Setting up rating curves using HEC-RAS

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Abstract

The calculation of discharge from stage measurement is a fundamental procedure in surface hydrology. The stage-discharge relationship at a gauging station is usually represented by a rating curve determined from a series of stage-discharge measurements. However, the establishment of a reliable rating curve is time consuming and often the larger flood events are not captured, such that the rating curve is extrapolated. In Norway about 14 % of the discharge data has to be extrapolated. Extrapolating beyond the upper limits of the established rating curve can clearly result in large errors. To overcome these difficulties involved with the traditional method for deriving rating curves, the use of a hydraulic model in the form of the HEC-RAS package is proposed for constructing a stage-discharge relationship. We set out to investigate the reliability and accuracy of the method, how to measure the profiles efficiently and to gain experience in choosing the best Manning's coefficient. Survey data and one discharge measurement from four Norwegian gauging stations that have reliable rating curves were considered in order to assess the adequacy of an HEC-RAS modelled rating curve. Generally, the results show that HEC-RAS modelling of stage-discharge curves calibrated according to an assumed Manning's number can be used as a useful and reliable tool at high water levels but can be inaccurate at lower stages.

Introduction

The amount of water passing a gauging station, the discharge, is typically calculated by transforming the recorded stage data to discharge by the means of an estimated stage-discharge relationship. This relationship, referred to as the rating curve, is assumed to be a one-to-one relationship between the measured stage and the discharge passing the gauging station. The rating curve is constructed by measuring the discharge and the corresponding stage at convenient times. The measured stage-discharge points are then fitted to a smoothing function, typically a power-law, which makes it easy to transform the automatically recorded stage into discharge time series. There are some problems associated with the traditional rating curve method: (1) Because it often takes several years before enough stage-discharge measurements are available for estimating an accurate rating curve, the procedure is expensive and time consuming; (2) Due to the concerns about the safety and applicability during flood conditions of the standard discharge measurements methods such as current meter, dilution and ADCP, large flood peaks discharges are often beyond the upper limits of the rating curve; (3) In small catchments the stage and discharge can change very rapidly, especially during floods, such that it becomes difficult to link the measured discharge to a unique stage value.

An alternative to the traditional method is to determine the rating curve using indirect procedures based on open-channel hydraulics. The general procedure for this is: (a) to measure channel cross-sections in the vicinity of the gauging station; (b) note the water surface at each cross-section to define the slope between the cross-sections; and (c) to define the roughness of the reaches. Although the indirect approach is considered less accurate than the traditional method because of the errors in the surveying and in the evaluation of the channel roughness (Bathurst 1984, Jarret 1987, Kirby 1987), it has sometimes been successful (e.g. Kean and Dungan Smith 2005).

This study presents the results from four gauging stations in Norway where rating curves have been derived using an indirect method in the form of the general-case computer model HEC-RAS 3.1.3, developed by the Hydrological Engineering Center of the U.S. Army Corps of Engineers (USACE 2005). The accuracy of the HEC-RAS rating curves is assessed by comparing them to the measured rating curves.

Data and model calibration

The data were collected during fieldwork July-August 2005. The heights in each section were measured with a levelling telescope. At the Strømstøa station we used an Acoustic Doppler instrument to measure the depths in the sections in the riverbed. The longitudinal water surface was only recorded once, at the same time as the profiling. The measured water surface is also connected to a water discharge measurement in the modelling. The following table 1 gives a short description of the gauging stations and photos i figures 1-4 shows typical segments of the investigated sections.

	Strømstøa	Magnor	Nautsundvatn	Bjørnegårdssvingen
Mean annual flow [m³/s]	300	39	170	42
Description of river bed	High degree of embeddedness, stones 10 cm + rocks up to >1m mid-river. Flat gradient, no supercritical flow sections.	Outlet from small lake (supercritical flow), mouth artificially dammed with large rocks	Mountain stream clean and steep bedrock channel. Determining profile supercritical.	Clean channel, flat. artificially dammed with large rocks. Determining profile supercritical.
Description of left river bank	Dense forest	Forest and brush	Light brush	Light brush
Description of right river bank	Light forest and brush	Brush and some trees	Brush and trees	Concrete wall and brush
Downstream reach boundary condition	Normal depth	Normal depth	Critical depth	Normal depth

Table 1. Keywords for describing the hydrology, river bed and river banks and selected boundary conditions at the 4 gauging stations.

