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The Dynamic Calibration of Tipping-Bucket Raingauges

Janusz Niemczynowicz

Dept. of Water Resources Eng.,
Lunds Institute of Science and Technology,
Sweden

The dynamic calibration of three types of tipping-bucket raingauges extensively used in the Nordic countries was performed. The tested and calibrated gauges were: "LTH gauge", PLUMATIC gauge and RIMCO gauge. It was found that with regard to all tested gauges, the volume of water which tips the bucket is not a constant characteristic for the gauge; it depends on rainfall intensity. Thus, in order to avoid errors, a calculation of the rainfall intensity or of rainfall volume from tipping-bucket registrations must go through empirical, usually non-linear calibration function. The procedure involved in the dynamic calibration of the tipping-bucket raingauges is described in the paper. Examples of typical calibration curves are provided. The magnitude of errors, in respect of measured rainfall intensity, which occur when linear gauge calibration is used is stated too.

Introduction

The rapid increase in the application of automatic data processing during the recent decade caused a major change in the approach to field data collection techniques. Since most data are processed in the computer, field data collection and registration should be made in computer compatible form. In accordance with this general requirement, a tipping-bucket gauge for rainfall measurements has been developed. This type of gauge produces rainfall data in digital form which can readily be processed by computers. In the course of the last ten years, raingauges of the tipping-bucket type have replaced almost every other type of raingauge. Many countries have their national networks of raingauges covered by tipping-bucket gauges.

Most of the manufacturers of tipping-bucket raingauges characterize the resolution of the gauges by stating the volume of water necessary to tip the bucket. This volume, usually expressed as millimetres water pilar, is suggested to be constant for the gauge. Thus, we may have a 0.1 mm gauge, a 0.5 mm gauge, and so on. Most users rely on the technical gauge descriptions supplied by manufacturers, using the given "gauge constant" direct when calculating rainfall depth and intensity. The calculation of rainfall depth for any time period is simply performed by multiplying the "gauge constant" by the number of tippings observed during this time period. Some users try to check the "gauge constant" and make their own calibration of the bucket, using a pipette for determining the volume of water necessary to tip the bucket. This procedure can only eliminate errors due to incorrect installation of the gauges; it does not eliminate errors due to the non-linear relation between rainfall intensity and the water volume per tipping.

In this paper, it will be shown that, as far as the tested tipping-bucket gauges are concerned, the volume of water which tips the bucket is not a constant, but a function of the rainfall intensity. In order to avoid errors, the calculation of the rainfall intensity or the rainfall volume must go by way of an empirical, usually non-linear, calibration function. The procedure according to which the dynamic calibration of the tipping-bucket raingauge is performed will be described, and examples of calibration functions will be provided. The magnitude of those errors with respect to measured rainfall intensity, which will occur if the "gauge constant" is used instead of the calibration function, will also be shown.

The idea of dynamic calibration is, of course not new, but the procedure given in this paper has, to my knowledge, not been described before. As far as I know, users who really make individual dynamic calibration of the tipping-bucket raingauges are very difficult to meet indeed.

Investigated Gauges

Three types of tipping-bucket gauges were tested and calibrated at the Department of Water Resources Engineering in Lund:

1) A gauge developed and manufactured at the department – the "LTH-gauge" see Fig. 1. LTH gauges were used in studies of the areal and dynamic properties of short-term rainfall performed in the city of Lund (Niemczynowicz 1984). Individual non-linear calibration functions were used during these studies. Twelve gauges were tested and calibrated.

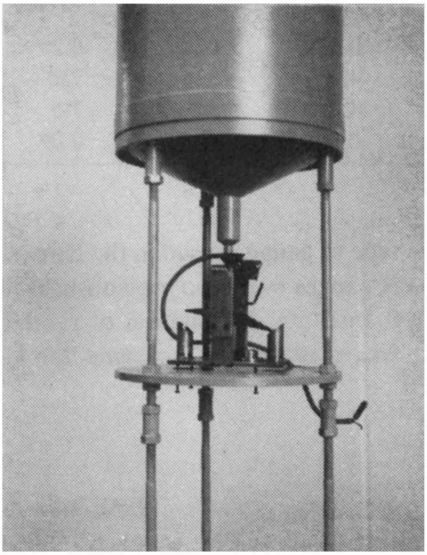

Fig. 1. The LTH gauge.

