SIMK® - Calibration of Streamflow - Gauging Stations in Rivers and Canals[1]

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1. Practical application of the SIMK® - calibration method

SIMK® is an universally applicable method, allowing precise stage and profile dependent calibrations of streamflow - gauging stations. In many international practical applications SIMK® has proved successful for many years. SIMK® is based on the numerical simulation of the strongly stage and profile dependent dimensionless velocity ratios $k = v_m / v_l$. The numerical simulation is performed by application of a high resolution finite - element fluid dynamics model.

SIMK® ▸ **Sim**ulation of $\mathbf{k} = v_m / v_l$

v_m	area averaged mean velocity $v_m = Q / A$ of the wetted section
v_l	punctual or line - averaged measured local velocity

Fig. 1 SIMK® - radar - streamflow - gauging station Schrottenbaummühle / Ilz (orderer: WWA Passau / Germany)

[1] A PDF - version of this paper may be downloaded from http://www.isar-consult.de.

Fig. 2 Bridge mounting of two radar sensors, providing continuous contact free stage and velocity measurements of the Ilz river (orderer: WWA Passau / Germany)

Fig. 1 shows exemplarily a typical practical application of the SIMK® - calibration method. The photo was taken from the road bridge shown in fig. 2 towards upstream. It shows the approaching flow of the streamflow - gauging station Schrottenbaummühle in the Bavarian Ilz river. This streamflow - gauging station is operated by the German water resources office (WWA) Passau. According to fig. 2 two radar sensors were mounted underneath the bridge. These radar sensors provide continuous and contact free measurements of the stages h and local surface velocities v_l of the Ilz. In 3 minutes intervals these values are measured and digitally stored in the monitor of the streamflow - gauging station.

Before starting the continuous radar discharge measurements the strongly stage and profile dependent dimensionless velocity ratios $k(h) = v_m / v_l$ had been determined once by application of the SIMK® - calibration - method. SIMK® provides accurate velocity ratios k(h) for the full range of relevant (high-) water level variations $h_{min} \leq h \leq h_{max}$ by taking into account the individual site specific hydraulic boundary conditions of the measuring site Schrottenbaummühle. The result of the SIMK® - calibration is a site specific stage dependent k - h - calibration - table, being stored digitally in the monitor of the streamflow - gauging station. Based on the actual measured water levels h, the corresponding velocity ratios $k(h) = v_m / v_l$ are selected online from this digitally stored k - h - calibration - table.

Therefore one single stage dependent SIMK® - calibration of the streamflow - gauging station enables continuous online determinations of precise site specific velocity ratios $k(h) = v_m/v_l$, corresponding to the actual stage measurements h. These k - values permit accurate stage dependent online - transformations of the actually measured local surface velocities v_l into the area - averaged mean velocities $v_m = k(h) * v_l$ and thus into the requested discharges $Q = A * v_m$ of the Ilz river.

The measured values h and v_l and the corresponding discharges Q are stored digitally according to the measurement frequency Δt. The instantaneous values and all digitally stored historical h, v_l and Q - values are online available at any time via remote data transmission, which can be realized by means of modems or alternative data transmission devices. Therefore, these SIMK® - based discharge measurements may be used immediately and without any postprocessing and without any delay e. g. for actual flood reporting, flood forecasting and flood warnings.

2. Task of the SIMK®- method

The basics of the SIMK® - calibration method were developed at the Hydraulic Institute of the Technical University of Munich [4]. They are based on the simple continuity equation:

$$Q = A(h) * v_m \qquad (1)$$

with

Q [m^3/s] requested discharge,

A [m^2] stage h dependent wetted section,

v_m [m/s] area averaged mean velocity $v_m = Q / A$,

v_l [m/s] at a known cross sectional position (x,y) measured local flow velocity.

Since the area averaged mean velocities v_m of the wetted section usually deviate from the punctual or line - averaged measured local velocities v_l, accurate discharge measurements additionally require accurate knowledges of the stage and profile dependent dimensionless velocity ratios

$$k_l = v_m / v_l \qquad (2)$$

which have to be determined by calibration. Substitution of (2) into (1) provides

$$Q = A(h) * k_l(h) * v_l \qquad (3)$$

(3) reveals, that accurate discharge measurements depend to the same extent on the accuracy of

- the profile and stage dependent cross sectional area A(h),
- the likewise profile and stage dependent dimensionless velocity ratios k(h) and
- the local velocities v_l(x,y), being measured at known cross sectional positions x, y.

For hydraulically suitable choosen discharge measuring sites accurate stage dependent determinations of A(h) based on a known cross sectional profile and measured stages h are usually simple geometric tasks, needing no further explanations. According to manufacturer' s informations the local velocities v_l can be measured with accuracies of at least ± 2%, if the application requirements of the manufacturers are considered.

The dimensionless scaling factors k_l(h) mainly depend on the known geometry parameters

- profile shape,
- actually measured (high-) water level and
- the position (x,y) of the local velocity measurement v_l(x,y)

and to a smaller extent on the reynolds number Re and the wall roughness k_s [4]. For hydraulically suitable choosen flow measuring sites and installation positions of the velocity sensors strongly profile and stage dependent scaling factors in the rage of

$$60\ \% \leq k_l \leq 120\ \% \qquad (4)$$

have to be expected for typical river and canal profiles. The velocity ratios k_l are strongly effected by the type and position of the local velocity measurement v_l(x,y). Especially for close to natur rivers within the same measuring cross section stage dependent k_l - value variations of approximately 10 to 25% are typical for constant positions of the local velocity measurements.

However, for hydraulically unsuitable choosen discharge measuring sites or for hydraulically unsuitable installation positions of the velocity sensors even substantially larger variations of the dimensionless velocity ratios k_l(h) have to be considered. For example, if the measuring site is positioned directly downstream a sharp river bend or directly downstream a big bridge pier or directly upstream of a weir, dead water zones or even local return flow zones may appear in the vicinity of the local velocity measurements. This has to be expected particularly in high water situations. However, the k - values, corresponding to local velocities, being measured in dead water zones, may reach values of several 100%. Velocities, being measured in typically strongly stage dependent local return flow zones, even require negative k - values.

From that it follows:

1. For discharge measuring sites or for installation positions of the velocity sensors, which are choosen hydraulically unsuitable, accurate discharges can typically not be determined, even if very precise stage and velocity measurements are available, because the locally measured velocities v_l are not sufficiently representative for the area - averaged mean velocities v_m of the whole wetted section.
2. In contrast, for hydraulically suitable choosen discharge measuring sites and for hydraulically suitable choosen installation positions of the velocity sensors, the local velocity measurements v_l are characteristic of the requested area - averaged velocities v_m. However, the corresponding dimensionless velocity ratios $k_l = v_m / v_l$ are by no means constant, but they may be subject to strong stage dependent variations.
3. Therefore, (3) reveals, that even based on hydraulically suitable choosen discharge measuring sites and hydraulically suitable choosen installation positions of the velocity sensors and based on very accurate stage and velocity measurements the

requested discharges Q cannot be determined more exactly, than permitted by the available knowledge of the corresponding scaling factors $k_l = v_m / v_l$. These site specific k - values typically strongly depend on the profile shape and on the actual (high-) water level.

Thus, the discharge measuring sites and the installation positions of the velocity sensors have to be choosen hydraulically suitable. However, even if this minimum requirement is fulfilled, accurate stage and velocity measurements have to be complemented by an universally applicable procedure, which provides the strongly profile and stage dependent k(h) - scaling - functions, being defined in (2). This method must provide site specific velocity ratios k(h) accurately, short - term and for the complete range of stage variations

$$h_{min} \le h \le h_{max} \qquad (5)$$

which may occur at the discharge measuring site, comprising extreme high - water levels. This procedure is the SIMK® - calibration method, being described in the following section.

3. SIMK® - basics

(2) shows, that the dimensionless scaling fators $k_l = v_m / v_l$, required for the calibration of a discharge measuring site, exactly correspond to the product of v_m and the reciprocal value of the axial velocity distribution $v_l(x,y)$ of the river or the canal profile. Hence, universal determinations of k_l require detailed knowledge of the dimensionless relations between the turbulent axial velocity distributions v(x,y) and the corresponding area averaged mean velocities $v_m = Q / A$ of the stage dependent wetted sections.

The calibration method **SIMK®** is based on the **sim**ulation of the dimensionless profile and stage dependent scaling factors $\mathbf{k_l}$. For this turbulent velocity distributions are simulated for rivers or canals of any shape and size by means of a numerical fluid dynamics model. The axial velocity distributions are strongly influenced by secondary currents, which prevail within the profile cross section and which originate from impediments of the turbulent impulse exchange in the vicinity of the profile boarders and the free water surface [4]. Therefore the axial velocity distributions $v_l(x,y)$ and thus the corresponding scaling factors $k_l = v_m / v_l$ strongly depend particularly on the site specific profile shape and on the actual stage. However, profile shape and stage of a river or canal are known or continuously measured. Since the utilization of the precise knowledge of these especially predominant geometrical factors requires precise considerations of the site specific profile shape and of the actual measured stages, the SIMK® - calibration method allows precise and detailed adaptable finite - element discretisations of the stage dependent wetted sections of rivers or canals of any size and shape.

This is exemplarily illustrated in Fig. 3, showing the finite - element - discretisation of a jointed measuring cross section in Muka Keratan / Malaysia, comprising a 20 m wide concrete canal, which is restricted by sheet pilings and grass - covered forelands of different widths, being likewise limited by sheet pilings and being flooded in case of high water situations only. In this 43 m wide measuring cross section very different wall roughnesses and significantly varying stages in the range of approximately $24.0 \le h \le 29.0$ m had to be taken into account.

In this cross section an ultrasonic transit - time - system has been installed, providing continuous measurements of line - averaged velocities v_l, occuring along the ultrasonic path, being defined by the mounting positions of the corresponding ultrasonic sensors. Since continuous velocity measurements were requested for the full range of stage variations, the ultrasonic sensors had been mounted according to fig. 3 below the lowest expected water level of 23.20 m onto opposite sheet pilings of the main canal. Fig. 3 shows the finite - element - discretisation for the expected maximum water level of approximately HHW = 29.0 m, corresponding to an expected maximum discharge of approximately $Q_{max} = 450\ m^3/s$.

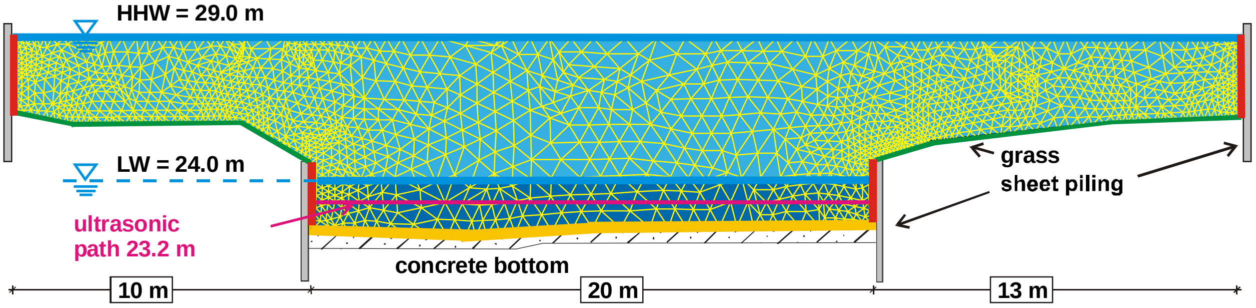

Fig. 3 Finite - element - discretisation of a jointed measuring cross section of an ultrasonic transit - time streamflow - gauging station, installed in Muka Keratan / Malaysia for the maximum water level HHW

Fig. 3 reveals, that profiles of any shape may be stage dependently discretisized very exactly and in great detail by means of the universally adaptable finite - element - triangulation. Moreover, based on these triangulations wall roughnesses, being exposed to significant variations along the hydraulic perimeter of the cross section, can easily be taken into account in great detail. This is achieved, because any wall roughness can be assigned independently of each other to every outside edge of the finite - element - mesh. In the SIMK® - model these varying wall roughnesses are individually considered for every outside edge of the finite - element - mesh based on the universal logarithmic law of the wall [4]. For instance, smaller wall roughnesses (k_s in mm) were assigned to the smooth concrete invert of the main canal than to the grass - covered forelands. Especially large wall roughnesses were assigned to the vertical sheet pilings. According to (5) analogous finite - element - discretisations had also been generated for systematically varied lower water levels h.

Based on these detailed stage dependent finite - element - assignments of the profile shape and the varying wall roughnesses, the corresponding turbulent axial velocity distributions of the river or the canal are simulated by means of the SIMK® - model. Simultaneous simulations of the very influential turbulence driven secondary currents enable highly accuracte SIMK® - simulations of the axial velocity distributions. The detailed considerations of river and canal profiles of any shapes and of any wall roughness variation enable universal applicabilities of the SIMK® - calibration method, being proved in [4] by extensive comparisons of simulated and measured velocity distributions. The application of the standard SIMK® - calibration method is restricted to gradual changes of the velocity distribution of the river or canal in flow direction, because all gradients in flow direction are neglected, since they are assumed to be much smaller than the gradients, occuring within the cross section. Many years‘ international practical experiences reveal, that in most cases this condition can be fulfilled in good approximation, if hydraulically suitable discharge measuring sites are choosen. Detailed descriptions of the basics and conditions of the SIMK® - model are provided in [4]. Comprehensive descriptions are given in [6], [8] and [10].

4. Verifications of the SIMK® - calibration device

The efficiency of the SIMK® - flow model was proven by calculating turbulent velocity distributions for profiles of different shapes and by comparing the simulated velocity distributions with precise lab measurements, provided by different authors.

For instance, the isovels in the right half of fig. 4 show the axial velocity distribution, measured contact free by Nezu and Rodi [11] by means of laser Doppler measurements in the left half of a partially filled rectangular canal. These measurements match very well the turbulent axial velocity distribution, being simulated by means of the SIMK® - model and being shown in the left half of fig. 4. The typical dip of the maximum velocity below the free surface and the bulging of the isovels towards the profile wall, which are very characteristic features of the turbulent velocity distribution of the investigated profile shape, are simulated by means of the SIMK® - model with high accuracy and in great detail.

The reason for this close correspondence is clarified by comparing the corresponding simulated and measured turbulence driven secondary currents, being shown in fig. 5. The bottom corner of the rectangular canal causes a strong secondary current along the bisector towards this corner, which drives a clockwise rotating surface vortex and a counter clockwise rotating bottom vortex.

Close to the free surface the turbulent velocity fluctuations are reduced in vertical direction and enlarged in horizontal direction. Therefore in the vicinity of the free water surface the turbulent velocity fluctuations become anisotropic, causing substantial reductions of the vertical turbulent impulse exchange and for continuity reasons substantial enlargements of the horizontal turbulent impulse exchange. This characteristic free surface induced anisotropy is strongly stage dependent and causes substantial enlargements of the horizontal components of the surface vortex in the vicinity of the free surface. These enlargements generate a strong convective impulse transport from the profile bank towards the profile center, which causes substantial reductions of the axial surface velocities.

Moreover, this characteristic free surface induced stage dependent anisotropic turbulence, occuring close to the free surface, causes an enlargement and a shift of the surface vortex from the profile bank towards the profile center. Thereby the bottom vortex is pushed into the profile corner and is reduced due to the increasing influence of the wall friction. Hence, the surface vortex exceeds the bottom vortex clearly with respect to extension and maximum velocity. In the center of the profile the strong vertical current of the surface vortex, directed from the free surface towards the bottom causes a significant dip of the maximum axial velocity below the free surface. This velocity dip is typical for compact rectangular profiles.

