Building Better Stage-Discharge Rating Curves

Dr. Amartya Kumar Bhattacharya
BCE (Hons.) (Jadavpur), MTech (Civil) (IIT Kharagpur), PhD (Civil) (IIT Kharagpur), Cert.MTERM (AIT Bangkok), CEng(I), FIE, FACCE(I), FISH, FIWRS, FIPHE, FIAH, FAE, MIGS, MIGS – Kolkata Chapter, MIGS – Chennai Chapter, MISTE, MAHI, MISCA, MIAHS, MISTAM, MNSFMFP, MIIBE, MICI, MIEES, MCITP, MISRS, MISRMTT, MAGGS, MCSI, MMBSI
Chairman and Managing Director,
MultiSpectra Consultants,
23, Biplabi Ambika Chakraborty Sarani,
Kolkata – 700029, West Bengal, INDIA.
E-mail: dramartyakumar@gmail.com

Stream discharge is, arguably, the single most valuable environmental variable required for the effective management of food supply, energy generation, industrial production, transportation, health, and for the protection of global ecosystems. It is also one of the most difficult variables to measure and monitor on a continuous basis in natural streams and rivers. The derivation of an empirical relation between stage (i.e. water level) and discharge (i.e. streamflow) is fundamental to the production of almost all information about fresh water quantity. This relation can be explained from first principles. Civil Engineers have progressively simplified the theory into equations: first to explain the relevant variables (e.g. the Bernoulli equation), then to collapse them into terms that explain the majority of the variance, assuming the physical properties of freshwater are constants (e.g. the Manning equation) and finally to reduce the equation to a univariate form (the stage-discharge equation) valid for steady, uniform flow conditions. Civil Engineers are skilled at unveiling the truth from scatter plots of stage and discharge measurements. Armed with a set of working hypotheses that explain not only the underlying form, but also all deviations from that basic shape, Civil Engineers are able to build better rating curves. They are able to efficiently perform, explain and defend their work. A true curve will hold its shape as the density of rating measurements increases and will predict accurately in extrapolated zones such that new data outside the previously calibrated range is likely to also agree with the curve. Any residuals will make intuitive sense: for example, if a rating measurement is affected by backwater it will plot left of the curve while a measurement during rapidly rising stage will plot to the right. Informative residuals are essential for accurate modelling of the dynamic processes governing flow in a natural channel.

Rating curve development is a continuous learning process that requires continuous feedback. The curve can be no better than the field observations. The end uses of derived discharge data must be considered in evaluating whether the available field information is sufficient to derive data that are fit for the intended purpose. Effective rating curves can only be produced in the context of an effective monitoring programme. An effective monitoring plan includes a Quality Management System that documents quality, service and security objectives consistent with a client focus. Site selection and/or stream engineering are critical predictors of success for the development and maintenance of rating curves. Site access can affect the timing and frequency of field visits. Uniformity of flow can affect the accuracy of discharge measurements. The characteristics of the control features can affect the stability and sensitivity of the stage-discharge relation. Civil Engineers evaluate the suitability of technologies for reliability, accuracy, sensitivity and precision requirements over the entire range of conditions. They constantly re-examine their network as better alternatives emerge or location-specific experience increases. Development of skills by training is never complete. The quality of analysis of even the most experienced of Civil Engineers can benefit from focused opportunities to hone their skill through training and knowledge-sharing. Access to a modern data management system that is optimised for advanced data analysis is also a key element of an effective monitoring programme.

There are many simplifying assumptions underlying the use of rating curves. To be effective, a comprehensive understanding of these assumptions is essential. Civil Engineers understand and employ a hydraulics-based approach to curve-fitting. They interpret the hydraulic factors in a larger context inclusive of the dynamic influences of hydrology, weather, fluvial geomorphology and aquatic and riparian ecology. They ensure that all mathematical, statistical, and physical constraints have been addressed. A key assumption of statistical approaches to curve fitting is that the data have the same probability distribution and are mutually independent. This assumption is almost invariably false for stage-discharge rating measurements. There is rarely an adequate sample size of well-spaced measurements per curve segment and per period of applicability for robust statistical analysis. Rating measurements can have uncorrected bias that is only qualitatively understood. The representativeness of rating measurements depreciates as a function of temporary conditions and/or transition between control regimes. Furthermore, the randomised residuals from a statistical curve fitting process make it impossible to understand, and hence model, dynamic processes.