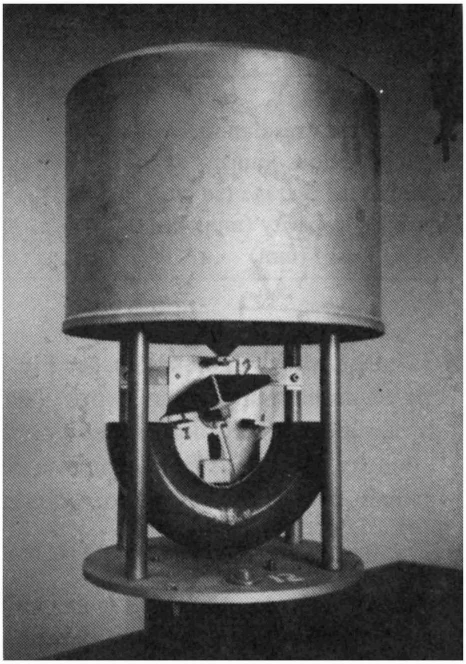

Fig. 2. The PLUMATIC gauge.

Fig. 3. The RIMCO gauge.

Table 1 – Technical data concerning the tipping-bucket gauges used in the investigation.

Gauge	LTH	RIMCO	PLUMATIC
Manufactured in	Sweden	Australia	Norway
Rainfall depth resolution, average for all intensities (mm)	0.035	0.20	0.20
Funnel area, average (sq cm)	428	324	750
Measuring capacity (mm/min)	4.2	6.3	7.5
Wetting losses (mm)	0.06	0.07	0.09

2) The PLUMATIC raingauge, see Fig. 2. This type of gauge is used in the Norwegian national raingauge network. The Plumatic gauges were also previously used by Swedish Meteorological and Hydrological Institute. Calculation of rainfall intensity, both in Norway and in Sweden was made using the same for all gauges, non-linear calibration equation

$$i = (0.198533 + 0.001467\,N)\,N$$

where i – rainfall intensity in mm/min
N – number of tippings/minute.

The plumatic raingauges are presently used in an investigation of altitude effects in Swedish mountain regions. Individual, non-linear calibration curves are used in this investigation. Twelve gauges were tested and calibrated.

3) The RIMCO raingauge, see Fig. 3. Eight RIMCO gauges were used in urban hydrological studies performed by the Department in Tunis (Niemczynowicz and Hogland 1983). This gauge is used in the Danish national network of raingauges. Two gauges were tested and calibrated.

Technical data regarding these gauges are given in Table 1.

Calibration Procedure

As was mentioned before, the volume of water which makes the bucket tip is not a constant but is depending on the rainfall intensity. Different methods have been used by manufacturers and users in order to avoid, or provide corrections for this non-linearity. For example, the shape of the bucket in the LTH gauge was especially designed to avoid non-linearities by diminishing the tilting time and by ensuring the quick evacuation of water from the bucket after tilting. The edges of the bucket and the pillars supporting it have capillary splits. When the bucket strikes upon the supporting pillar, the capillary suction from the splits sucks the bucket almost dry in less than one second. The RIMCO gauge has a siphon placed between the funnel

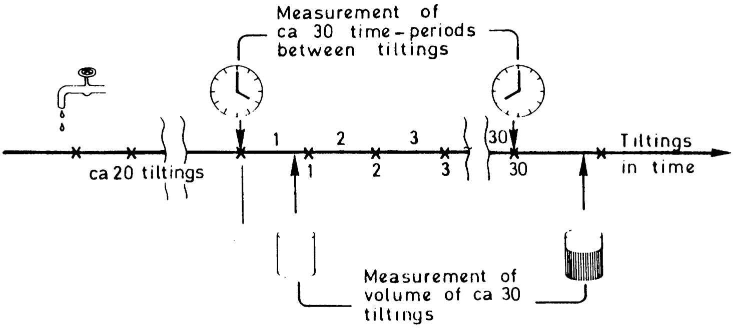

Fig. 4. Scheme showing the dynamic calibration of a raingauge.

and the bucket. A siphon is designed to empty a constant volume of water to the bucket. Some users make their own calibration, either a static one by means of measuring the bucket volume (Edwards *et al* 1974), or a dynamic calibration by measuring the time between tiltings at a constant flow rate (Calder and Kidd 1978).