The simulation was performed using HEC-RAS 3.1.3 (USACE 2005). This program performs one-dimensional hydraulic calculations for i.a. steady flow water surface profiles. It can model both sub- and supercritical as long as mixed flow regime water surface profiles. In our case study we wanted to model the water surface at the gauging station, which means one has to model the entire river reach that is believed to affect the water level at the gauging station. We therefore included one cross-section upstream of the gauging station as well as several cross-sections downstream. The river reach in most cases contained both sub- and supercritical sections and was therefore modelled as a mixed flow regime. The modelling was performed three times for each station: 1) The Manning's roughness constant was selected on the basis of observed type of channel characteristics (substrate, vegetation, etc) which were compared with descriptions in the HEC-RAS hydraulic manual (USACE 2002) and case-studies by USGS (USGS 1987), 2) the model was calibrated to best fit the water surface measured in the cross-sections and 3) the model was calibrated to best fit the stage-discharge curve at the gauging station. The results were then compared to see if there are any common features.

Figure 1. Determining profile at Magnor gauging station. Supercritical flow in profile at low water level.

Figure 2. Determining profile at Bjørnegårdssvingen gauging station. Supercritical flow in profile at low water level.

Figure 3. Determining profile at Nautsundvatn gauging station. Supercritical flow in profile at low water level.

Figure 4. Determining profile at Strømstøa gauging station. Subcritical flow in profile.

Results and discussion

Magnor

As showed in figure 5, the result of the simulation with pre-selected Manning's n overestimates discharge at low water levels and slightly underestimates discharge at stages above mean annual flow. The Manning's n after calibration simulating the measured water surface only gives about 1/3 of the discharge compared to the stage-discharge curve at annual mean flow level. We were able to obtain a good fit to the stage-discharge curve at this station by choosing a higher friction number in the determining section and the next section upstream.

	Pre-selected Manning's n			Manning's n after calibration according to measured water surface			Manning's n after calibration according to stage-discharge curve		
Section no.	LOB*	Channel	ROB*	LOB	Channel	ROB	LOB	Channel	ROB
5	0.073	0.045	0.06	0.07	0.05	0.06	0.07	0.035	0.06
4	0.073	0.045	0.06	0.07	0.05	0.06	0.07	0.04	0.06
3	0.073	0.045	0.06	0.07	0.1	0.06	0.07	0.08	0.06
2	0.073	0.055	0.06	0.07	0.11	0.06	0.07	0.11	0.06
1	0.073	0.045	0.06	0.07	0.06	0.06	0.07	0.04	0.06
0	0.073	0.045	0.06	0.07	0.14	0.06	0.07	0.035	0.06

*LOB: Left overbank channel, ROB: Right overbank channel

Table 2. Summary of Manning's n selected at the Magnor gauging station before and after calibration. The station is situated in section 4. Section 2 was, at the time we did fieldwork (low water level) the determining section for the water level in section 4.