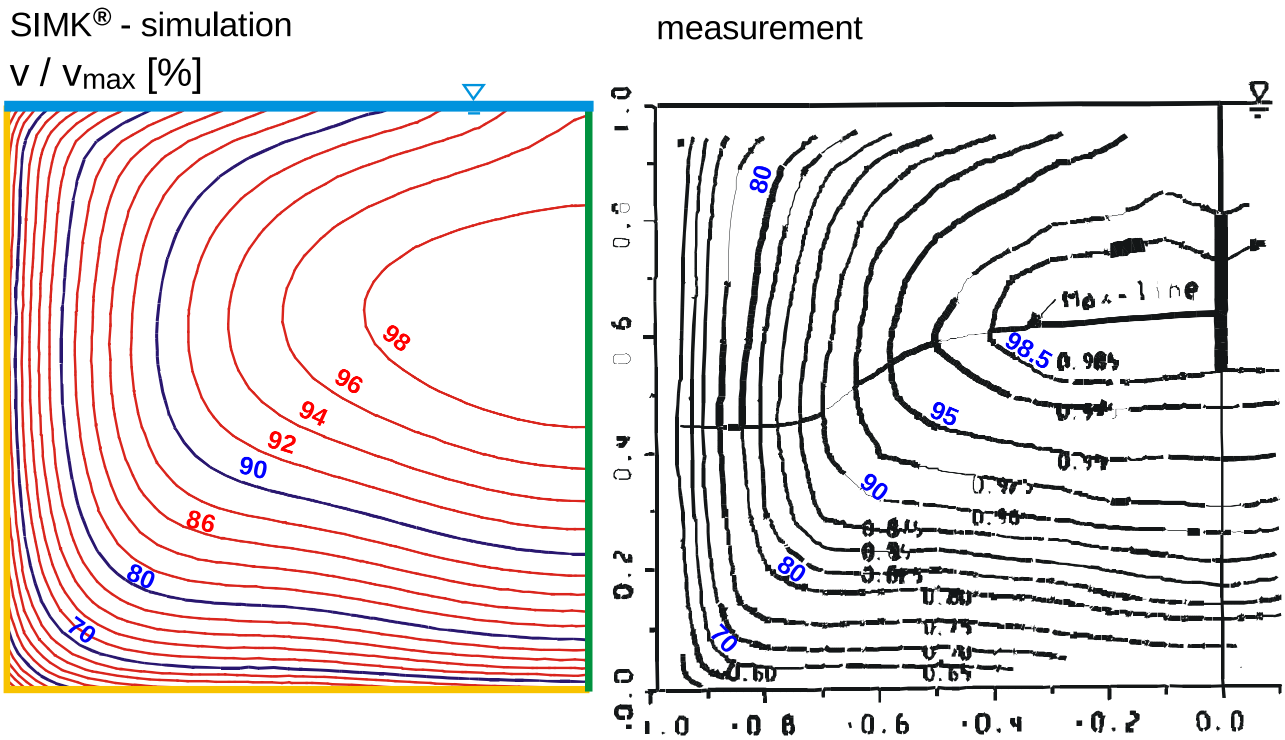

Fig. 4 By means of the SIMK® - model simulated and measured [11] axial velocities in the left half of a rectangle canal

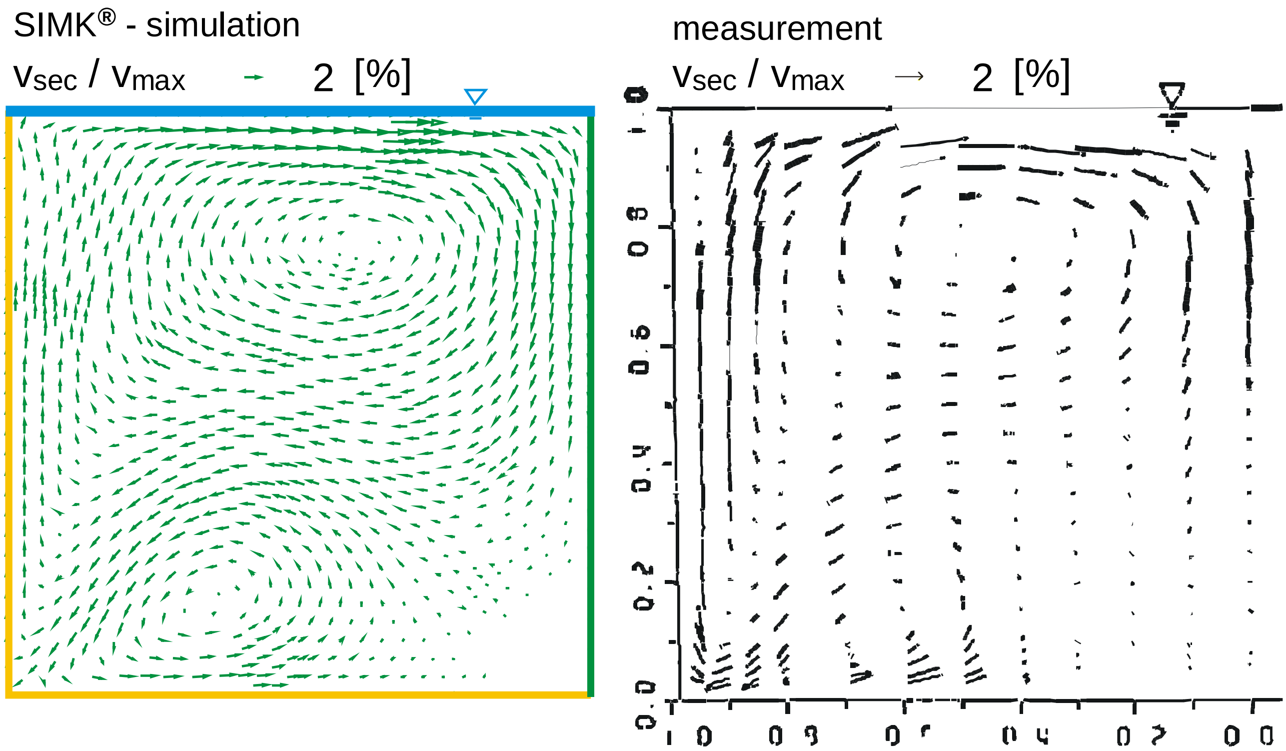

Fig. 5 By means of the SIMK® - model simulated and measured [11]] secondary velocities in the left half of a rectangle canal

Analogously many additional characteristic features of turbulent axial velocity distributions can be simulated and explained by means of the corresponding turbulence driven secondary currents, which are strongly influenced by the profile shape and the stage dependent level of the free water surface [4].

The SIMK® - model precisely takes into account these dominant influences of profile shape and stage. Therefore the SIMK® - model allows detailed and accurate stage dependent simulations of turbulent axial and secondary velocity distributions for profiles of any size and shape.

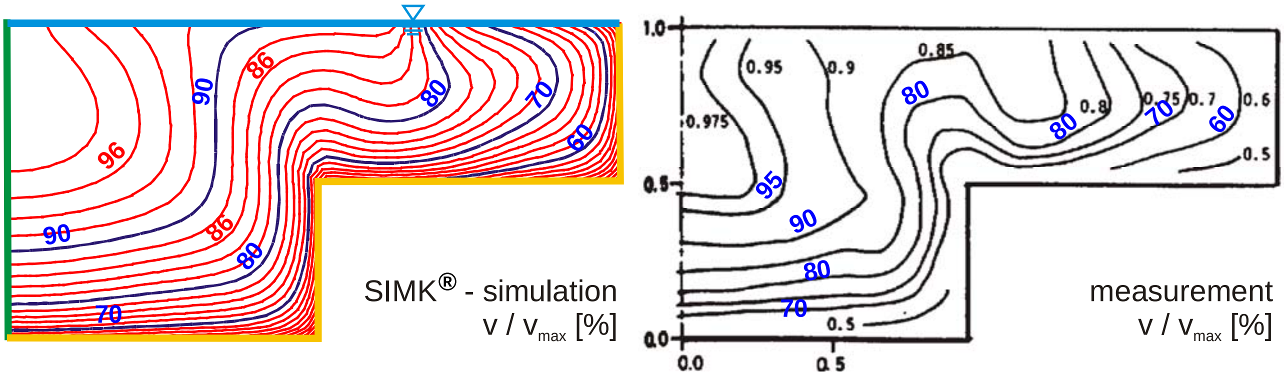

Fig. 6 By means of the SIMK® - model simulated and measured [15] axial velocities in the left half of a schematic foreland profile

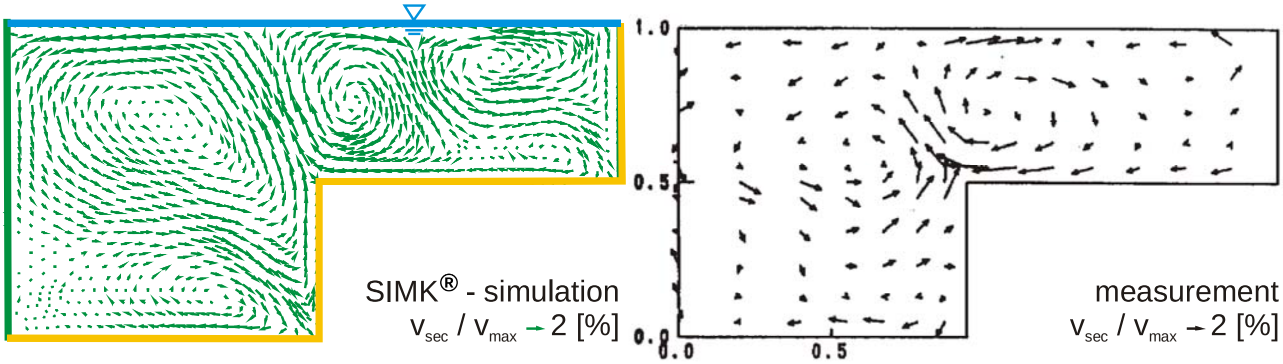

Fig. 7 By means of the SIMK® - model simulated and measured [15] secondary velocities in the left half of a schematic foreland profile

The universal applicability of the SIMK® - model on profiles of any shape is exemplarily illustrated in fig. 6 and 7, showing comparisons of simulated turbulent velocity distributions with hot film measurements of Tominaga, Nezu and Ezaki [15] for the right half of a schematic symmetrical foreland profile. As expected, the more complicated profile shape causes more complicated structures of the turbulent velocity distribution. For instance, the set back profile corner generates particularly strong secondary currents along the bisector of this corner, which are, however, directed from the corner towards the profile center and thus just vice versa to the secondary currents, generated by the salient profile corner of the rectangular canal. This strong corner current in the separation plane of the foreland profile drives a system of five counterrotating secondary vortexes within one half of the schematic foreland profile. Fig. 7 reveals, that each of these five vortexes is simulated by means of the SIMK® - model in great detail and in close correspondence to the hot film velocity measurements of Tominaga, Nezu and Ezaki [15].

[4] comprises approximately 20 additional comparisons of simulated and measured turbulent velocity distributions for further profile shapes and different water levels. In spite of the very different profile shapes, all of these simulations show close agreements with the measurements. Hence, high accuracies of the SIMK® - model may also be expected in case of irregular river profiles. Since the turbulence driven secondary currents and their strong influences on the axial velocity distributions are simulated reliably and in great detail, the SIMK® - model allows accurate and detailed calculations of the strongly profile and (high-) water level dependent velocity relations $k_l = v_m/v_l$, defined in (2).

Site specific SIMK® - calibrations of streamflow - gauging stations purposeful apply the hydraulic basic laws, underlying the SIMK® - model in order to conclude the area averaged mean velocity v_m and thus the requested discharge $Q = A * v_m$ based on a single or very few local velocities v_l, being measured at hydraulically suitable choosen positions (x,y) of the discharge measuring cross section.

SIMK® - calibrations do not use any absolute values of the simulated velocities, but only the simulated dimensionless velocity ratios $k(x,y) = v_m / v(x,y)$. Because these scaling factors typically strongly depend on the measured stages, but for Reynolds numbers, being typical for rivers and canals, depend only very slightly on the absolute values of the likewise measured velocities, SIMK® - calibrations are very well applicable in case of backwater, because the backwater influence is not simulated, but actually measured by means of h and v_l.

5. Field inspections of the SIMK® - calibration method

Several professional authorities have verified the accuracies and the universal applicability of the SIMK® - calibration method by comparing the discharges, being determined by means of the SIMK® - calibration method for canals and rivers of very different sizes, shapes and roughnesses with independent reference discharge measurements.

5.1 Laboratory for hydraulic engineering and water - resources management of the Technical University of Munich (VAO)

In the Obernach laboratory for hydraulic engineering and water - resources management of the Technical University of Munich (VAO) SIMK® - discharge - measurements were performed in a 2.5 m wide straight rectangular canal for three different stages. Stages h were measured by means of a staff gauge and the maximum velocities v_{max} were measured by means of a propeller current - meter. The stage dependent local positions (x,y) of the very flat and hence in practise very easily determinable velocity maxima (cf. fig. 4) and the corresponding likewise stage dependent dimensionless velocity ratios $k_{max} = v_m / v_{max}$ were determined by means of the SIMK® - model. Besides v_{max} no additional velocities were measured. Tab. 1 summarizes the resulting SIMK® - discharges $Q_{SIMK} = A(h) * k_{max} * v_{max}$, being

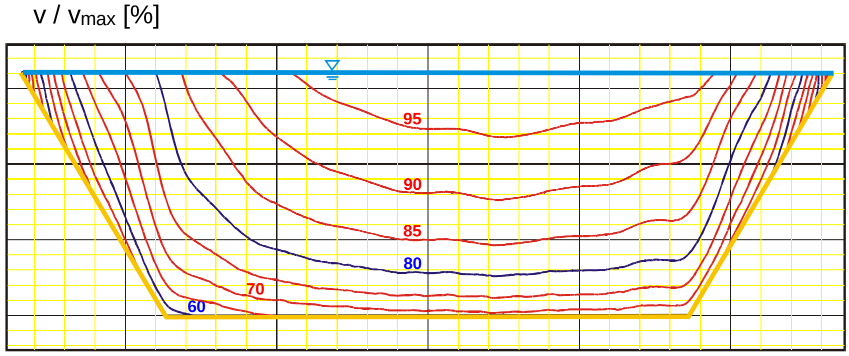

Fig. 8 By means of the SIMK® - model simulated turbulent velocity distribution in a curved trapezoidal canal of the VAO [14]

determined according to (3) exclusively based on the measured values h and v_{max} and the corresponding scaling factors k_{max}, being determined by SIMK® - calibration.

In analogous manner the two additional discharges Q_{SIMK}, stated in tab. 1, were determined for a curved trapezoidal canal with a movable bed. This trapezoidal canal is characterized by a bottom width of $b_s = 1.71$ m, slope gradients of 1 : 3 and a radius of curvature of R = 40 m, whose influence is taken into account in the SIMK® - model. Fig. 8 shows exemplarily a superelevated representation of the axial velocity distribution of the trapezoidal canal, simulated by means of the SIMK® - model. According to fig. 8 steeper velocity gradients dominate along the right outside bank than along the left inside bank of the curved canal. This unsymmetrical velocity distribution results from the additional bend - induced centrifugal forces, generating additional secondary currents, which are directed towards the outside bank near the free surface and towards the inside bank near the canal bottom. This large bend - induced secondary vortex results from the effect, that the axial velocities increase from the bottom of the canal towards the free surface. Since the bend - induced centrifugal forces are substantially increased by increasing velocities, the upper part of the cross section is exposed to larger centrifugal forces than the lower part of the cross section.