Neither precautions taken by manufacturers nor static calibration can completely eliminate non-linearities in gauge response and errors in measured rainfall intensity.

If a linear gauge response is assumed, the rainfall intensity (I) is simply calculated by

$$I = V\frac{n}{t} \tag{1}$$

where n – a number of tiltings during time t.
V – a bucket volume assumed to be constant for all rainfall intensities.

Assuming that the character of the bucket response is non-linear, the rainfall intensity (I) will be a function of a tipping rate n/t, and the bucket volume will not be a constant

$$I \equiv f\frac{n}{t} \tag{2}$$

The developed calibration procedure is aimed at finding the shape of the function expressed in Eq. (2) by direct measurements of the tipping rate n/t with regard to several discrete, known rainfall intensities. The same calibration procedure was applied to all the previously listed tipping-bucket gauges.

A constant water flow, simulating a constant rainfall intensity of about 1 mm/min was supplied to the funnel of the gauge. The volume of water running out of the two buckets was collected separately during about 20 tiltings; the adjustment screws were regulated so that both buckets gave approximately the same volume of water, and the volume of one tipping was approximately equal to the nominal (i.e. stated by the manufacturer) volume. After about 20 tiltings assuring a "steady state" with respect to inflow and outflow, calibration measurements started. The water running from both buckets was collected during about 30 to 200 tiltings; its volume was measured with a burette, and the time required for the same number of tiltings was registered by a stop-watch (see Fig. 4). In order to eliminate possible errors due to different volumes from the two buckets, an even number of tiltings should be measured. Now, knowing the number of tiltings, the time and the volume, the exact value of rainfall intensity could be calculated and related to at tilting rate (number of tiltings in time).

In this way, between 15 and 25 different rainfall intensities within the measuring range were tested, each of them giving one point on the calibration diagram. All gauges were calibrated using the same procedure.

Typical Results

The results of the calibration were tabulated, and the tilting rate was plotted against the rainfall intensity. It was found that a simple power equation fits very well with the data

$$I = a N^{b} \tag{3}$$

where I – the rainfall intensity in mm/min.
N – the tilting rate in tippings/min. ($N = n/t$).
a and b are parameters.

and

$$V = \frac{I}{N} \tag{4}$$

where V – the bucket volume in mm.

Combination of Eqs. (3) and (4) defines bucket volume as functions of the tilting rate N and the rainfall intensity I

$$V = a N^{b-1} = I^{1-1/b} a^{1/b} \tag{5}$$

By means of a linear regression on the logarithm values of the rainfall intensity and the tilting rate, the parameters of the power Eq. (3) can easily be obtained. Parameter a is a rainfall intensity with a tilting rate of 1 tilting/minute; parameter b defines the degree of non-linearity; in case of $b = 1$, the calibration equation is linear and the bucket volume is constant for all intensities.

The calibration functions of all the tested gauges appeared to be more or less non-linear. Fig. 5 shows a typical example of a calibration curve for the LTH gauge. It can be seen from the figure that the observed points fit very well to the power equation line. It is also evident that errors in calculated rainfall intensity will occur, if a constant volume per tipping is assumed (straight line in Fig. 5).

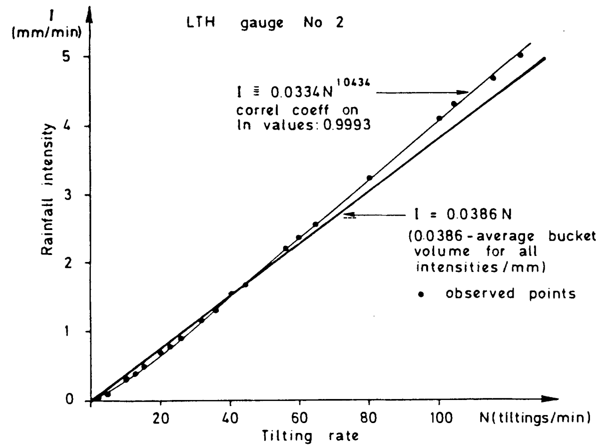

Fig. 5.
An example of a calibration curve for the LTH gauge.
LTH gauges.