There are two key advantages of using a hydraulics-based approach to stage-discharge rating curves: (1) Civil Engineers can more effectively evaluate curve shape and complexity and (2) it becomes more intuitive to model systematic departures from the fundamental controlling features. Conservation of mass, energy and momentum ensure that for any stream reach the sum of energy of flow (pressure, potential and kinetic) and energy ‘lost’ to forces resisting that flow (friction and turbulence) remains constant. Civil Engineers understand the various forces and energy transitions: for example, they can readily observe effective head above point of zero flow, sub-critical or super-critical flow, onset of bank overflow and influence of cross-section features and stream-bed composition. These observations, correctly interpreted, can provide an a priori estimate of rating equation parameters. A rating curve developed using a hydraulics-based approach can be modified using the same approach. Systematic deviations from the curve can be readily explained by hydraulic factors that are known to be changing. A conceptual cause and effect explanation for the variance forms working hypotheses that are tested by the examination of relevant evidence. Demonstrably valid conclusions (e.g. influence of aquatic vegetation) are used to shape a response to the deviations from the rating curve over time and with respect to stage. Understanding the science is achieved by effective training as discussed before in the context of relevant field experience. Whereas a pure theorist will be frustrated by the uncertainties of a poorly constrained hypothesis, a pure experimentalist will be frustrated by the amount of variance in a poorly constrained trial-and-error solution. The most efficient path to achieving rating curve proficiency is through experience in the field grounded in effective theoretical training.

A systematic approach should be taken to analyse the data. Refinement is best achieved within an orderly process. Systematic analysis of the data is achieved by developing working hypotheses and then rigorously testing these hypotheses against observations. This approach supports the use of all types of evidence in evaluating the truthfulness of a rating model. The evidence for this analysis must be curated and managed with care. The offset of the rating equation can be evaluated from field observations either explicitly (e.g. sill elevation) or implicitly (e.g. cross section analysis for channel control). The exponent of the rating curve can be estimated by considering the channel shape and velocity head through the controlling reach. The breakpoints in the rating curve and the range of effective transition across a breakpoint can be evaluated by cross-section analysis and/or by considering the channel roughness and velocity head. Given these key pieces of information, the task of fitting a rating curve to measurements is simply a matter of adjusting the plotting position and fine tuning the initial estimates. 'Goodness of fit' for measurements to this initial plot of the curve is a function of the validity of the assumptions made about the measurements and the control conditions. In a perfect world, Civil Engineers would be working with ideal conditions. However, rating curves are needed for the real world, making it necessary to systematically expose changing conditions or errors in assumptions and to develop context for appropriate mitigation. Civil Engineers consider their field notes and measurement details when they evaluate deviations from the rating curve. When appropriate, they characterise the expected variance in hydraulic geometry with residual plots of the discharge-depth, discharge-width and discharge-velocity relations. They develop ratings for stage-area and stage-velocity, if needed, to inform the shape of curve extensions. Assumptions about control conditions are evaluated in the context of photographs, sketches, field notes and in the measurement details. The full history of rating measurements and curves is examined to identify trends, cycles and transient excursions from an assumption of stability. It is worthwhile to consider time series of the rating curve residuals in the context of the stage hydrograph when developing a working hypothesis to explain any systematic departures.