Since the SIMK® - model takes into account these bend - induced additional effects, the SIMK® - model also allows realistic simulations of turbulent velocity distributions in long - stretched river bends, which often appear in practise.

5.2 Federal institute of hydrology (BfG)

The advantage of the comparative measurements, carried out in the VAO is, that the SIMK® - discharge measurements could be compared with very precise reference measurements, being based on accurate stage measurements upstream a triangular discharge - measurement weir. However, it is disadvantageous, that the discharge verifications could not be carried out in natural rivers and that the discharges, realizable in the VAO, are substantially smaller than the discharges, occuring typically in big canals and large rivers.

Tab. 1 Verification of 5 SIMK® - discharge measurements in a straight rectangular and a curved trapezoidal canal

canal	h [m]	A [m²]	Q_{SIMK} [l/s]	Q_{VAO} [l/s]	**ΔQ [%]**
rectangle,	0.89	2.22	223	231	**-3.5**
b = 2.49 m	1.48	3.69	254	253	**0.5**
	1.91	4.76	319	302	**5.6**
trapezoid,	0.159	0.349	27.6	27.6	**0.0**
b_s = 1.71 m	0.161	0.353	37.3	37.8	**-1.3**

Hence, the attainable accuracies of SIMK® - calibrations were additionally investigated in large - scale field tests. For this the German federal institution of hydrology (BfG) ordered stage dependent SIMK® - calibrations for ten different waterway - canals and rivers, located in the regions of Berlin and Saxony. Based on these calibrations the BfG performed SIMK® - discharge - measurements in these waters and compared the results with independent reference discharge measurements, typically carried out by means of propeller current - meters. Water depths in the range of $2.4 \leq t \leq 7.0$ m and canal widths in the range of $14 \leq B \leq 70$ m were investigated. In the Elbe river the BfG analyzed different up to 200 m wide river cross sections, taking into account wide flooded forelands. These BfG - practise tests comprised systematic discharge variations in the range of

$$0.5\ m^3/s \leq Q \leq 1500\ m^3/s \qquad (6)$$

These extensive BfG - field tests were finished successfully and are documented in [12]. On behalf of these ten extensive field tests comparative discharge measurements are introduced in the following sections, which were carried out by the BfG in the streamflow - gauging station Dresden in the Elbe river and in the streamflow - gauging station Mühlendamm in the Spree - Oder - waterway in the center of Berlin.

5.2.1 Dresden / Elbe

The streamflow - gauging station is located in downtown Dresden in a long - streched bend of the Elbe river. The mean water depth amounts to ca. 3.0 - 3.5 m. In high water situations water depths of 8.0 m may be exceeded. The mean water level width of the Elbe amounts in Dresden to approximately B = 110 m. Due to extensive floodings of the wide forelands the water level width can increase to approximately B = 160 m.

Fig. 9 shows a strongly superelevated representation of the dimensionless turbulent velocity distribution of the Elbe, being simulated by means of the SIMK® - model. Fig. 9 shows for the Elbe river likewise fig. 8 for the curved trapezoidal canal of the VAO a clear shift of the velocity maximum towards the outside bank of the cross section, which is caused by the bend - induced centrifugal forces. In addition, fig. 9 reveals, that between the outside bank and the center of the river close to the free surface an approximately 30 m wide and up to 0.6 m deep yellow marked cross sectional area exists, in which the axial velocities vary only slightly between 95 and 100% of the maximum velocity. This result of the SIMK® - model was used to perform precise discharge measurements in the Elbe river with very low expenditure. Therefore only three single velocities were measured within the yellow marked area by means of a propeller current - meter. Under the simplified assumption that the average of these three locally measured velocities v_l represents approximately 97.5% of the maximum velocity v_{max} of the wetted section A, the area - averaged mean flow velocity v_m and thus the discharge Q of the Elbe was concluded. These SIMK® - based discharge measurements Q_{SIMK}. had been repeated by the BfG for 12 very different stages h. The results of this fast discharge evaluation procedure [12] are summarized in Tab. 2.

For reference purposes tab. 2 additionally comprises the measuring results Q_{Profil}. Each of

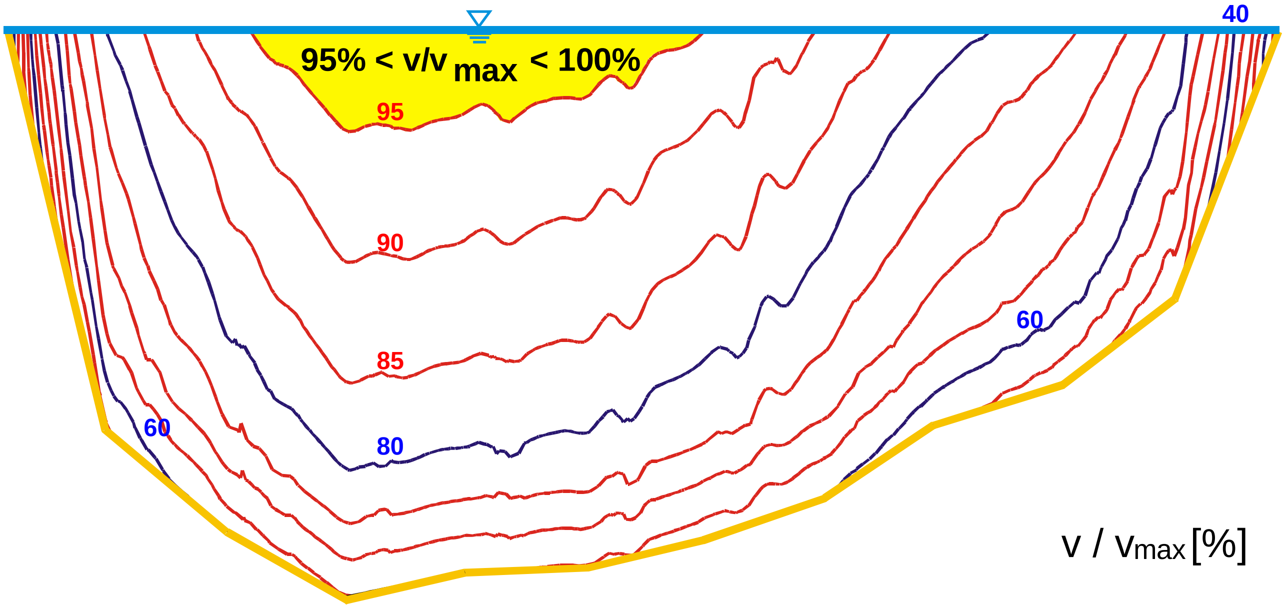

Fig. 9 Superelevated representation of the turbulent velocity distribution of the streamflow - gauging station Dresden / Elbe, simulated by means of the SIMK® - model (orderer: BfG, Germany [12])

Tab. 2 Verification of 12 SIMK® - discharge measurements, performed in the Elbe river in Dresden [12]

no	date	A [m²]	Q_{Profil} [m³/s]	Q_{SIMK} [m³/s]	ΔQ [%]
1	11/10/94	236.1	153.8	158.6	**3.1**
2	11/17/	236.0	151.9	156.9	**3.3**
3	01/19/95	317.5	269.4	271.3	**0.7**
4	01/25/	488.7	634.8	592.5	**6.7**
5	04/05/	601.8	844.2	825.1	**2.3**
6	04/18/	526.5	719.8	723.8	**0.6**
7	07/18/	287.8	235.1	237.8	**1.1**
8	07/25/	277.7	223.0	216.0	**3.1**
9	10/11/	285.8	228.1	228.9	**0.4**
10	10/19/	273.7	201.4	212.1	**5.3**
11	03/29/96	505.3	670.0	638.1	**4.8**
12	04/03/	384.0	403.7	403.9	**0.0**
				mean:	**2.6**

Elbe (km 57.8) streamflow - gauging station Dresden

with:

A: area of the wetted section

Q_{profil}: evaluation of propeller current-meter measurements

Q_{SIMK}: SIMK - evaluation of v_{max}

ΔQ: $\Delta Q = | Q_{SIMK} - Q_{PROFIL} | / Q_{Profil}$

these reference discharges Q_{Profil} results from the cross sectional integration of a detailed survey of the velocity distribution of the river, requiring ca. 100 to 200 individual propeller current - meter velocity measurements. These velocity measurements were carried out by the BfG within the whole wetted section of the Elbe river.

Although tab. 2 reveals, that the investigated discharges vary significantly in the range of $152 \leq Q_{Profil} \leq 844$ m³/s, the discharge divergences between Q_{SIMK} and Q_{Profil} vary only slightly between 0.0 and 6.7 %. The average discharge divergence of the 12 investigated comparisons amounts to 2.6 %. Comparable results would also have been achieved, if the surface velocities of the Elbe had been measured continuously and contact free by means of a radar or a video velocity sensor, being mounted underneath the bridge (cf. fig. 2).

It has to be noted, that the good correspondences of all comparative discharge measurements, summarized in tab. 2, had been achieved not under lab conditions, but under large - scale practise conditions. In particular the Elbe shows a natural riverbed. The bottom roughness and the energy gradient of the river had to be estimated for the SIMK® - calibrations. These estimations were merely based on the general information „sand bottom and grass - covered forelands“ and on a rough evaluation of the mean discharge of the Elbe. Although the flow measuring site is positioned in a typical river bend of the Elbe and although in each case only three single local velocities were measured close to the free surface, the high measuring accuracies, given in tab. 2 were achieved by means of the SIMK® - calibration method. Comparably good results had also been achieved for the other comparative discharge measuring sites of the BfG [12] and for numerous other comparable streamflow - gauging stations.

Tab. 2 reveals, that the SIMK® - calibration method allows precise discharge measurements not only in small canals, but also in big rivers. The high accuracies were reproduceably achieved, although the energy gradients and bottom roughnesses had to be estimated. Despite of these rough estimations SIMK® allows precise discharge measurements, because SIMK® does not take into account any of the simulated absolute velocity values, which strongly depend on the estimated energy gradients and the likewise estimated bottom roughnesses. Instead, SIMK® only takes into account dimensionless velocity ratios $k_l = v_m / v_l(x,y)$, being concluded from the turbulent velocity simulations. However, in contrast to the absolute velocity values v_l, the SIMK® based dimensionless calibration factors $k_l = v_m / v_l$ are almost independent of the actual energy gradients, as long as Reynolds numbers in the range of

$$10^5 \leq Re \leq 10^8 \qquad (7)$$

may be assumed, indicating high turbulent velocity distributions, being typical for rivers and big canals. Therefore for hydraulically suitable choosen installation positions of the velocity sensors realistic estimations of the bottom roughnesses allow accurate calculations of the velocity relations $k_l = v_m / v_l$. Therefore, the combination of practically available roughness informations as for example „sand bottom and grass - covered forelands“ and extensive long - term project experiences are sufficient for accurate SIMK® - determinations of the requested dimensionless scaling factors $k_l = v_m / v_l$. The very decisive influences of the actual backwater dependent energy gradients and the actual bottom roughnesses are not taken into account based on any kind of simulation, but based on the continuously measured local velocities v_l, directly reflecting the decisive influences of the actual backwater dependent energy gradients and the actual bottom roughnesses. Hence, in contrast to simple stage measurements, the additionally realized continuous local velocity measurements of the SIMK® - procedure allow accurate discharge measurements even in case of time varying backwater influences (e.g., as a result of seasonal fluctuating vegetation or of any disturbances or obstacles, positioned downstream the flow measuring site).

5.2.2 Mühlendamm / Spree - Oder - waterway in Berlin

Fig. 10 to 13 exemplarily show typical SIMK® - results, ordered by the BfG for the calibration of the streamflow - gauging station Mühlendamm, located in the Spree - Oder - waterway in downtown Berlin [12]. The finite - element - mesh, shown in fig. 10 illustrates the adaptable capture of the cross section geometry. The lateral sheet pilings and the substantially smoother sand bottom of the profile are considered in the SIMK® - model by different wall roughnesses. Fig. 11 shows the dimensionless relation of the turbulent velocity distribution $v(x,y) / v_{max}$, simulated by means of the SIMK® - model. The different wall roughnesses cause steeper velocity gradients close to the profile bottom than near the vertical sheet pilings. Clearly recognizable are the sgnificant dip of the velocity maximum below the free surface, the strong bend back of the isovels closely to the bank areas of the free surface and the strikingly bulging of the isotaches towards the vertical walls. These effects are caused by the profile dependent turbulence driven secondary currents [4], being likewise calculated by means of the SIMK® - model and being shown in fig. 12.

The requested calibration factors k_l follow from the evaluation of the axial velocity distribution, shown in fig. 11. For this the same results are shown in fig. 13 in a different form. Instead of v_l / v_{max} fig. 13 shows an superelevated representation of the relation v_m / v_l, representing the product of v_m and the inverted velocity distribution of the Mühlendamm cross section, being identical with the distribution of the requested dimensionless scaling factor $k_l = v_m / v_l$, being defined in (2). The local coordinate system, being additonally shown in fig. 13, allows an easy identification of the cross sectional positions (x,y), at which the local velocities $v_l(x,y)$ are measured, for instance, by means of a propeller current - meter (cf. fig. 9 and tab. 2) or by means of a radar sensor, being mounted above the water level (cf. fig. 2) or by means of an ultrasonic - Doppler - sensor, being installed on the bottom or the vertical walls of the canal ([2], [5], [9]). The isoline plot of $k_l = v_m / v_l$, shown in fig. 13, allows a direct identification of the requested scaling factor $k_l(x,y)$, being valid for the position (x,y), at which the local velocities $v_l(x,y)$ are measured. However, v_l, k_l and the stage dependent cross sectional area A(h) are sufficient to calculate the requested discharge Q (cf. (3)).

SIMK® is not limited to punctual velocity measurements v_P at any known position $P(x=x_P,y=y_P)$ of the cross section, but analogously SIMK® is also applicable to any kind of line - averaged velocity measurements, which provide measuring signals, that represent the mean velocities v_{AB}, occuring along a known straight measuring distance A - B, being defined by the exactly known start position $A(x=x_A,y=y_A)$ and end position $B(x=x_B,y=y_B)$ of the velocity measuring path. For instance, ultrasonic - transit - time - systems supply measuring signals, representing the line - averaged mean velocities v_{AB}, being measured along the ultrasonic path A - B, whose local position is precisely defined by the exactly known mounting positions A and B of the ultrasonic transducers, being typically installed on both sides of the cross section. Just as any punctual velocity measurement v_P, line - averaged velocity measurements v_{AB} can also be regarded as local velocity measurements v_l, which generally also deviate from the area - averaged velocities $v_m = Q / A$ of the cross section, being required for the final determination of the discharge Q. However, adding the local velocity measuring paths A - B of the ultrasonic - transit - time - system to fig. 13 and averaging the simulated velocity relations $k_l = v_m / v_l$ along these ultrasonic paths provides exactly the requested calibration factors $k_{AB} = v_m / v_{AB}$ of the ultrasonic system. Fig. 13 exemplarily shows the SIMK® - based scaling factors $k_{l1} = v_m / v_{AB} = 91.6$ % and $k_{l2} = 98.2$ % respectively, being determined in the described way by means of the SIMK® - model for the Mühlendamm waterway cross section for a specified stage and for exactly known installation positions of the ultrasonic transducers.