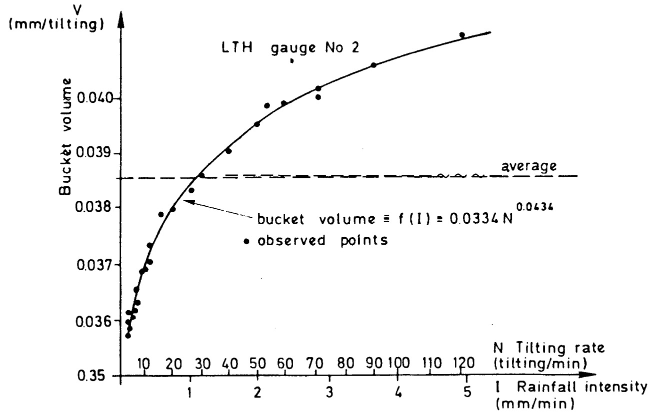

Fig. 6.
An example of the relation between bucket volume and rainfall intensity for one of

Fig. 6 shows an example of a non-linear relation between bucket volume and rainfall intensity. Assuming that the intensity values calculated on the basis of the calibrated power equation are true (correlation coefficient with observed values 0.9993), the errors which appear due to the assumption of linearity were calculated for this gauge. Table 2 shows these errors for the whole measuring range of rainfall intensity.

In spite of the efforts to make all the LTH buckets identical, significant differences between the gauges were found. Table 3 supplies the calibration parameters for all LTH gauges, showing the individual differences.

Note that errors presented in Tables 2 and 4 are caused by non-linearity of the gauge response only, total measurement errors may be of course much higher.

A test of the RIMCO gauges showed very slight non-linearity in the calibration function. Obviously, the siphon arrangement dosing a constant water volume to the bucket is very effective. The non-linearity of the calibration function, expressed

Table 2 – Errors in calculated rainfall intensity when using a constant bucket volume. Example for LTH gauge No 2.

Tilting rate N tiltings/min	Calculated rain-fall intensity		% error
	linear calibr. I=0.0386 N mm/min	non-linear calibr. I=0.0334 N 1.043 mm/min	100x
1	2	3	(2-3)/3
0.5	0.0193	0.0162	19.1
1	0.0386	0.0334	15.5
5	0.1930	0.1791	7.2
10	0.3861	0.3691	4.6
20	0.7722	0.7606	1.6
30	1.1583	1.1614	–0.3
40	1.5444	1.5680	–1.5
50	1.9305	1.9790	–2.5
60	2.3166	2.3937	–3.2
80	3.0888	3.2317	–4.4
100	3.8610	4.0879	–5.4
120	4.6330	4.9337	–6.1

Table 3 – Calibration parameters for the LTH gauges. (a and b are parameters in Eq. (3).

Gauge No	a	b	Correlation coefficient between ln values	Average volume per tipping mm
1	0.0358	1.035	0.9997	0.0390
2	0.0334	1.043	0.9998	0.0386
3	0.0366	1.030	0.9998	0.0399
4	0.0364	1.029	0.9998	0.0393
5	0.0375	1.031	0.9998	0.0411
6	0.0357	1.020	0.9998	0.0376
7	0.0321	1.049	0.9999	0.366
8	0.0323	1.051	0.9995	0.0372
9	0.0294	1.048	0.9996	0.0331
10	0.0399	1.017	0.9999	0.0417
11	0.0350	1.020	0.9995	0-0378
12	0.0294	1.026	0.9986	0.0315

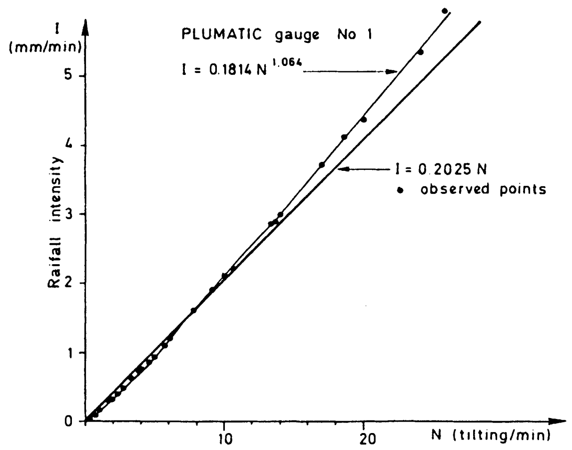

Fig. 7.
An example of a calibration curve for PLUMATIC gauge.