It needs to be ensured that corrections accurately model dynamic in-channel processes that influence the hydraulic relation. If validity of the current method is ever in question, the fundamental model used to derive discharge and/or the system for gathering observations must be reviewed. A well-conceived rating curve reveals changes in channel dynamics in a clear pattern of residuals. Change can be abrupt, in the case of debris on the control, or it can be gradual, when modelling the life cycle of aquatic plants. It can apply over the full range of stage (e.g. uniform deposition over the bed) or the influence can be limited to a specific range of stage (e.g. some types of vegetation effects). Civil Engineers mitigate systematic variance by modifying the rating model, either with shift corrections or by transitioning to a new curve. Residual variance about the curve can be highly informative of measurement uncertainty and/or control insensitivity. Recurring variance can be avoided by root cause analysis that results in preventive actions. Variance that is unavoidable needs to be investigated with the investigation resulting in corrective actions. Civil Engineers also look for unexpectedly low variance, for instance, when shifts in ratings are not detected because the frequency and/or timing of measurements are inadequate. In this case the rating curve analysis informs changes to the scheduling of field operations. Managing variance is predicated on a comprehensive understanding of both the underlying in channel processes and business processes. The development of highly effective corrective and preventive actions requires systematic analysis of the data in the context of governing physical and biological dynamics and/or technological influences. The decisions for altering any data must conform to a trusted procedure.

The results of any rating analysis must be subjected to qualification. First-hand field experience is the best source of information for the assessment of data quality. The measurement and monitoring of discharge under natural conditions can be a difficult undertaking. A common consequence of diverse operational conditions is data of varying reliability. The quality of data depends on five key considerations - compliance with a trusted procedure, site location, site-specific suitability of the technology used, training and experience of the Civil Engineer and the use of a good data management system with advanced analysis and diagnostic capabilities. Evaluation of data quality must also consider the explanation and supporting evidence for the shape of the curve and approaches for modelling departures from the curve. A hydrometric dataset is incomplete without a comprehensive explanation of data quality. This includes dataset notes as well as 'per value' quality indicators. Data grading should be a true reflection of the confidence with which the data can be used and these grades should be understandable, consistent and reproducible. It is valuable to indicate the 'approval level' (aka 'age' and 'version') of the data to indicate the likelihood for further review and possible revision of the data. Civil Engineers pro-actively manage data quality. In many cases the same factors that hurt data quality also hurt efficiency, productivity and service delivery.

Civil Engineers are held accountable for their work. Civil Engineers have found that using a rigorous, hydraulics-based approach makes it easier to perform, explain and defend their work. This requires compliance with trusted procedures, evidence based evaluation of working hypotheses, modelling not only the form of the curve but also any deviations from the curve, root cause analysis of unexplained deviations, review and analysis for corrective and preventive actions and qualification of the results. Rating curve development begins before the gauge is even established. Consideration of the control sensitivity to discharge, fluvial geomorphology, aquatic biology and any seasonal influences are a pre-condition for effective rating curves. The suitability of the gauging site is one of the best predictors for discharge measurement quality. The choices made in technologies used to monitor stage and to measure discharge take into consideration the influence of local conditions on technological performance. The timing and frequency of field visits is a result of rating curve analysis rather than the other way around. The observations made during field visits are attentive to the hydrological, hydraulic, biologic and geomorphological details that are essential to understand the form and limits for extension, of a rating curve as well as to explain potential departures from the curve. The shape of the rating curve is constrained by the interpretation of parameters based on field observations. Segmentation of the rating curve, if required, is supported by physical evidence. Extrapolation beyond the calibrated range of the rating curve is physically realistic and supported by supplementary evidence. Modelling of departures from the curve is based on a deep understanding of the physical or biological processes influencing change in channel conveyance. All variables that are known to respond in harmony with the controlling forces for these physical processes are considered in evaluating transitions through time. The process of developing effective rating curves is supported by effective data management. A wide range of curated evidence is readily available for meaningful interpretation and analysis. The intuitive shaping of curve form and extent is readily constrained by the explicit control of model parameters. The qualification of derived discharge is explicitly linked to the strength of the rating calibration. Reliable stage-discharge rating curves require investment in planning, technology, training, field operations and software. Obtaining a discharge record is an expensive business. Hydrometric technologies are changing, data delivery is changing, and the demographic profile of Civil Engineers is changing. A good approach is not only resilient to change in any of these factors but can exploit these changes for the continual betterment of data products and services. Ultimately, as a result of using a good approach Civil Engineers can make better decisions for the equitable use, management and protection of the world's limited water resources.