Purposeful repetitions of the SIMK® - simulations of the turbulent velocity distributions and of the corresponding SIMK® - k - value - evaluations for

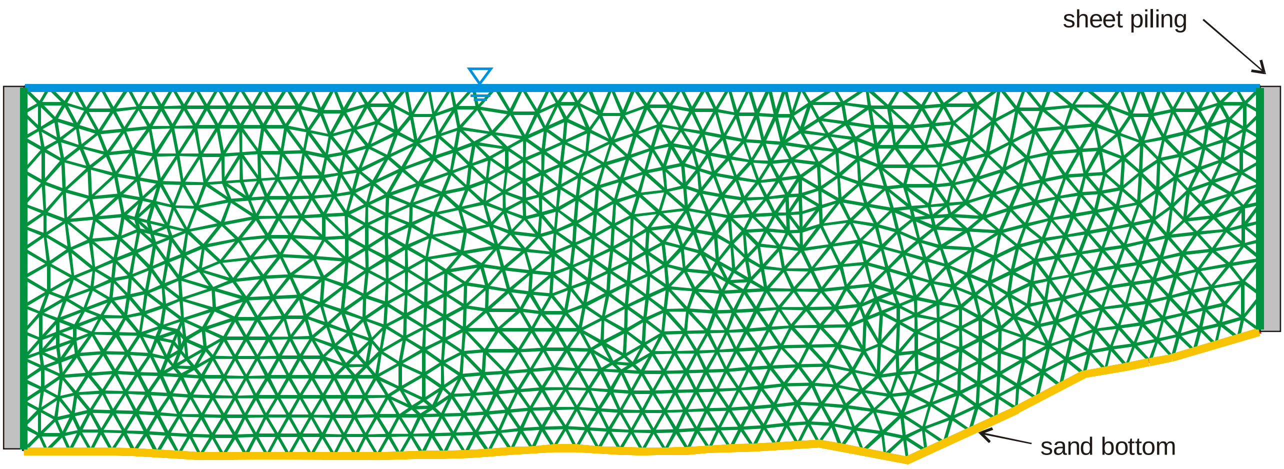

Fig. 10 *Finite - element - mesh of the profil Mühlendamm in the Spree - Oder - waterway in Berlin (orderer: BfG, [12])*

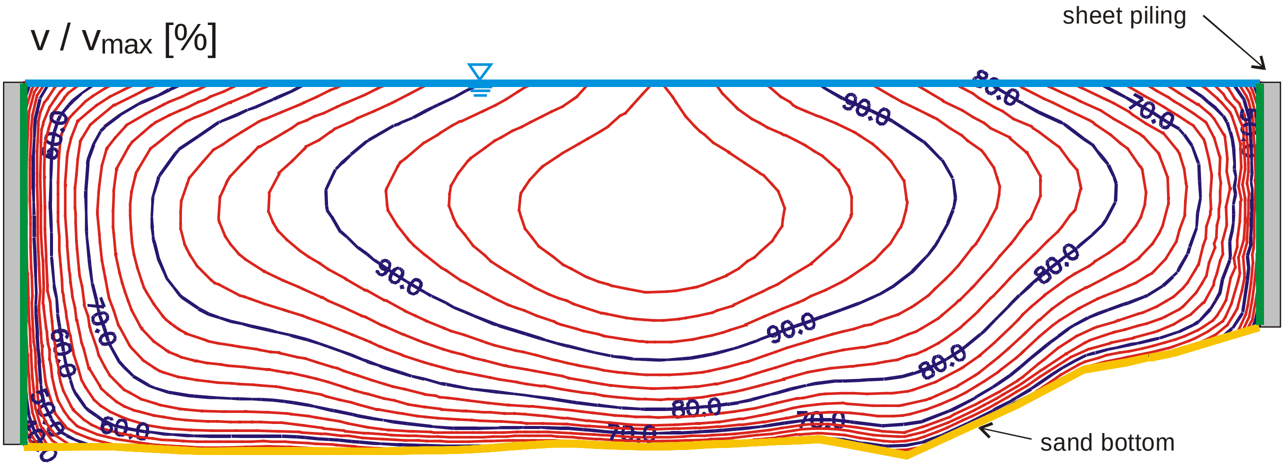

Fig. 11 *By means of the SIMK® - model simulated turbulent axial velocity distribution for the Mühlendamm cross section in the Spree - Oder - waterway in Berlin (orderer: BfG, [12])*

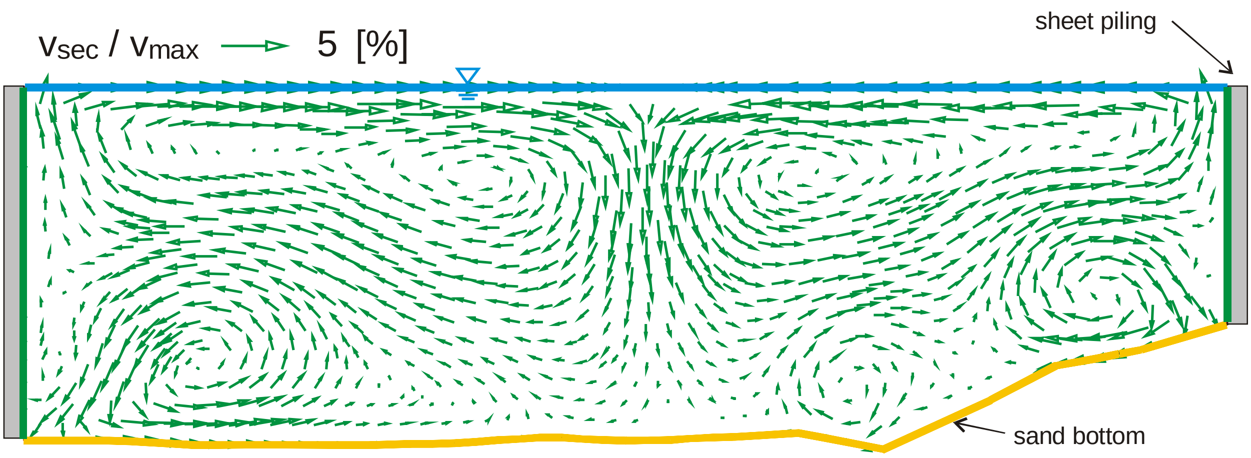

Fig. 12 *By means of the SIMK® - model simulated turbulent secondary velocity distribution for the Mühlendamm cross section in the Spree - Oder - waterway in Berlin (orderer: BfG, [12])*

systematically varied stages h provide the necessary profile and stage dependent calibration functions $k_l(h)$ of the investigated cross section and the investigated velocity sensor configuration for the complete range of practical relevant (high-) water level variations, being defined in (5). Since the calibration factor k_l and the cross sectional area A are profile and stage dependent functions, both factors can be summarized to the likewise profile and stage dependent reduced cross sectional area

$$A_{red}(h) = A(h) * k_l(h) \tag{8}$$

Thus (3) may be simplified to

$$Q = A_{red}(h) * v_l \tag{9}$$

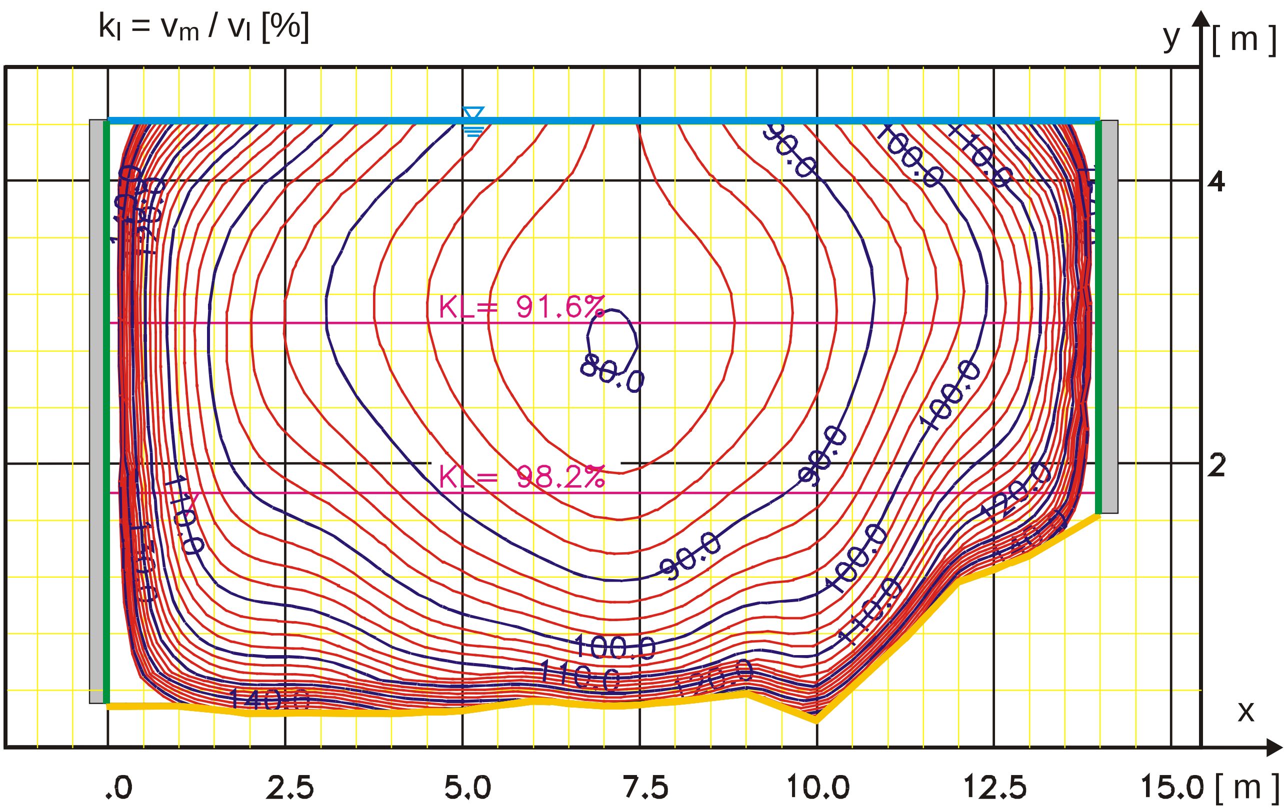

Fig. 13 Simulated cross sectional distribution of the scaling factors $k_l = v_m / v_l$ for the Mühlendamm profile with additional k - value - evaluation for two predefined ultrasonic pathes (orderer: BfG [12])

Formally (9) corresponds to the simple continuity equation (1). However, in contrast to the geometrical cross sectional area A(h) of equation (1) the reduced cross sectional area $A_{red}(h)$ of equation (9) comprises not only geometrical informations, but according to equation (8) additionally strongly profile and stage dependent hydraulic informations, being provided by means of the SIMK® - method. Based on the area averaged flow velocities v_m of the whole wetted section equation (1) comprises the same hydraulic information. However, since v_m can not be measured directly, (1) is not suitable for continuous (online-) evaluations of local velocity measurements. In contrast the second factor of equation (9) corresponds precisely to the local flow velocities v_l, which can be measured by means of alternative physical methods, because the the SIMK® - calibration method is applied, to transform the complementary hydraulic informations from the second to the first factor of equation (9).

Based on the comparative discharge measurements, carried out by the BfG, chapter 5.2.1 summarizes the reasons for the predominant influences of

- the profile shape,
- the actually measured (high-) water levels h and
- the positions (x,y) of the local velocity measurements $v_l(x,y)$

on the dimensionless calibration factor $k_l = v_m / v_l$. All of these purely geometrical parameters are exactly known immediately after the completion of the stage measurements. Therefore SIMK® is an universally applicable method, utilizing all of these exactly known geometrical input informations for the purposeful generation of precise hydraulic output informations, being provided in form of strongly profile and (high-) water level dependent calibration factors $k_l = v_m / v_l$.

These SIMK® - based hydraulic output informations are exclusively considered in the likewise strongly profile and stage dependent first factor $A_{red}(h)$ of equation (9). The great advantage of this SIMK® - concept results from the fact, that the second factor of (9) becomes a pure velocity measurement value, which can be recorded continuously by means of alternative types of velocity sensors and which becomes completely independent of any additional hydraulic information for all kind of profile shapes, water levels and sensor positions.

Therefore, based on this universally applicable SIMK® - concept, it becomes completely sufficient, to measure local velocities $v_l(x,y)$ continuously and reproduceably at any hydraulically suitable choosen and exactly known local cross sectional position (x,y) and simply multiply these actually measured local velocity values $v_l(x,y)$ with the corresponding profile and stage dependent reduced cross sectional areas $A_{red}(h)$.

Due to the accurate and strongly profile and stage dependent SIMK® - transformation of the exactly known geometrical input informations into the corresponding hydraulic output informations, summarized in the site specific $A_{red}(h)$ - function, the very simple multiplication of A_{red} and v_l provides precise discharge values Q even in case of complicated profile shapes, time varying backwater influences and significantly fluctuating (high-) water levels.

This procedure requires only one single SIMK® - determination of the strongly profile and (high-) water level dependent $A_{red}(h)$ - function and the digital storage of the corresponding simple A_{red} - h - lookup - table in the monitor of the streamflow - gauging station. Immediately afterwards the continuous flow measurements can permanently take full advantage of this single SIMK® - calibration by selecting the actually valid $A_{red}(h)$ - factor online from the digitally stored A_{red} - h - lookup - table based on the actually measured stage h. The $A_{red}(h)$ - factor, corresponding to this actual stage measurement h is simply extracted from the A_{red} - h - lookup - table and is multiplied with the measured local velocity $v_l(x,y)$. According to equation (9), the result of this very easy and fast multiplication is the requested discharge Q, which can be provided in this way online for the complete range of practically relevant stage variations (5) including extreme high water with high accuracies and without any further postprocessing.

Therefore an unique SIMK® - calibration of a streamflow - gauging station enables accurate and continuous determinations of actual discharges, which may be used for instance for flood reporting, flood forecasting, flood warning, for optimal flood control of limited reservoirs and for many other kinds of flow controls.

Discharge evaluations, which are directly based on the continuity equation (1), require permanent interpretations of local velocity measurement values ($v_l \Rightarrow v_m$). These permanent interpretations are typically very expensive and time consuming. Consequently discharge evaluations based on the continuity equation (1) are inappropriate for fast online flood reporting, flood forecasting, flood warning, for optimale flood control of limited reservoirs and for many other kinds of flow controls.

In contrast, the comparison of the equations (1) and (9) reveals, that SIMK® is a method, which effectively replaces permanently required and typically very time consuming interpretations of local velocity measurements ($v_l \Rightarrow v_m$) with a systematic and, therefore, only once required transformation of exactly known geometrical informations into the corresponding site specific hydraulic informations ($A \Rightarrow A_{red}$). Hence, SIMK® causes unique investment costs, but no running operating expenses. On the contrary, SIMK® allows significant reductions of earlier existing running operating expenses. Therefore, the advantages of a SIMK® - calibration can be used permanently without any running operating expenses by an unique update of the A_{red} - h - lookup - table, which has to be stored digitally in the monitor of the streamflow - gauging station.