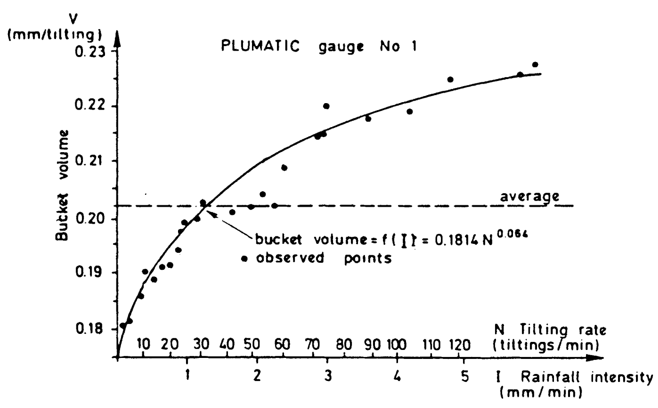

Fig. 8.
An example of the relation between bucket volume and rainfall intensity for one of PLUMATIC gauges.

as parameter b in Eq. (3), is 1.013 for both tested gauges. This results in a very small error in the calculated rainfall intensity, if it is assumed that the volume of the buckets is constant with regard to all the intensities. This error, calculated as described before, is less than 0.5 percent for the intensities 0-2 mm/min and about 2 percent for the maximum intensity of about 5 mm/min. The nominal value of the bucket volume given by the manufacturer, i.e. 0.2 mm/tipping, was found to be very accurate too; the average volume from calibration for all intensities was 0.2008.

PLUMATIC raingauges were found to have the most non-linear calibration functions of all three types of tested gauges. Fig. 7. shows an example of a typical calibration curve for the PLUMATIC raingauge; Fig. 8 shows the relation between bucket volume and rainfall intensity for the same gauge. Table 4 shows an example of error calculation regarding one of PLUMATIC gauges. Table 5 supplies calibration parameters for all tested PLUMATIC gauges.

Table 4 – Errors in calculated rainfall intensity when using a constant bucket volume. Example for PLUMATIC No 1.

Tilting rate N tiltings/min 1	Calculated rainfall intensity linear calibr. I=0.2025 N mm/min 2	 non-linear calibr. I=0.1814 N 1.064 mm/min 3	% error 100x (2-3)/3
0.5	0.1013	0.0868	16.7
1	0.2025	0.1814	11.6
2	0.4051	0.3790	6.9
4	0.8102	0.7930	2.2
6	1.2152	1.2213	–0.5
8	1.6203	1.6590	–2.3
10	2.0254	2.1030	–3.7
15	3.0381	3.2380	–6.2
20	4.0508	4.3980	–7.9
25	5.0635	5.5770	–9.1
30	6.0762	6.7710	–10.3

Table 5 – Calibration parameters for 12 PLUMATIC gauges.

Gauge No	a	b	Correlation coefficient between ln values	Average volume per tipping, mm
1	0.1814	1.064	0.9999	0.2022
2	0.1807	1.045	0.9998	0.1947
3	0.1888	1.037	0.9998	0.1974
4	0.1919	1.044	0.9999	0.2024
5	0.1856	1.050	0.9999	0.1975
6	0.1594	1.051	0.9998	0.1731
7	0.2158	1.030	0.9997	0.2263
8	0.1794	1.057	0.9997	0.1940
9	0.1865	1.052	0.9999	0.1971
10	0.1841	1.056	0.9999	0.1897
11	0.1868	1.047	0.9999	0.1952
12	0.1913	1.031	0.9999	0.1952

The Calculation of Low Rainfall Intensity

A non-linear tipping-bucket calibration should be also used in the calculation of low rainfall intensities when the tilting rate is below one tilting per registration period. In this case, the registration sequence consists of readings without tilting ("empty periods") and readings with only one tilting ("one-tilting readings"). An average tilting rate N, which is less than one for this case, should be found using some kind of smoothing procedure. It can easily be done automatically by testing the data concerning the existence and length of "empty periods" between "one-tilting readings". Accordingly, such a smoothed tilting rate N can be found with the aid of – for example – following equation

$$N = \frac{2}{m1 + m2 + 2}$$

where $m1$ and $m2$ = the numbers of empty time periods before and after an actual "one- tilting reading".

The rainfall intensity is then calculated on the basis of Eq. (3), and this intensity is assigned to half of the empty periods before and after an actual one-tilting reading. An additional smoothing of the rainfall intensity can be carried out by means of, for instance, moving averages.