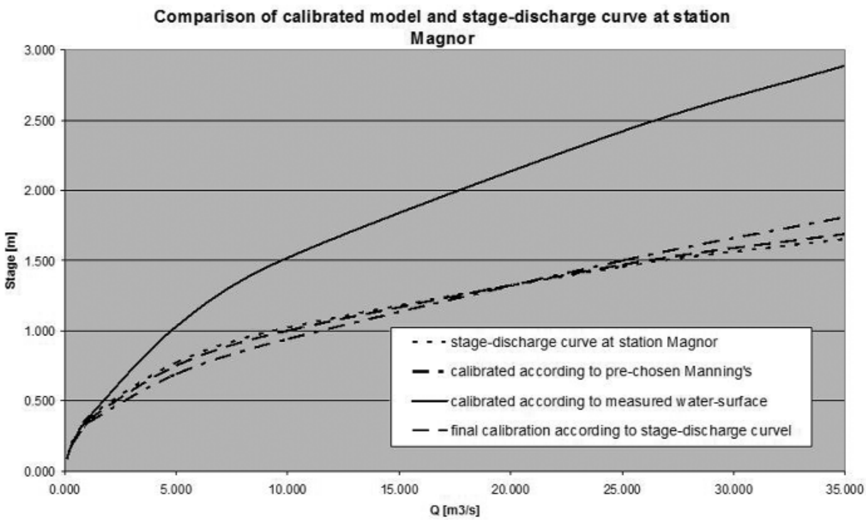

Figure 5. Comparison of the 3 calibrated models and the stage-discharge curve for the gauging station situated in section 4 at Magnor.

Strømstøa

Both the two first calibrations overestimates discharge at low water levels and underestimates discharge at stages above mean annual flow. It was also impossible to match the curve at the lowest level in the final calibration but it makes a good fit to the upper part of the rating curve. The final Manning's n values are generally lower than the pre-selected ones, which could be caused by a very high degree of embeddedness and also smoothness caused by algae growth. This situation was not described in any of our reference literature.

	Pre-selected Manning's n			Manning's n after calibration according to measured water surface			Manning's n after calibration according to stage-discharge curve		
Section no.	**LOB***	**Channel**	**ROB***	**LOB**	**Channel**	**ROB**	**LOB**	**Channel**	**ROB**
11	0.1	0.04	0.06	0.1	0.04	0.06	0.07	0.04	0.06
10	0.1	0.04	0.07	0.1	0.04	0.07	0.07	0.04	0.06
9	0.1	0.04	0.07	0.1	0.04	0.07	0.07	0.04	0.06
8	0.1	0.055	0.07	0.1	0.03	0.07	0.07	0.03	0.06
7	0.1	0.055	0.07	0.1	0.037	0.07	0.07	0.04	0.06
6	0.1	0.055	0.07	0.1	0.04	0.07	0.07	0.04	0.06
5	0.1	0.055	0.07	0.1	0.04	0.07	0.07	0.04	0.06
4	0.1	0.04	0.07	0.1	0.06	0.07	0.07	0.04	0.06
3	0.1	0.055	0.07	0.1	0.10	0.07	0.07	0.04	0.06
2	0.1	0.04	0.07	0.1	0.04	0.07	0.07	0.04	0.06
0	0.1	0.04	0.07	0.1	0.04	0.07	0.07	0.035	0.06

*LOB: Left overbank channel, ROB: Right overbank channel

Table 3. Summary of Manning's n chosen before and after calibration at the Strømstøa gauging station, situated in section 10. Section 8 was, at the time we did fieldwork (low water level) the determining section for the water level at the gauging station. There were no sections with supercritical flow in this river reach.

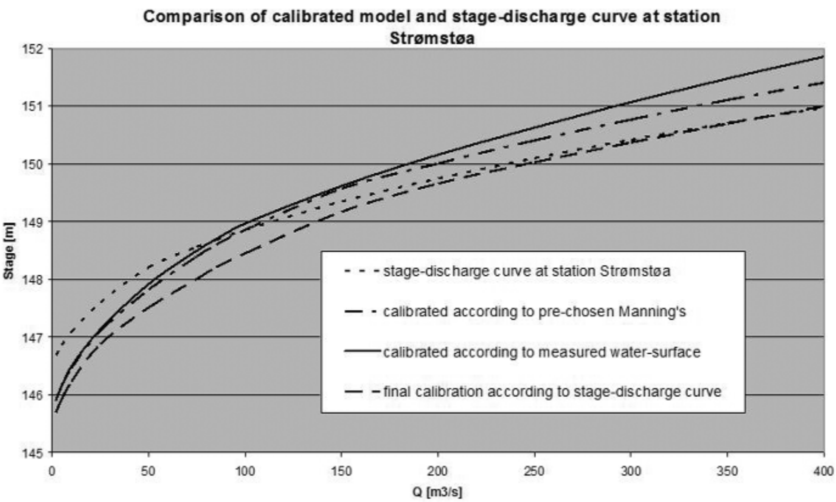

Figure 6. Comparison of the 3 steps of calibrated models and the stage-discharge curve for the gauging station situated in section 10.