The explained SIMK® - calibration of the streamflow - gauging station Berlin - Mühlendamm (cf. fig. 10 to 13) was repeated in the described way for systematically varied stages and the calibration results were used for continuous video discharge measurements in the Spree - Oder - waterway. Moreover, within the scope of a 4 - month test measurement, the water surface of the Spree - Oder - waterway was continuously filmed by means of a video camera, being mounted laterally of the approximately 14 m wide canal. Based on these video films the surface velocities v_l of the canal were determined contact free and continuously within an exactly defined small window by means of a digital picture processing software. On behalf of the BfG the stage dependent dimensionless scaling factors $k_l = v_m / v_l$ and the reduced areas $A_{red}(h)$, corresponding to the videowindow of the canal surface were determined based on fig. 13 and equation (8) by means of SIMK® - calibration. Based on these video measurements of the

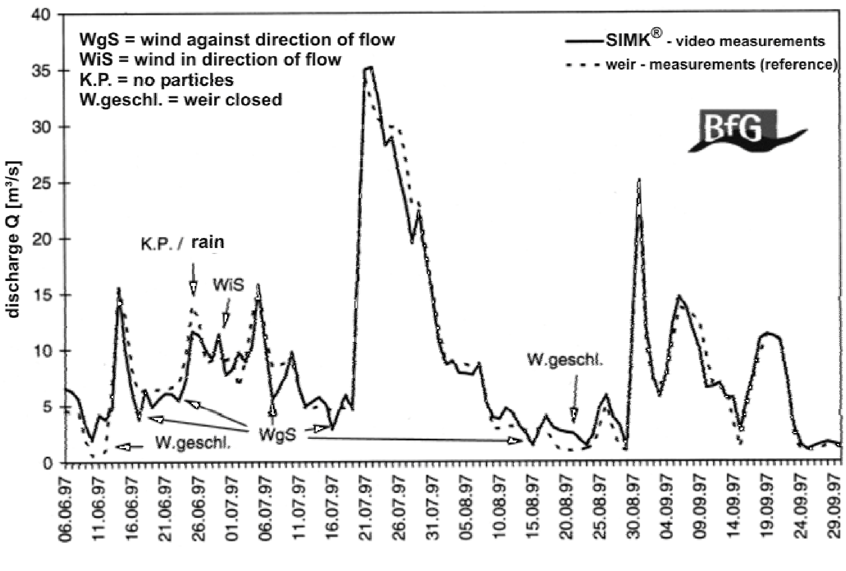

Fig. 14 Comparison of SIMK® - video discharge measurements with simultaneous weir discharge measurements in the streamflow - gauging station Mühlendamm in the Spree - Oder - waterway in downtown Berlin (orderer: BfG, [12])

surface velocities v_l and the corresponding stage dependent reduced areas $A_{red}(h)$, the requested discharges Q_{SIMK} were determined according to (9). This video - streamflow - gauging station was pursued by the BfG for a period of 16 weeks.

Fig. 14 shows comparisons of the SIMK® - based video discharge measurements Q_{SIMK} with the discharges Q_{Weir}, which the BfG calculated from water - levels, being measured simultaneously upstream a 14 m wide weir, located approximately 200 m downstream the video camera. For the whole measuring period both hydrographs are in good correspondence, especially for large discharges. [13] contains detailed explanations and judgements of these SIMK® - video discharge measurements.

It has to be noticed, that the mean water cross sectional area of the Spree - Oder - waterway amounts to ca. $A = 55\ m^2$. Consequently for discharges of $Q < 5\ m^3/s$ mean velocities of only $v_m < 0.1$ m/s occur in this canal. As expected the corresponding small surface velocities v_l were falsified for the time being by wind (cf. fig. 14). An important intention of the 4 - month BfG - field measurements was, to investigate and to document practical relevant application limitations of video discharge measurements, caused by wind, rain and other disturbing influences. Fig. 14 reveals, that video discharge measurements are virtually no more influenced by wind, if the surface velocities exceed values of $v_l = 0.25$ m/s. Therefore in case of surface velocities $v_l > 0.25$ m/s stage dependent SIMK® - calibrations can typically be applied, to measure the discharges in rivers and canals continuously with high accuracies based on contact free video - or alternative radar - measurements of the surface velocities. With smaller surface velocities for the time being low wind induced falsifications of the measurements have to be taken into account. Therefore in case of surface velocities $v_l < 0.25$ m/s alternative velocity measuring procedures should be preferred.

5.3 German Water Resources Office (WWA) Weilheim

For the radar - streamflow - gauging station Rissbachdüker, being installed in the Rissbach torrent, which is shown in fig. 15, wind induced falsifications of the velocity measurements certainly can be excluded, because in this torrent surface velocities of approximately $v = 1.3$ m/s have to be expected even in case of mean water flow. The radar - streamflow - gauging station Rissbachdüker is located very close to the Austrian - German border. Ca. 5 km upstream of the high water storage reservoir Sylvensteinsee the Rissbach torrent flows into the Isar river. The Rissbach torrent drains an approximately 182 km² large area of the alpine mountain chain Karwendelgebirge. Hence, the Rissbach is a steep torrent, being characterized by very fast and very large stage and discharge fluctuations. The streamflow - gauging station Rissbachdüker, shown in fig. 15 is only ca. 20 m wide and is limited by very steep rock walls. In the torrent cross section, shown in fig. 15, the Whitsun high water 1999 caused high water discharges of approximately $Q_{max} = 345\ m^3/s$ [1], which completely destroyed a cable way installation, which was previously installed in the torrent cross section, shown in fig. 15.

On behalf of the German Water Resources Office (WWA) Weilheim the radar surface velocity measuring system, being well recognizable in fig. 15, was calibrated by means of the SIMK® - model for the complete practical relevant stage variation range (5), including even higher water levels than the maximum water levels, which occured during the Whitsun high water 1999. This stage dependent SIMK® - calibration of the streamflow - gauging station Rissbachdüker is exclusively based on the digital photo, shown in fig. 15 and on a precise geometrical survey of that torrent cross section, in which the surface velocities v_l are measured contact free by means of the radar velocity sensor, shown in

Fig. 15 SIMK® - radar streamflow - gauging station Rissbachdüker / Rissbach (orderer: WWA Weilheim)

fig. 15. Based on extensive long - term project experiences and on the digital photo, shown in fig. 15 the bottom and wall roughnesses of the Rissbach torrent were estimated.

Based on the (high-) water level dependent SIMK® - calibration of the streamflow - gauging station Rissbachdüker the cross sectional positions ($x=x_P$, $y=h$), at which the surface velocities $v_l(x,y)$ should be measured contact free by means of the radar velocity sensor, had been optimized. Afterwards the stage dependent calibration functions $k(h) = v_m / v_l$ and $A_{red}(h) = A(h) * k(h)$, defined in the equations (2) and (8), were determined for the optimized sensor position and the optimized sensor adjustment based on the the SIMK® - simulations.

The radar velocity sensor, shown in fig. 15, was positioned and adjusted according to the SIMK® - optimized positions ($x=x_P$, $y=h$) of the local surface velocity measurements. Finally, the stage dependent calibration function $A_{red}(h)$, corresponding to this optimized sensor installation, was digitally stored in the monitor of the radar system. According to equation (9) this configuration of the radar system enables continuous online - determinations of the actual discharges Q of the Rissbach, which can be remotely accessed, digitally stored and transmitted without any postprocessing by means of a GSM - modem or by means of an alternative remote access data transmission system.

These SIMK® - based discharges Q_{SIMK}, determined in the described way, were verified by the WWA Weilheim, while they were compared with independent reference discharge measurements Q_{Ref}, being mainly based on tracer measurements. The WWA Weilheim documented their examinations in [3] and finally evaluated their verifications of the SIMK® - based contact free radar - discharge measurements in the Rissbach torrent, shown in fig. 15, as follows: „Based on a simple river cross section, the SIMK® - method provides almost identical discharge values Q_{SIMK}, compared with stage related reference flow data $Q_{Ref}(h)$, being determined based on many years‘ great expense.“

5.4 German Water Resources Office (WWA) Passau

The accuracies of the SIMK® - radar streamflow - gauging station Schrottenbaummühle / Ilz, described in chapter 1, were also verified by independent reference discharge measurements of the German Water Resources Office (WWA) Passau. Since stages h_R and surface velocities v_R of the Ilz are measured continuously and contact free in intervals of three minutes by means of the radar system, shown in fig. 2, several Ilz floods could be recorded digitally already a few weeks after putting this measuring site into operation.

Fig. 16 exemplarily shows a flood of ca. 12 hour's duration (about HQ_1), which occured at night from 10/07/2003 on 10/08/2003 in the section of the Ilz river, shown in fig. 1 and which was recorded by means of the SIMK® - radar - system free of failure. During this Ilz flood the stages rose by about Δh_R = 0.8 m and the surface velocities rose from v_R = 0.97 m/s by ca. 250 % up to v_R = 2.47 m/s. Within 18 hours the discharges, being recorded by means of the SIMK® - radar - system increased tenfold from Q_{SIMK} = 3.4 up to Q_{SIMK} = 33.2 m^3/s. As expected the flood increase is steeper than the following flood decrease. In the evening 10/07/2003 continuously increasing discharges of up to ca. 25% within only 30 minutes were recorded during this relatively small Ilz flood. This time period is approximately as long as the duration of a complete velocity profile measurement, being performed by means of a propeller current - meter.

Approximately 20 m downstream the Ilz bridge, shown in fig. 2, the staff gauge Schrottenbaummühle is located, where the Ilz stages h_{WWA} are measured by the WWA Passau for many years. In addition, between 05/28/1996 and 08/12/2003 the WWA Passau used the Ilz bridge, shown in fig. 2, to perform a total of 23 velocity profile measurements of the Ilz by means of propeller current - meters. This corresponds to an average measuring frequency of approximately 3.2 propeller current - meter measurements per year, which is typical for comparable streamflow - gauging stations.

The discharges Q_{WWA} of the Ilz river, being determined by evaluation of these propeller current - meter measurements and the stages h_{WWA} of the Ilz, being recorded simultaneously, are summarized in the table and in the graph of fig. 17. According to fig. 17 within approximately 7 years the WWA Passau was able to record stage variations in the range of $0.38 \text{ m} \le h_{WWA} \le 1.23 \text{ m}$ and discharge variations of $1.54 \text{ m}^3/\text{s} \le Q_{WWA} \le 25.22 \text{ m}^3/\text{s}$ by means of these propeller current - meter measurements. In addition on 01/28/2002 the WWA Passau succeeded to document a substantially larger flood in the Ilz river, being charaterized by a stage of h_{WWA} = 2.25 m and a discharge of Q_{WWA} = 99.6 m^3/s.

To enable direct comparisons of the contact free SIMK® - radar discharge measurements Q_{SIMK} with the propeller current - meter discharge measurements Q_{WWA}, provided by the WWA Passau, the radar based discharges Q_{SIMK}, being measured between 04/11/2003 and 06/24/2003 were plotted as a function of the stages h_{WWA}, being simultaneously measured by the WWA Passau.

WWA Passau
Radar - Streamflow Gauging Station Schrottenbaummühle / Ilz

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Ingenieurbüro für Wasserwirtschaft GmbH
www.isar-consult.de

Schrottenbaummühle		measuring value	min	mean	max	Σ [T.m³]
0205	discharge	Q_{SIMK} [m³/s]	3.41	14.17	33.17	2448
0011	velocity	v_R [m/s]	0.973	1.656	2.471	
0010	stage	h_R [m]	0.61	0.96	1.42	

measuring period: **from 10/07/2003**
until 10/09/2003

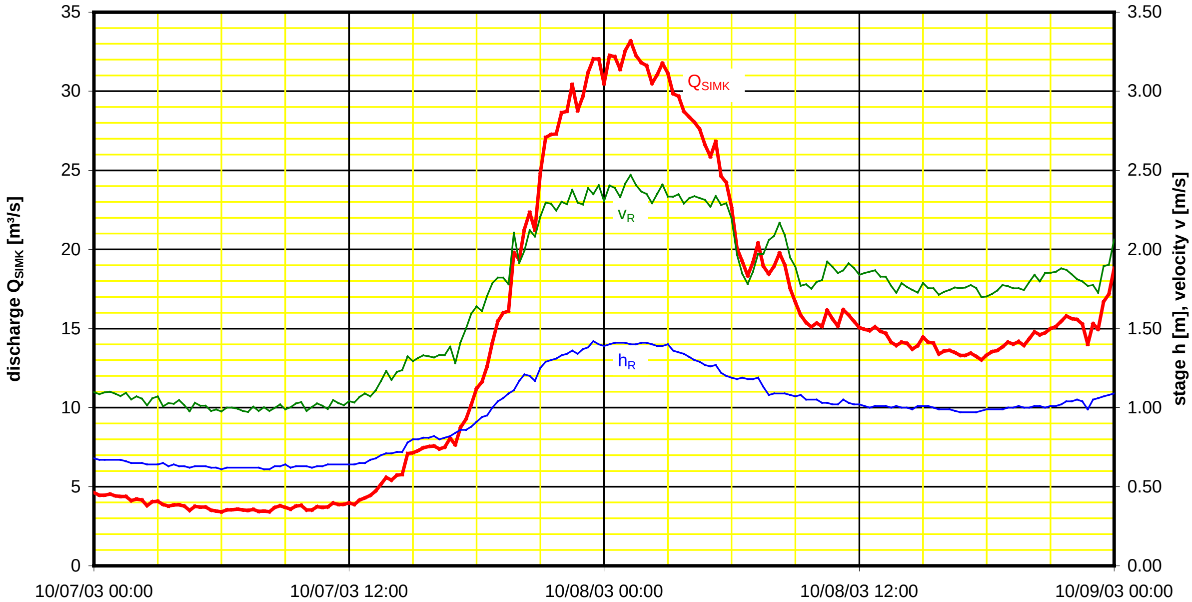
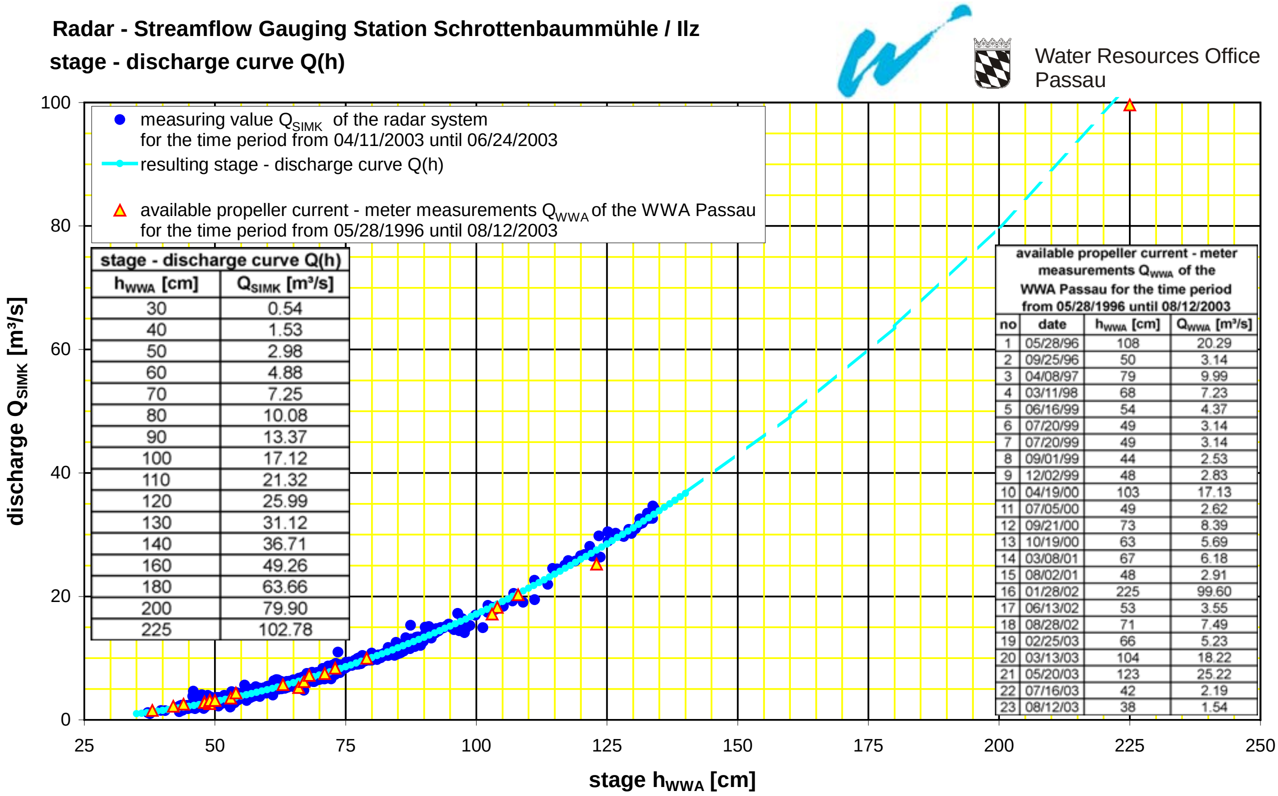


Fig. 16 Detailed and failure free flood recording by means of the SIMK® - radar streamflow - gauging station Schrottenbaummühle / Ilz, shown in fig. 1 and 2 (orderer: WWA Passau)

Based on these SIMK® - radar discharge measurements Q_{SIMK}, being performed continuously for a selected measuring interval of $\Delta t = 3$ minutes, corresponding to a frequency of ca. 175000 SIMK® - radar discharge measurements per year, 36000 Q_{SIMK} / h_{WWA} - measurement pairs were generated within eleven weeks, being additionally shown in fig. 17.