Wetting Losses

Losses of water due to the wetting of the funnel area, the passage to the bucket and the bucket itself were measured with respect to the three tested types of gauges. The volume produced by an even number of tippings was measured, starting with a dry and a wet gauge respectively, the difference being the wetting losses. The average values of the wetting losses for the three gauges are given in Table 1.

A Field Check of Calibration

A special control routine for checking the stability of calibration parameters in the field was developed. A well-defined volume of water was poured to the funnel from a vertical, pipette-like pipe through a small hole. The diameter of the pipe was about 1 cm and the length 100 cm, the volume thus corresponded to about 20 tiltings on the RIMCO and PLUMATIC gauges and 200 tilting on the LTH gauge. When the hole at the bottom of the pipe is opened, the water passes through the gauge, simulating a rainfall whose intensity gradually changes from high to low. This results in a repeatable sequence of tiltings during consecutive minutes, a sequence which is characteristic for the gauge. The number of tiltings during each minute is counted in the field and compared with the original sequence from calibration in the laboratory. If the difference between the original and the field calibration sequence is judged to be unacceptable, the gauge must be taken to the laboratory for recalibration.

Conclusions

The relation between tilting rate and rainfall intensity was found to be non-linear where all three types of tested tipping-bucket gauges were concerned. The degree of non-linearity varies between different types of gauges and between individual gauges.

The volume of water which tips the bucket is a function of the rainfall intensity. If the constant volume of one tipping is used in the calculation of rainfall intensity, an error with regard to calculated intensity will occur. This error is particularly high with regard to small and high intensities; extreme values of rainfall intensity are smoothed down.

The RIMCO raingauge shows a very slight non-linearity in the calibration function. The error due to using a "gauge constant" instead of a nonlinear calibration function does not exceed 2% for the total measuring range. The PLUMATIC raingauge shows the highest degree of non-linearity. The "gauge constant" error rises to about 10% at the extremely high intensity of 5 mm/min., and to about 16% at the low intensity of 0.1 mm/min.

Unnecessary errors in measured rainfall intensity and rainfall volume could be avoided if all raingauges of the tipping-bucket type were subjected to individual, dynamic calibration.

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Address:
Department of Water Resources Engineering,
Lunds Institute of Science and Technology/
University of Lund,
Box 118,
S-221 00 Lund,
Sweden.

Review

Transport of Suspended Solids in Open Channels

Proceedings of Euromech 192, Munich, 11-15 June, 1985

W. Bechteler (Ed)
A. A. Balkema/Rotterdam/Boston 1986, $ 59 (£ 35)

This book of 270 pages contains most of the papers presented at Euromech Colloquium No. 192: *Transport of Suspended Solids in Open Channels*.
The papers are divided into the six sessions of the meeting:

1) Flow Structures as related to suspended transport. This section contains an invited lecture by B. M. Sumer and papers on the influence on the flow field from the suspended sediment, settling of fine cohesive sediments, motion of suspended particles under different hydrodynamic conditions.
2) Concentration distribution and transport of suspended load under steady flow conditions. Invited lecture by L. C. van Rijn. The papers in this section deal with the concentration distribution of the sediment, the unit stream power theory, models for non-equilibrium situations and transport in fixed bed channels.
3) Reservoir sedimentation. This section covers different aspects of sedimentation: design strategy for reservoirs, models for sedimentation in channels and streams, sensitivity analysis, modelling of settling basins by turbulence models, and experiments on delta formation.
4) Resuspension, suspended and bed load interaction. The main subjects are: bed forms, the theory of physical models, and presentation of advanced field measurements of turbulence and suspended sand.
5) Suspended sediment transport under non-steady flow conditions. The two papers present mathematical models for suspended transport of sand and cohesive sediment, respectively.
6) Special topics: Distribution of trace metals in solution and particulates, field measurement techniques, effect of suspended load on flow in meandering channels, prediction of sediment yield.

The proceedings from the Euromech 192 cover many aspects of suspended sediment transport and contain many contributions of high quality. The reviewer finds that the area of field data and field measurement techniques perhaps is the one best covered by interesting papers.

It should be kept in mind though that the main purpose of the Euromech meetings is that researchers can present and discuss the results of recent and current research work. This book therefore does not, and can not be expected to give a general presentation of the subject. It can be of interest to scientists working actively with suspended sediment transport, but will be of less value for engineers working with sediment transport problems.

Rolf Deigaard