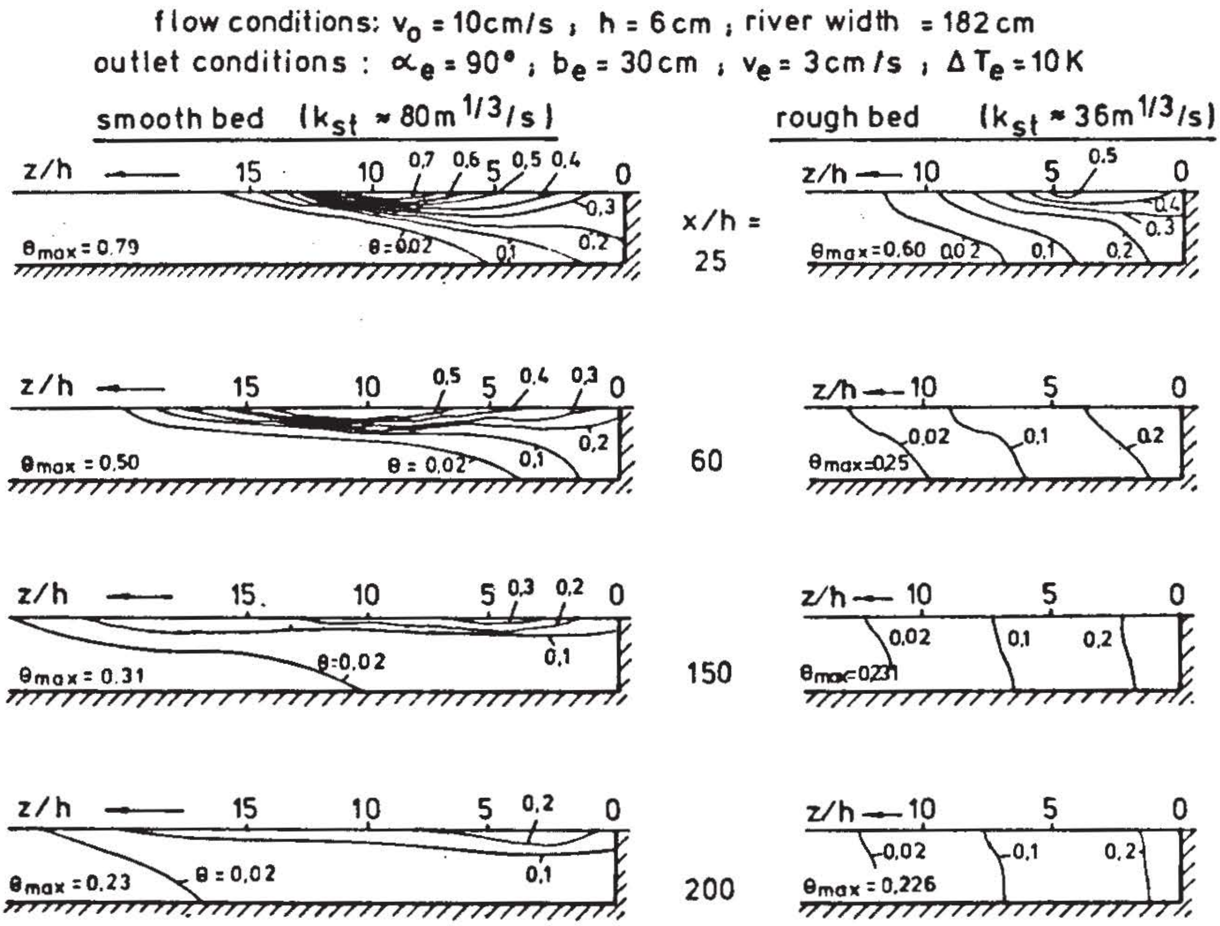

Fig. 4.10: Cross-Sectional Isotherms Downstream of a Lateral Discharge over the Whole Water Depth for Smooth and Rough Flume Bed under Otherwise Identical Flow Conditions (According to Schatzmann et al., 1978)

Fig. 4.10 confronts cross-sectional isotherms for smooth and rough flume beds. The turbulence generated at the rough bed prevents the development of stratification. On the other hand, for a smooth bed the density-induced lateral spreading leads to a fast broadening of the warm water plume. The "lead" due to this effect may result under certain hydraulic conditions in a faster excess temperature reduction over shorter distances.

4.4 Summary and Evaluation

Mixing and transport of water constituents in the near-field of a discharge may be modelled with sufficient accuracy using undistorted hydraulic models. This is valid equally for neutrally buoyant and buoyant (density differences due to salt content or temperature differences e.g.) effluents.

Mixing phenomena can be modelled correctly only for the near-field, where bed friction and decay processes or heat loss to the atmosphere are of secondary importance. A distortion is necessary for modelling these processes, and thereby the mixing processes are also distorted. In general, this is not permissible for river models without loosing exact similarity because of the necessary distortion of the shape of the cross-section. Under certain exceptional circumstances, however (e.g. for very large aspect ratios), a distortion may be acceptable for river models.

A combination of undistorted hydraulic near-field models and simple numerical far-field models is advantageous for dealing with mixing and transport processes in rivers, because the flow direction is given and the dynamics of far-field mixing is comparatively simple.

Moreover, hydraulic models are particularly suited for the investigation of individual subregions, for each of which different similarity laws may be significant; so that different distortions may be necessary.