The propeller current - meter discharge measurements Q_{WWA} and the SIMK® - radar discharge measurements Q_{SIMK} show good correspondence for the available range of water level variations of $0.38 \text{ m} \leq h_{WWA} \leq 1.23 \text{ m}$, being documented my means of the propeller current - meter measurements. The propeller current - meter discharge measurements and the SIMK® - radar discharge measurements show small variations, resulting in slightly varying discharges Q_{SIMK} and Q_{WWA} for identical water levels h_{WWA}. These small variations of the individual measuring values correspond to the highly turbulent current character of the natural Ilz river (cf. fig. 1). This is revealed by the trend curve Q(h), which was calculated based on all available Q_{SIMK} / h_{WWA} - value pairs for the eleven weeks SIMK® - radar measuring period. This trend curve corresponds to the Q - h - stage - discharge curve of the staff gauge Schrottenbaummühle / Ilz. Q(h) is additionally shown graphically and in tabular form in fig. 17. Fig. 17 reveals, that the eleven weeks maintenance - free SIMK® - radar discharge measurements Q_{SIMK} enabled the generation of a Q(h) - stage - discharge curve for the staff gauge Schrottenbaummühle / Ilz, which is almost identical to the Q(h) - stage - discharge curve, being derived for the same measuring site based on 23 propeller current - meter discharge measurements, which were performed by the WWA Passau within approximately seven years.

Consequently, fig. 17 reveals, that unique SIMK® - calibrations enable even in natural river segments like the Ilz, shown in fig. 1, continuous, reproduceable and precise online discharge measurements, being available immediately after completion of the installation for the complete practical relevant range of stage and discharge variations of the investigated river. These SIMK® - based continuous discharge measurements neither require any site visits nor any expeditious postprocessing of the measuring values. Therefore in contrast to expensive and time - consuming propeller current - meter based discharge measurements SIMK® - based continuous maintenance - free discharge measurements are very suitable e. g. for fast flood reporting, flood forecasting, flood warning, for optimized flood control of limited reservoirs and other flow controls and for cost effective short - term supplies of complete Q(h) - stage - discharge curves.



stage - discharge curve Q(h)	
h_{WWA} [cm]	Q_{SIMK} [m³/s]
30	0.54
40	1.53
50	2.98
60	4.88
70	7.25
80	10.08
90	13.37
100	17.12
110	21.32
120	25.99
130	31.12
140	36.71
160	49.26
180	63.66
200	79.90
225	102.78

available propeller current - meter measurements Q_{WWA} of the WWA Passau for the time period from 05/28/1996 until 08/12/2003			
no	date	h_{WWA} [cm]	Q_{WWA} [m³/s]
1	05/28/96	108	20.29
2	09/25/96	50	3.14
3	04/08/97	79	9.99
4	03/11/98	68	7.23
5	06/16/99	54	4.37
6	07/20/99	49	3.14
7	07/20/99	49	3.14
8	09/01/99	44	2.53
9	12/02/99	48	2.83
10	04/19/00	103	17.13
11	07/05/00	49	2.62
12	09/21/00	73	8.39
13	10/19/00	63	5.69
14	03/08/01	67	6.18
15	08/02/01	48	2.91
16	01/28/02	225	99.60
17	06/13/02	53	3.55
18	08/28/02	71	7.49
19	02/25/03	66	5.23
20	03/13/03	104	18.22
21	05/20/03	123	25.22
22	07/16/03	42	2.19
23	08/12/03	38	1.54

Fig. 17 Q - h - stage - discharge curve of the staff gauge *Schrottenbaummühle / Ilz based on eleven weeks maintenance - free online - SIMK® - radar - discharge measurements and on the postprocessing of seven years historical propeller current - meter discharge measurements of the WWA Passau*

At the discharge measuring site Schrottenbaummühle / Ilz the SIMK® - based continuous discharge measurements were carried out fully automatically, contact free and, hence, maintenance - free. Only eleven weeks after completion of the installation a SIMK® - based Q(h) - stage - discharge curve was generated, being almost identical to the Q(h) - stage - discharge curve, which was derived for the same measuring site based on expensive and time - consuming postprocessings of all propeller current - meter discharge measurements, carried out by the WWA Passau within more than seven years. This confirms the final judgement of the SIMK® - calibration method of the WWA Weilheim, quoted in chapter 5.3.

Hence, the attainable accuracies of SIMK® - based discharge measurements are at least not worse than those of propeller current - meter based discharge measurements in canals (cf. chapters 5.1 and 5.2.2) and in natural rivers (cf. chapters 5.2.1, 5.3, 5.4 and 5.5). However, in contrast to very time - consuming, expensive and therefore typically very rarely performed propeller current - meter based discharge measurements, continuously performed SIMK® - based discharge measurements do neither require any maintenance - costs nor any postprocessing of measuring values. In contrast to propeller current - meter based discharge measurements, SIMK® - based discharge measurements permit short measuring intervals of a few minutes or even a few seconds, if required. Since in contrast to personnel - intensive propeller current - meter based discharge measurements, SIMK® - based discharge measurements may be performed continuously and contact - free, they are very suitable for maintenance - and failure - free high frequency fast flood reporting, flood forecasting and flood warning and for simultaneous high resolution recordings of short time rare flood events at all relevant measuring sites of a complete catchment area. Moreover, in contrast to personnel - intensive propeller current - meter based discharge measurements, SIMK® - based discharge measurements are immediately available and thus online - capable.

On account of the measuring accuracies, documented in fig. 17 and on account of the explained advantages of the SIMK® - based discharge measurements, the WWA Passau intends temporary operations of mobile SIMK® - radar discharge measurement systems. These mobile radar systems are mounted for the time being at existing river bridges, to measure at short notice complete flood effected stage and discharge hydrographs in high temporal resolution and to determine the corresponding Q(h) - stage - discharge curves of these rivers according to fig. 17 within short time periods, at reasonable prices, in great detail and with high accuracies.

5.5 German Water Resources Office (WWA) Landshut

The digital photo, shown in fig. 18 was taken from the European bridge Kelheim in the upstream direction. It shows the typical approaching flow conditions of the streamflow - gauging station Kelheim, which is operated in the Danube river by the German Water Resources Office (WWA) Landshut. At this position the Danube river is characterized by a low water depth of ca. t = 1.1 m and a low water suface width of approximately B = 105 m. During the Whitsun high water 1999 a high water depth of approximately t = 7.7 m was measured at this site, being ca. Δt = 6.6 m larger than the low water depth of the Danube river. During the Whitsun high water 1999 the water suface width increased to ca. B = 194 m, being almost twice as large as the low water suface width. During the Whitsun high water 1999 the large forelands, being well recognizable in fig. 18 were flooded by more than 2 m.

From the Danube bridge Kelheim the WWA Landshut regularly carries out propeller current - meter based discharge measurements. Since the stage dependent wetted area of the Danube river comprises several hundred square meters, this kind of discharge measurements requires numerous individual propeller current - meter measurements, which are very expensive and time - consuming, especially in case of high water. In order to verify the achivable accuracies and the practical applicability of the SIMK® - calibration method and in order to avoid or at least strongly reduce the regularly repeated expenditure of the expensive and time - consuming propeller current - meter measurements, a SIMK® - calibration of the Danube streamflow - gauging station Kelheim was provided on behalf of the WWA Landshut.

This stage dependent SIMK® - calibration revealed, that in the Danube river cross section, shown in fig. 18, independent of the actual stage h the maximum axial velocities v_{max} always occur within an approximately 20 m wide external - concentric positioned part of cross section, being stationarily located close to the free water surface of the river. Based on these SIMK® - results, the WWA Landshut was recommended, to carry out only three individual propeller current - meter velocity measurements v_l within this exactly defined approximately 20 m wide part of the cross section, being located close to the free water surface of the river. For all practically relevant stages h the maximum of these three local velocity measurements $\max(v_l)$ can be

Fig. 18 SIMK® - streamflow gauging station Kelheim / Danube river (orderer: WWA Landshut)

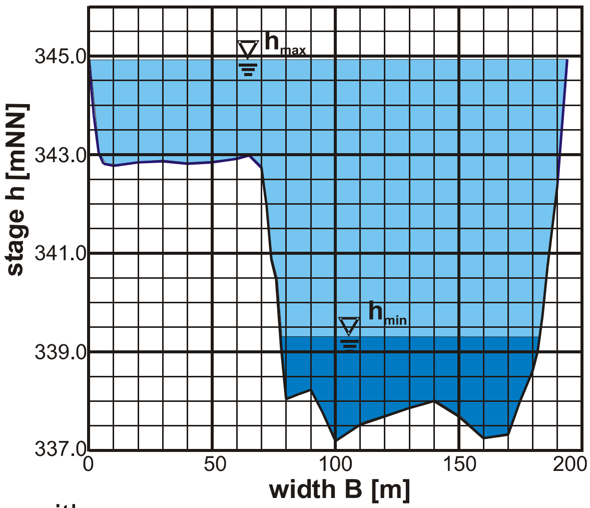
Tab. 3 Verification of the stage dependent SIMK® - calibration of the streamflow - gauging station Kelheim / Danube shown in Fig. 18 based on 28 historical propeller current - meter measurements of the WWA Landshut

no	date	A [m²]	Q_{Profil} [m³/s]	Q_{SIMK} [m³/s]	ΔQ [%]
1	**02/23/99**	**641.9**	**1392.9**	**1412.1**	**1.4**
2	03/23/99	305.1	479.5	489.1	**2.0**
3	04/27/99	284.9	450.1	457.6	**1.7**
4	**05/15/99**	**755.6**	**1646.6**	**1686.1**	**2.4**
5	**05/24/99**	**954.8**	**2048.7**	**2240.0**	**9.3***
6	06/16/99	353.5	573.9	560.6	**-2.3**
7	07/21/99	294.5	452.5	465.9	**3.0**
8	10/11/99	222.3	266.6	268.4	**0.7**
9	11/09/99	210.0	226.4	218.6	**-3.4**
10	01/20/00	238.5	314.1	320.1	**1.9**
11	04/13/00	289.0	452.5	450.8	**-0.4**
12	09/05/00	285.3	430.5	434.1	**0.8**
13	10/12/00	266.4	369.8	354.4	**-4.2**
14	11/23/00	235.4	282.7	256.6	**-9.2**
15	01/18/01	240.1	292.6	271.6	**-7.2**
16	03/06/01	366.1	659.8	652.2	**-1.2**
17	06/06/01	257.6	386.1	406.6	**5.3**
18	09/06/01	249.7	366.7	384.0	**4.7**
19	10/15/01	198.6	217.6	205.4	**-5.6**
20	11/13/01	213.6	254.8	244.8	**-3.9**
21	05/16/02	244.9	315.1	296.6	**-5.9**
22	07/25/02	208.5	242.6	242.5	**0.0**
23	**08/14/02**	**785.2**	**1700.0**	**1691.9**	**-0.5**
24	10/14/02	294.6	438.0	422.1	**-3.6**
25	12/17/02	268.6	354.5	345.9	**-2.4**
26	02/25/03	227.8	292.3	294.3	**0.7**
27	03/31/03	228.2	309.2	309.8	**0.2**
28	07/17/03	154.9	139.9	138.7	**-0.9**
				mean:	**-0.6**

* dike burst during the discharge measurement

Water Resources Office Landshut

Danube (km 2412.7) streamflow - gauging station Kelheim



with:

A: area of wetted section

Q_{Profil}: evaluation of propeller current-meter measurements

Q_{SIMK}: SIMK - evaluation of v_{max}

ΔQ: $\Delta Q = (Q_{SIMK} - Q_{Profil}) / Q_{profil}$

regarded as a good approximation of the maximum velocity v_{max} of the whole Danube river cross section. By means of the SIMK® - calibration method the stage dependent calibration functions $k_{max}(h) = v_m / v_{max}$ and $A_{red}(h) = A(h) * k_{max}(h)$, being defined in (2) and (8), were calculated for these maximum velocities v_{max} of the Danube river. Finally, (9) is applied, to determine the requested discharges Q_{SIMK} of the Danube river, based on three individual propeller current - meter velocity measurements v_l and one additional stage measurement h.

All 28 historical propeller current - meter based discharge measurements Q_{Profil}, being available in the WWA Landshut and being summarized in tab. 3 were evaluated subsequently based on this strongly simplified procedure. In tab. 3, Q_{Profil} indicates the resulting discharges, being determined based on the consideration of all individual propeller current - meter velocity measurements, being performed by the WWA Landshut within the whole Danube river cross section. In contrast, Q_{SIMK} indicates the discharges, being determined for the same cross section according to the above explanations by taking into account only three individual propeller current - meter velocity measurements, being performed at hydraulically optimized positions of the river cross section and by taking additionally into account the corresponding stage dependent calibration function $A_{red}(h)$, being provided by means of the SIMK® - calibration method. The values of $\Delta Q = (Q_{SIMK} - Q_{Profil}) / Q_{Profil}$, being provided in the last column of tab. 3 indicate the discharge differences refered to the reference discharges Q_{Profil}. Propeller current - meter velocity measurements, being performed, while the large forelands of the Danube river (cf. fig. 18) were flooded, are marked with boldface letters in tab. 3.

According to the average difference ΔQ = -0.6 %, given in tab. 3, the simplified SIMK® - based discharge measurements Q_{SIMK} provide almost identical results for the Danube streamflow - gauging station Kelheim as the complete propeller current - meter based discharge measurements Q_{Profil}, which are substantially more expenditious and which are not suitable for fast online discharge measurements. Discharge differences of ± 10% are reached for none of the 28 comparative measurements.