Nautsundvatn

This station is situated in a typical Norwegian mountain river. The riverbed is comprised of smoothly scoured bedrock. This situation was also not described in any of the references; the chosen Manning's numbers are therefore based on the suggested friction number for a built-up channel with concrete bottom from the HEC-RAS table (USACE, 2002). The calibration with this pre-decided Manning's n matches the curve both at the bottom and the top, which is above mean flow level but overestimates the discharge in the middle of the curve. The result after the second calibration to simulate the measured water surface generally underestimates the discharge. The final fitting matched the curve at all levels. Final Manning's n was higher than expected, especially in the sections where supercritical flow was observed.

	Pre-selected Manning's n			Manning's n after calibration according to measured water surface			Manning's n after calibration according to stage-discharge curve		
Section no.	LOB*	Channel	ROB*	LOB	Channel	ROB	LOB	Channel	ROB
300	0.04	0.03	0.045	0.04	0.045	0.045	0.055	0.05	0.06
89.5	0.04	0.03	0.045	0.04	0.045	0.045	0.055	0.06	0.06
67.5	0.04	0.03	0.045	0.04	0.045	0.045	0.055	0.08	0.06
63.5	0.04	0.03	0.045	0.04	0.25	0.045	0.055	0.11	0.06
44.5	0.04	0.03	0.045	0.04	0.25	0.045	0.055	0.06	0.06
0	0.04	0.03	0.045	0.04	0.2	0.045	0.055	0.11	0.06

*LOB: Left overbank channel, ROB: Right overbank channel

Table 4. Summary of Manning's n selected before and after calibration at the Nautsundvatn gauging station, situated in section 89.5. Section 67.5 was, at the time we did fieldwork (low water level) the determining section for the water level at the gauging station. There was supercritical flow in both this section and section 0.

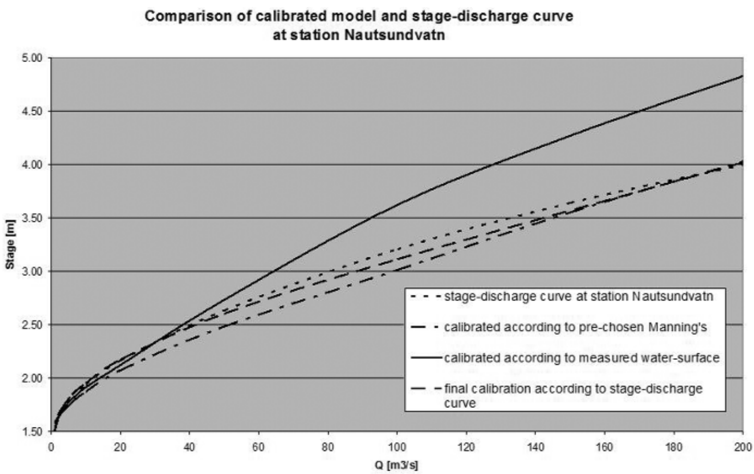

Figure 7. Comparison of the 3 steps of calibrated models and the stage-discharge curve for the gauging station situated in section 89.5.

Bjørnegårdssvingen
This riverbed consists partly of smoothly scoured bedrock but in the determining profile (section 2.5) there are also sharp rocks, while downstream from the gauging station (section 48) the riverbed is covered by smaller rocks and gravel. The Manning's n was chosen from the HEC-RAS table (USACE 2002) with a higher friction number in the determine profile. This station does not have a stage-discharge curve; the results are therefore compared with the discharge-measurements at the station. The calibration with this preselected Manning's n matched the curve; we therefore chose these values as the final friction numbers. The result after the second calibration to simulate the measured water surface underestimates the discharge.