The differences ΔQ, summarized in tab. 3 do not show any stage dependent trend, although the corresponding calibration factors k(h) are subjected to systematic strongly stage dependent variations. In particular it has to be emphasized, that the high water flow measurements, being performed, while the forelands of the Danube river were flooded and being marked with boldface letters in tab. 3, are characterized by very small differences ΔQ, although the flooding of the large forelands causes significant and systematic variations of the corresponding stage dependent scaling factors k(h).

Hence, the extensive verification results, summarized in tab. 3, reveal, that stage and profile dependent SIMK® - calibrations permit precise discharge measurements for the complete range of stage and discharge variations, especially including extreme high water situations.

Hence, the presented SIMK® - calibration results can be used for the streamflow - gauging station Kelheim, shown in fig. 18, to determine the actual discharges of the Danube river with high accuracies based on significantly simplified propeller current - meter velocity measurements or alternatively based on contact - free and therefore maintenance - and almost failure - free radar velocity measurements (cf. fig. 2).

6. Additional practical applications of the SIMK® - calibration method

For further streamflow - gauging stations additional independent comparative measurements exist, showing similar results like the field inspections of the SIMK® - calibration method, explained in chapter 5. Hence, in the following no additional field inspections of the SIMK® - calibration method are introduced, but exemplarily six realized practical applications of the SIMK® - method are presented, demonstrating typical further application possibilities of the SIMK® - method.

Fig. 19 shows the dimensionless turbulent velocity distribution, being simulated by means of the SIMK® - model based on the finite - element - discretisation of the jointed measuring cross section Muka Keratan / Malaysia, shown in fig. 3. The velocity distribution, shown in fig. 19, was simulated for the maximum depth of flow of t = 7 m, causing both forelands to be flooded by approximately 3 m. In the transitional zones between the main canal and both forelands highly turbulent separation zones exist, being characterized by the steep horizontal velocity gradients, shown in fig. 19. These separation zones, being typical for foreland profiles (cf. fig. 6, fig. 18 and tab. 3), are simulated by means of the SIMK® - model based on detailed finite - element - discretisations of the cross sections (cf. fig. 3) without any additional data input.

Based on the velocity distribution, shown in fig. 19 and based on additional SIMK® - simulations of analogous stage dependent velocity distributions, the stage and profile dependent calibration function k(h) was determined for the ultrasonic path, being additionally shown in fig. 19. The corresponding k - h - table was provided according to chapter 5.2.2 and was digitally stored in the monitor of the ultrasonic - transit - time discharge measuring system Muka Keratan.

Fig. 20 shows the German streamflow - gauging station Helmarshausen in the Diemel river, being a typical low mountain range river. In this streamflow - gauging station an ultrasonic - transit - time velocity measuring system was installed, which was calibrated on behalf of the German state environmental office Kassel by means of stage dependent SIMK® - simulations.

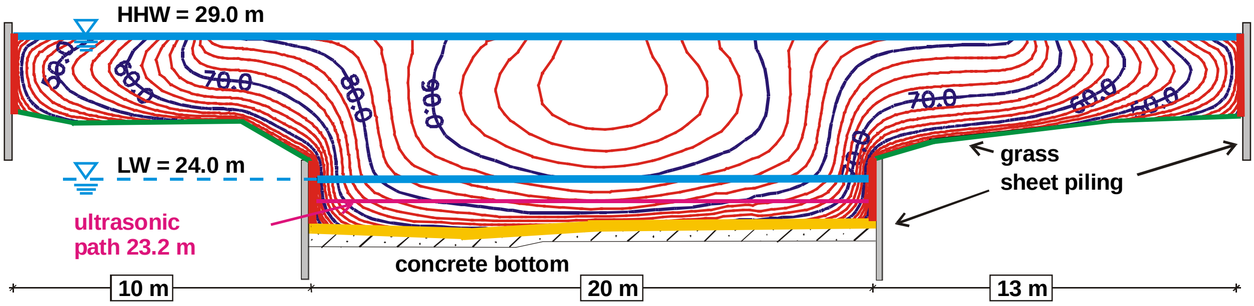


Fig. 19 SIMK® - high water calibration of the ultrasonic - transit - time streamflow - gauging station Muka Keratan / Malaysia for the maximum water level HHW (cf. Fig. 3)

Fig. 20 SIMK® - ultrasonic - transit - time streamflow - gauging station Helmarshausen / Diemel, Germany (orderer: state environmental office Kassel)

Fig. 21 shows the two level - crossed path - ultrasonic - transit - time streamflow - gauging station Bruckhäuser, being installed in the German Kollbach brook. This ultrasonic - transit - time velocity measuring system was calibrated by means of stage dependent SIMK® - simulations, being performed on behalf of the German Water Resources Office (WWA) Pfarrkirchen. On the left slope of the river bank both ultrasonic transducers of the two upper ultrasonic paths, being installed above the mean water level, are clearly recognizable. In contrast to the permanently flooded lower ultrasonic paths, the upper ultrasonic paths are activated only in case of rare high water situations.

By means of this ultrasonic - transit - time system a high water of up to Q_{max} = 49.7 m^3/s was recorded on 01/28/2003 in the Kollbach brook, causing the water level to increase to a maximum level, which fell only a few decimeters below the bottom of the bridge. For the time being this high water caused a significant flooding of both upper ultrasonic paths. During this high water the WWA Pfarrkirchen carried out several propeller current - meter based discharge measurements, which were in close agreement with the continuous SIMK® - based ultrasonic - transit - time - discharge measurements.

Fig. 22 also shows a two level - crossed path - ultrasonic - transit - time streamflow - gauging station, being calibrated by means of the SIMK® - method. This site is located in Marpent in the Escaut river, being a typical lowland river in Northern France. The Escaut river is characterized by very low slopes and velocities.

Fig. 23 shows the 4.5 m deep trapezoidal channel Alzkanal, which is operated by the German hydroelectric company Alzwerke as headrace channel of their hydro power station Burghausen. The bottom and the steep slopes of this approximately A = 50 m^2 large headrace channel consist of very smooth concrete, which causes only relatively low friction losses, although in this channel large mean velocities of approximately v_m = 1.9 m/s are typical. The hydraulic efficiency of the headrace channel and thus the total hydraulic efficiency of the whole hydro power station is strongly influenced by seasonally varying algae growth in the headrace channel. To record the significant efficiency influence of these seasonal varying algae growth, an ultrasonic transit - time streamflow - gauging station was installed in the Alzkanal on behalf of the Alzwerke Burghausen.

Due to the absolutely straight and undisturbed approaching flow conditions of the streamflow - gauging station Guflham, shown in fig. 23, the installation of a single path - ultrasonic - transit - time system was sufficient, which was stage dependently calibrated by means of the SIMK® - method.

Fig. 21 SIMK® - ultrasonic - transit - time streamflow - gauging station Bruckhäuser / Kollbach, Germany (orderer: WWA Pfarrkirchen)

Fig. 22 SIMK® - ultrasonic - transit - time streamflow - gauging station Marpent / Escaut, France

Fig. 24 shows the streamflow - gauging station Mehring in the Mosel river, which was calibrated by means of the SIMK® - method on behalf of the German federal institute of hydrology (BfG). Mean water flow conditions of this site are characterized by a water level width of approximately B = 156 m, a maximum water depth of ca. t_{max} = 9.1 m in the middle of the river and a mean discharge of ca. MQ = 290 m^3/s. In case of a 200 - yearly high water HQ_{200} ca. 3.5 m higher water levels, substantially larger velocities and high water discharges of approximately HQ_{200} = 4000 m^3/s are expected in this section of the Mosel river.

At the streamflow - gauging station Mehring / Mosel, shown in fig. 24, the stages h and the corresponding local velocities v_l are measured continuously and simultaneously by means of a H - ADCP - system (“horizontal acoustic doppler current profiler“). The measurement values h and v_l are converted online into the corresponding discharges Q based on a site specific and strongly stage dependent k - h - table, which was determined on behalf of the BfG by means of the SIMK® - calibration procedure and which is stored digitally in the monitor of the ADCP - system.

H - ADCP - velocity measuring systems are flexible applicable, because it is relatively easy, to

Fig. 23 SIMK® - ultrasonic - transit - time streamflow - gauging station Guflham / Alzkanal (orderer: Alzwerke Burghausen)

Fig. 24 SIMK® - H - ADCP - streamflow - gauging station Mehring / Mosel - Germany (orderer: federal institute of hydrology (BfG))

mount them in the vicinity of the river banks, at existing bridge piers or comparable existing structures. However, H - ADCP - systems do not measure local velocities v_l in the direct vicinity of the mounting positions, but at configurable horizontal distances from these mounting positions.

The remote measuring positions (x,y), at which the H - ADCP - system measures the local velocities v_l, are exactly defined by means of the H - ADCP - software as small measuring cells. The site specific H - ADCP - cell positions were optimized by means of the SIMK® - method.

H - ADCP - velocity measuring systems enable strict spatial separations of sensor mounting positions and accurately determinable and configurable local velocity measuring positions. The great advantage of this strict separation concept is, that the installation of H - ADCP - systems is typically relatively simple, because frequently excisting structures like river bank walls and bridge piers can be used, to realize simple sensor mountings, although these structures are typically not located at hydraulically optimal velocity measuring positions, which typically do not exist nearby, but remote of these frequently excisting structures.

7. SIMK® - input data

SIMK® - calibrations of streamflow - gauging stations require merely the following input data:

- complete geometrical survey of the discharge cross section, in which the local velocities v_l are measured, comprising the complete range of practical relevant stage variation (5),
- rough classification of the state of the river sediments or the canal materials, the banks and the forelands (e. g. gravel, sand, meadow, concrete, sheet piling),
- layout maps and digital photos of the intended streamflow - gauging station and of the upstream and downstream regions,
- stage and discharge ranges to be evaluated ($h_{min} \le h \le h_{max}$ and $Q_{min} \le Q \le Q_{max}$) and,
- if available, exact or estimated informations about the types and the positions (x,y) of the local velocity measurements.

In case of radar measurements, it should be noted, that the surface velocities v_l are not measured directly below the radar velocity sensors, but, depending on the mounting angle of the radar sensor of typically 40^o - 60^o a little bit upstream or downstream of the radar sensor. Consequently in this case the cross section should also be surveyed a little bit upstream or downstream of the radar sensor. As far as possible the cross section coordinates should be provided in digital form (e.g., as x - y - Ascii - text file).

8. Extended SIMK®

For hydraulic reasons in the longitudinal section of a river or a canal those positions should be prefered for the installation of streamflow - gauging stations, which are characterized by small changes of the turbulent velocity distribution in flow direction (cf. chapter 3). At these prefered discharge measuring positions stable and uniform approaching flow conditions can be expected.

However, especially in big rivers these ideal measuring positions are not always realizable. Nevertheless accurate (high water -) discharge measurements are sometimes required even for river or canal segments, in which the velocity distribution strongly changes in flow direction.

Therefore, an extended SIMK® - version exists, providing accurate and reliable calibrations of streamflow - gauging stations, being located in river or canal segments, which are exposed to significant changes of the velocity distribution in flow direction. The extended SIMK® - method also provides stage dependent calibrations, including extreme high water conditions.

Extended SIMK® does not only take into account the geometry of the measuring cross section, but, in addition, the geometry of the upstream and downstream areas. Therefore, extended SIMK® enables the optimization of the positions (x,y) of the local velocity measurements and the accurate stage dependent determination of the corresponding calibration functions k(h) and A_{red}(h), being defined in (2) and (8), even if the bottom elevations, the horizontal flow directions or the cross sections of the river or the canal change significantly in flow direction. Additionally, extended SIMK® takes also into account highly turbulent separations of flow and reverse flow zones, which may be caused for example by sharp river bends, the mouths of tributaries or other inflows, outflows and / or any kind of obstacles, which influence the local flow regime of the river. Therefore, approaching flow conditions of the measuring site, being approximately parallel to the river banks, have not to be presumed in case of extended SIMK® - flow measurements.

Besides this significant stage inclinations perpendicular to the direction of flow, being especially relevant in case of large velocities and therefore being particular important in case of rare high water situations, are additionally considered with high accuracies and in great detail by means of the extended SIMK® - calibration method. Velocity dependent stage inclinations perpendicular to the direction of flow can be very important, because they can significantly influence the stage dependent calibration function A_{red}(h), being defined in (8) and because they must be considered by the optimal determination of hydraulically suitable positions for the local stage measurements h and by the accurate evaluation of these local stage measurements.

If necessary, extended SIMK® - also considers the influences of artificial structures like existing weirs, intake structures and outlets of hydro power stations and cooling water withdrawals, spillways, drops, bottom ramps, fender walls, groynes, culverts and bridge piers upon the stage dependent calibration functions k(h) and A_{red}(h), being defined in (2) and (8).

In the following sections three realized extended SIMK® applications are indroduced, which exemplarily reveal, that the increased extended SIMK® - calibration effort enables reliable and reproduceable discharge measurements even in case of extreme high water situations and even in case of strongly disturbed approaching flow conditions of the discharge measuring site. Hence, extended SIMK® - calibrations offer significantly enlarged application possibilities for continuous discharge measurements.

8.1 Ultrasonic streamflow - gauging station Araizeki - weir / Seta - River (Japan)

A typical practical application of the extended SIMK® - calibration method was provided for the ultrasonic transducer positions and the corresponding measuring paths, being schematically shown in fig. 25. This schematic view represents an ultrasonic transit - time - responder - streamflow - gauging station, being installed in the Japanese Seta - River. At the shown ultrasonic cross section, which is located approximately 80 km northeast of Osaka, the Seta - River comprises a total catchment area of approximately 3900 km^2, including the Biwa Lake, which is largest Japanese inland lake, comprising a water surface area of A = 674 km^2.

For operational reasons the ultrasonic discharge measuring system had to be installed in the Seta - River directly upstream the Araizeki - weir. The Araizeki - weir comprises ten separate weir fields, which can be regulated independently of each other and which are used for the sealevel

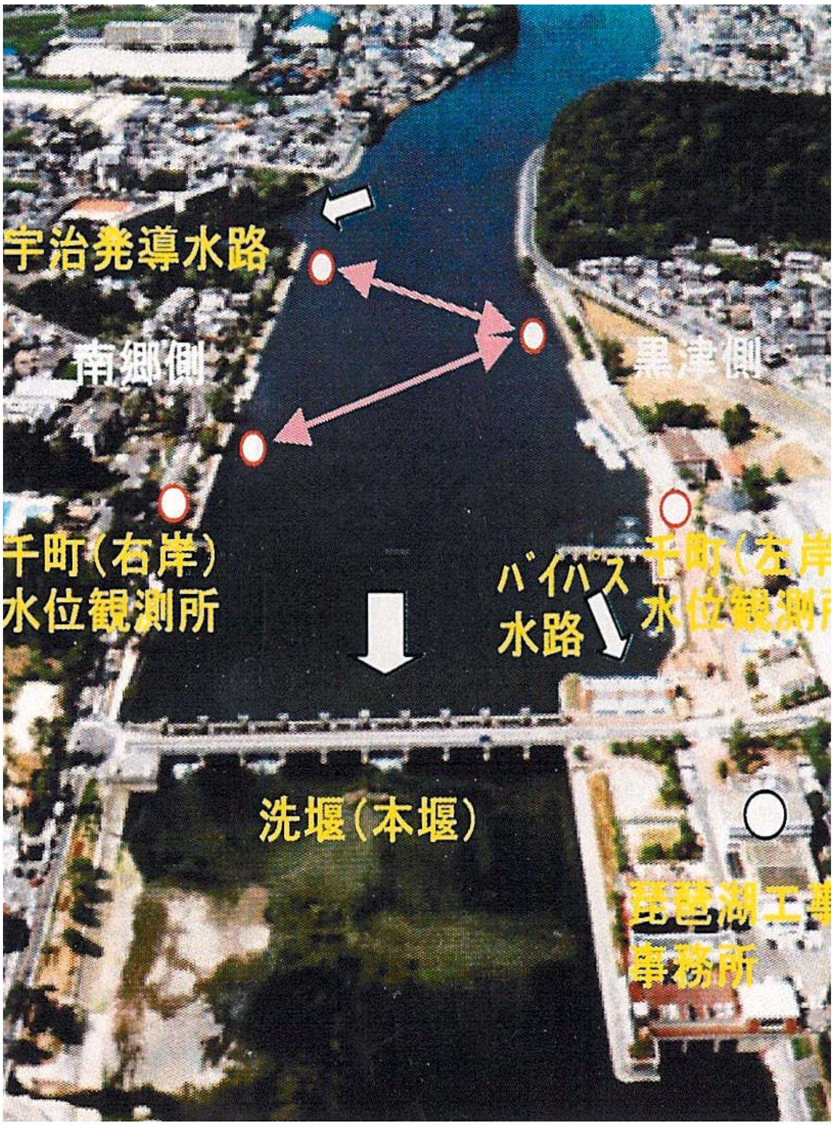


Abb. 25 SIMK® - ultrasonic - transit - time - responder - streamflow - gauging station, being located directly upstream the 130 m wide Araizeki - weir in the Seta - River, Japan

control of the large Biwa Lake retention area and for the flood protection of the Osaka region. The total discharge capacity of the Araizeki - weir amounts to ca. Q_{max} = 1200 m^3/s. At the selected ultrasonic measuring site the Seta - River is ca. 150 m wide.

Of course, the choosen position of the measuring site is by no means hydraulically optimal. For some regulating configurations of the Araizeki - weir strongly unsymmetrical approaching flow conditions have to be expected in the close vicinity of the ultrasonic discharge measuring system. Moreover, according to fig. 25 the selected measuring site is located directly downstream of a S - shaped river bend and directly downstream of the outlet to a canal hydro power station, which is marked by an arrow in fig. 25. Especially in case of mean and low flow conditions, the local approaching flow conditions are additionally influenced by the river hydro power station, which is located directly downstream the ultrasonic streamflow - gauging station on the left side of the Seta - River. In fig. 25 the upstream region of this hydro power station is marked by another arrow. The approaching flow conditions of this river hydro power station are additionally disturbed by five directly upstream located piers of an old weir construction, which is used nowadays as a hydraulic engineering museum.

Despite of these complicated and strongly discharge dependent approaching flow conditions of the Araizeki - weir and of the two hydro power stations, the ultrasonic discharge measuring system, schematically shown in fig. 25, was successfully calibrated by means of the extended SIMK® - method.

8.2 Radar streamflow - gauging station Vorderhornbach / Tyrolean Lech (Austria)

Fig. 26 shows the Lech - bridge Vorderhornbach, being located in the Tyrolean alps in Austria. At the upstream side of this bridge two radar sensors were mounted, providing continuous stage and surface velocity measurements of the Lech. On behalf of the E.ON hydropower GmbH this radar - streamflow - gauging station was likewise calibrated by means of the extended SIMK® - procedure.

The radar - streamflow - gauging station Vorderhornbach / Lech is located in the Tyrolean Lech valley ca. 36 km upstream of the inland lake Forggensee, which comprises a comparably small water surface area of A = 15 km^2. The discharge measuring site Vorderhornbach / Lech is used by the E.ON hydropower GmbH for actual flood reporting, flood forecasting, flood warning and for the optimale operation of the limited high water reservoir of the lake Forggensee, to reduce high water dangers in the large downstream valleys of the Lech and the Danube river.

At the radar - streamflow - gauging station, shown in fig. 26, the Tyrolean Lech river comprises a total catchment area of ca. 680 km^2, including many high - alpine mountains like the Austrian Parseier Spitze with a summit height of 3036 mNN. Hence, the Tyrolean Lech is a very branched

Fig. 26 SIMK® - radar streamflow - gauging station Vorderhornbach / Tyrolean Lech, Austria (orderer: E.ON hydropower GmbH)

wild river, being exposed to large high waters, which are often combined with significant floating matter (especially wild wood) - and bed - load transport. The morphology of the Lech river bed, predominantly consisting of coarse gravel, may change significantly due to flood. Regularly repeated cross section surveys revealed, that single Lech high waters may cause area - wise extensive bottom erosions of $\Delta s \geq 2.0$ m. At Vorderhornbach the bottom slope of the Lech amounts to ca. 6 ‰ and causes large velocities, which amount to approximately $v_m = 1.5$ m/s in case of mean flow conditions and which can quickly exceed values of $v_{max} = 4.5$ m/s in case of flood. During severe frost periods temporary ice drifts have also to be expected in the Tyrolean Lech.

Due to these complex hydraulic boundary conditions, it was extremely difficult, to select a suitable streamflow - gauging station in the longitudinal section of the Tyrolean Lech. To achieve sufficient forecasting times for the optimal operation of the high water reservoir of the Forggensee lake in case of high waters, the radar discharge measuring site had to be positioned far enough upstream of the Forggensee. On the other hand, a very big part of the 1432 km^2 large catchment area of the Forggensee reservoir should be comprised by the upstream radar - streamflow - gauging station. Hence, only the approximately 22 km long Tyrolean Lech river section between Vorderhornbach and Reutte came to consideration as a potential measuring site. Due to the high water induced very high velocities and instable river bed morphology, contact free stage and velocity measurements were required by the E.ON hydropower GmbH. Therefore preferred installation positions of the radar system were Lech bridges, which already exist within the ca. 22 km long Tyrolean Lech river section between Vorderhornbach and Reutte. However, within this river section only six Lech bridges exist from which five bridges are located in Lech sections, which are characterized by a very instable and partly strongly branched river bed morphology.

Therefore, the Lech bridge Vorderhornbach, shown in fig. 26 was finally selected as best available installation position for the radar - streamflow - gauging station. This bridge is located directly upstream a rock threshold, which crosses the river bed and which therefore reliably prevents bottom erosions. Fig. 26 reveals, that the Lech bridge Vorderhornbach is located in a right bend of the Lech. Downstream of this bridge the concave bend of the Lech river is fixed by rock, whereas upstream of the Vorderhornbach bridge the concave bend of the Lech river is is fixed by large and stable groynes. Since the Lech is not branched in the neighborhood of the Vorderhornbach bridge and since the Lech is characterized by a relatively small and stable cross section and by an exceptionally large bottom slope, contradictorily to most river segments of the Tyrolean Lech deposits are not to be expected in the vicinity of the selected measuring - position.

Hence, in this Lech section the river morphology is long - term stable and thus the selected measuring - position permits long - term reproduceable and stable discharge measurements. Even in spite of the temporarily expected high water induced large surface velocities in the range of v_{max} > 5 m/s, being often combined with significant floating matter transport (especially wild wood) and during severe frost periods possibly additionally combined with ice drift, the contact free radar measurements (cf. fig. 2) from the existing Vorderhornbach Lech bridge enable maintenance - and almost failure - free stage and velocity measurements.

However, due to the upstream groynes along the concave bend of the Lech river and above all due to the massive bridge piers the approaching flow conditions of the Vorderhornbach discharge measuring site are strongly disturbed, especially in high water situations. Moreover, due to the large velocities, the existing river bend and the existing bridge piers by no means horizontal water levels can be expected for the selected measuring cross section Vorderhornbach, especially not in high water situations.

Instead, significant river bend induced cross sectional stage differences of up to $\Delta h = 0.5$ m between the enlarged water levels along the concave river bend and the reduced water levels along the convex river bend and additional even much larger water level differences, occuring in the vicinity of both massive bridge piers, can not be neglected, if accurate discharge measurements are aspired for this streamflow - gauging station. These strongly stage dependent nonlinearities of the turbulent velocity distributions and the corresponding nonlinearities of the likewise strongly stage dependent calibration functions k(h) and A_{red}(h), being defined in (2) and (8), were accurately and in great detail simulated and evaluated for optimized stage and velocity sensor positions of the radar - streamflow - gauging station Vorderhornbach / Lech by means of the extended SIMK® - method. This extended SIMK® - calibration included evaluations for extreme Lech high waters of up to Q_{max} = 750 m^3/s.

8.3 Ultrasonic streamflow - gauging station estuary barrage / Tonegawa (Japan)

Fig. 27 shows an aerial foto of the approximately 600 m wide Tonegawa estuary barrage, being operated tide dependent, to minimize saltwater intrusions into the Tonegawa lower course and to avoid flood induced damages. The Tonegawa estuary barrage is located approximately 80 km east of downtown Tokyo and 19.5 km upstream of the Tonegawa - mouth into the pacific ocean. With a mean water discharge of ca. Q_m = 350 m^3/s and a maximum high water discharge of approximately Q_{max} = 16000 m^3/s the Tonegawa is the largest Japanese river. Upstream the Tonegawa a multilevel ultrasonic - transit - time - system was installed, which was calibrated by means of the extended SIMK® - procedure for different stages and discharges and for alternative positions of the ten gates of the Tonegawa estuary barrage.

9. SIMK® - advantages

SIMK® transforms existing or simply available geometrical basis informations into hydraulic characteristics, describing the site specific strongly geometry and stage dependent flow conditions of the streamflow - gauging station. SIMK® provides these site and stage specific hydraulic characteristics not only for mean water, but above all also for high water. The SIMK® - results are summarized in a very small site and stage dependent simply applicable dimensionless calibration function $k(h) = v_m / v_l$.

SIMK® is characterized by:

- universal applicability on rivers and canals of any shape and size,
- systematic stage dependent calibrations including extreme high water levels,
- high accuracies,
- adaptable manufacturer independent combination possibilities with any kind of punctual (e. g. propeller current - meter, ultrasonic Doppler, H - ADCP or radar Doppler) or line averaged (e. g. ultrasonic transit - time) velocity measurements,
- independence of the actual (high water) discharge and therefore,
- discharge independent fast availability at any time.

SIMK® - calibrations supply very simple k - h - and A_{red} - h - tables,

- which have to be determined only once
- and which are digitally stored in the monitor of the streamflow - gauging station.

Fig. 27 SIMK® - ultrasonic - transit - time - streamflow - gauging station, being located upstream the Tonegawa estuary barrage, Japan

Immediately afterwards these SIMK® - results allow accurate discharge measurements

- even in backwater situations
- for the complete range of stage variations (including extreme high water).

Hence SIMK® enables fast realisations of adaptable streamflow - gauging stations, being characterized by

- small one time investment costs,
- no continuous operating costs,
- high accuracies,
- maintenance - free operation,
- almost failure - free operation,
- the feasibility of realizing very small measuring intervalls (in the range of a few minutes or even seconds) and
- immediate
- digital online availability of the actual discharge measurement values at any time
- without any additional post-processing.

Therefore SIMK® offers special advantages for short - term, fast, accurate, maintenance - free, cost effective and, if required, fully automated solutions of the following tasks:

- synchronous and continuous capture and recording of the high water discharges of all relevant flow measurement stations of a catchment area,
- online - output and remote data transfer of actual (high water) discharge measurement data,
- flood reporting,
- flood forecasting,
- flood warning,
- optimale flood control of limited reservoirs and
- short - term supply of complete Q - h - stage - discharge curves.

References

[1] Bavarian Agency for Hydrology (LfW):
Internet presentation of the Bavarian flood reporting service, http://www.hnd.bayern.de.

[2] * Burggraf, R., Kölling, C.:
SIMK - Durchflussmessungen in den Hauptsammlern des Münchner Kanalnetzes, Nürnberger Wasserwirtschaftstag vom 27.06.2002 des ATV - DVWK - Landesverbandes Bayern, Nürnberg 2002.

[3] Hannweber, M.:
Erfahrungsbericht des Sachgebietes Gewässerkunde zum SIMK - Durchflussmessverfahren, internal report of the German Water Resources Office (WWA) Weilheim, Weilheim 2001.

[4] Kölling, C.:
Finite - Element - Simulation der Geschwindigkeitsverteilung in Kanälen und teilgefüllten Rohrleitungen. (Finite - Element - Simulation of the velocity distribution in canals and partly filled pipelines), PhD - Thesis, accepted by the Hydraulic - Institute of the Technical University of Munich, report Nr. 60, Munich / Germany 1994.

[5] Kölling, C., Petroff, A. M.:
New Finite Element Model accurately predicts velocity profiles.
Proc. of the 67th Water Environment Federation Conference, pp. 327 - 338. Chicago 1994.

[6] Kölling, C.,Valentin, F.:
SIMK - Abflussmessungen. Wasserwirtschaft 85 (1995), Nr. 10.

[7] Kölling, C.:
Kalibrierung von Abflußmeßstellen mit Hilfe des SIMK - Verfahrens,
Workshop Ultraschall - Durchflußmessungen der Bundesanstalt für Gewässerkunde, Berlin 1996.

[8] Kölling, C.:
Praxiserfahrungen über SIMK - Durchflußmessungen in Flüssen und Kanälen.
Internationales Wasserbau - Symposium Planung und Realisierung im Wasserbau. Heft 82 des Lehrstuhls für Wasserbau und Wasserwirtschaft der TU München, S. 565 - 582, München 1998.

[9] Kölling, C.:
SIMK - Kalibrierung von Durchflußmeßanlagen, Heft 19 der ATV - DVWK - Schriftenreihe Durchflußmessung an Regenüberlaufbecken“, Hennef, September 2000.

[10] * Kölling, C.:
SIMK® - Kalibrierung von Durchflussmessstellen in Flüssen und Kanälen,
International Seminar „New developments in flow measurements in natural and artificial flumes“, Hydraulic - Institute of the Technical University of Munich, Munich / Germany March 2004.

[11] Nezu, I., Rodi, W.:
Experimental study on secondary currents in open channel flow.
21st IAHR Congress, Proc. Vol. 2, pp. 114-119. Melbourne 1985.

[12] Siedschlag, S.:
Erfahrungen mit dem SIMK - Verfahren bei der Durchflussermittlung an Bundeswasserstraßen im Zusammenhang mit unterschiedlichen Methoden zur lokalen Fließgeschwindigkeitsmessung, report 1099 of the German federal institute of hydrology (BfG), Berlin 1997.

[13] Siedschlag, S.:
Durchflussermittlung mit Hilfe digitaler Bildverarbeitung und SIMK - Kalibration.
Wasserwirtschaft 88 (1998), Nr. 6.

[14] Strobl, T., Aufleger, M.:
Überprüfung von SIMK - Durchflussmessungen an der Versuchsanstalt für Wasserbau und Wasserwirtschaft in Obernach vom 10.10.95, internal report of the Obernach laboratory for hydraulic engineering and water - resources management of the Technical University of Munich (VAO), Obernach 1995.

[15] Tominaga, A., Nezu, I., Ezaki, K.:
Experimental study on secondary currents in compound open - channel flows.
Proc. of the 23rd IAHR Congress, Ottawa 1989, pp. A15-A22.

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