	Pre-selected Manning's n			Manning's n after calibration according to measured water surface			Manning's n after calibration according to stage-discharge curve		
Section no.	**LOB***	**Channel**	**ROB***	**LOB**	**Channel**	**ROB**	**LOB**	**Channel**	**ROB**
50	0.05	0.035	0.045	0.05	0.04	0.045	0.05	0.035	0.045
49	0.05	0.035	0.045	0.05	0.04	0.045	0.05	0.035	0.045
48	0.05	0.035	0.045	0.05	0.04	0.045	0.05	0.035	0.045
44	0.05	0.035	0.045	0.05	0.04	0.045	0.05	0.035	0.045
34	0.05	0.035	0.045	0.05	0.04	0.045	0.05	0.035	0.045
25	0.05	0.035	0.045	0.05	0.04	0.045	0.05	0.035	0.045
10	0.05	0.035	0.045	0.05	0.17	0.045	0.05	0.035	0.045
2.5	0.05	0.055	0.045	0.05	0.1	0.045	0.05	0.055	0.045
0	0.05	0.035	0.045	0.05	0.04	0.045	0.05	0.035	0.045
-20	0.05	0.035	0.045	0.05	0.04	0.045	0.05	0.035	0.045

*LOB: Left overbank channel, ROB: Right overbank channel

Table 5. Summary of Manning's n selected before and after calibration at the Bjørnegårdssvingen gauging station, which is situated in section 48. Section 2.5 was, at the time we did fieldwork (low water level) the determining section for the water level at the gauging station.

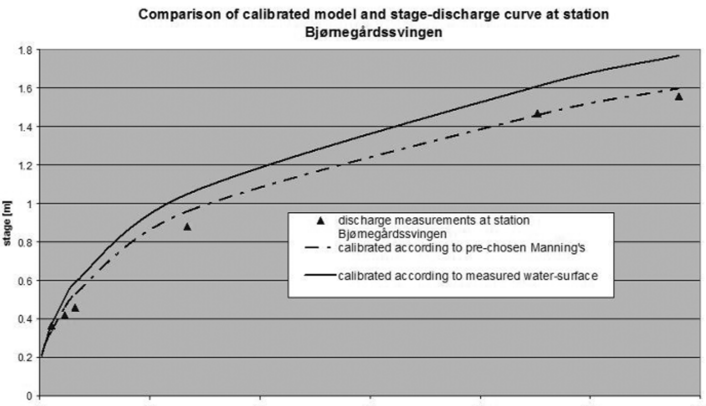

Figure 8. Comparison of the 2 steps of calibrated models and the discharge measurements for the gauging station Bjørnegårdssvingen.

The simulation results after the calibrations with pre-selected Manning's n generally overestimated the discharge at the lowest stages compared to the original stage-discharge curve at all four stations. The results after calibration to simulate the measured water level were unreliable at all of the stations. The fieldwork was done during the summer that is the dry season; therefore all water surfaces are at low water levels. If calibrated to simulate the water surface at higher water levels, the results would probably be different. The pre-selected Manning's numbers did not vary much from the final Manning's n, but we underestimated the Manning's numbers in the sections with supercritical flow.

Conclusions

Compared to the original stage-discharge curve, calibrations with pre-selected Manning's roughness numbers have a tendency to give slightly more water at low water-levels and slightly less water at stages above mean annual flow. Calibrations according to the one measured water surface gave, in every case, significantly underestimated discharge. The Manning's n selected from the HEC-RAS Manning's table (USACE 2002) or from the book "Roughness Characteristics of Natural Channels" (USGS 1987) provided good estimates, except in sections with supercritical flow were the values were underestimated. Generally, the results show that HEC-RAS modelling of stage-discharge curves calibrated according to assumed Manning's numbers can be used as a useful and reliable tool at high water levels but can be inaccurate at lower stages.

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