Australasian Hydrographer

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AUSTRALIAN
HYDROGRAPHERS
ASSOCIATION

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JACQUIE BELLHOUSE

Editor’s Introduction

Welcome to the November 2017 issue of the AHA Journal.

This month you will find two great papers from the 2016 AHA conference covering some of the more traditional aspects of hydrography and, in recognition of their recent achievement in achieving professional certification, profiles for Certified Practising Hydrographers, **Judith le Gresley** (WA) and **Ben Harrison** (Qld).

The last couple of months since our last journal have been a busy time in the industry. While I did touch on some of the great work being done by the Bureau of Meteorology (BoM) and its subcommittees (in the introduction to the August 2017 issue) some of our readers have requested more info:

The periodic review of the National Industry Guidelines for hydrometric monitoring is now underway. To manage the review, in 2017, the BoM Water Monitoring Standardisation Technical Committee (WaMSTeC) established three subcommittees.

Below is an update on their functions and progress:-

- The **ADCP subcommittee**, led by Mark Randall (Qld Department of Natural Resources and Mines), has made great progress. It has completed the initial review of guidelines 8, 9 and 10 which deal with Acoustic Doppler instrumentation, and has prepared a series of proposed changes for consultation.The Bureau is now calling for comment on the proposed changes, which are published on the Bureau’s website (http://www.bom.gov.au/water/standards/consultation.shtml). The consultation period for the proposed changes opened on the 5th of October and will run for 10 weeks through to 15 December 2017.
- The **Groundwater subcommittee**, led by Kevin Dennis (DEWNR[1]) is also making great progress with some draft content already developed. The subcommittee has been tasked with supplementing and extending the existing National Industry Guidelines for hydrometric monitoring 0 to 7 to ensure they cover the why, what, how and where of groundwater monitoring practice.
- The **Review of Guidelines 0 to 7 subcommittee**, led by myself, are due to have their first get together in mid-November. This team has been tasked with reviewing all other feedback on the current National Industry Guidelines for hydrometric monitoring 0 to 7 and amending the content where appropriate. This subcommittee will work closely with the Groundwater team.

Each subcommittee is operating within a TOR which defines the purpose and activities for which they are responsible. While they are working concurrently they will coordinate at various stages of the review process.

A **Technical Reference Group** (TRG) will contribute to the review process of guidelines 0-7 including the revised groundwater monitoring guidance. The TRG will consider the input received through the open industry consultation and make recommendations regarding final revised guideline drafts. It is intended that TRG members will include representatives from all hydrographic aspects. If anyone is interested there are still spots available.

The Bureau’s role is to contribute secretariat support to each of the subcommittees and the TRG. In addition, the Bureau will facilitate coordination between subcommittees to prepare the revised guidelines for WaMSTeC endorsement.

Regards
Jacquie Bellhouse
Journal Editor

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[1] SA Department of Environment, Water and Natural Resources.

BILL BARRATT

From the President

During the year, AHA has built on the Carver not-for-profit business model adopted in April 2016 and introduced a number of efficiencies in how we run the association.

AHA has now published its Governance Plan which includes an annual cycle defining the responsibilities of Executive Committee and National Office. In the coming weeks the committee will have a strategy review meeting as part of the annual governance cycle.

After our successful 2016 conference in Canberra, AHA is planning for the 2018 conference and hopes to announce the location early in the new year.

Over the last 12 months, we have hosted a Christmas event in Perth and assisted an ADCP Regatta at Jindabyne, both in partnership with industry.

Training has seen some exciting progress. AHA has now signed a Memorandum of Understanding with TAFE NSW to help hydrographers achieve the Diploma of Water Industry Operations (Hydrography) NWP50715.

The AHA now delivers distance learning in 7 subjects. Since AHA is not an RTO, on completion of AHA subjects our students can apply for recognition of prior learning from TAFE NSW towards the Diploma.

The Training Coordination is now run through the National Office, reducing our costs. John Skinner took on the role of training consultant in 2016 reporting to the National Office. At that time the course material for several subjects had to be revised. These subjects were completed and the elements were approved against the criteria.

AHA's job advertising service continues to attract strong support from industry, getting information about employment opportunities to our members.

AHA next challenge is to review Professional Certification, working with an Industry Think Tank, to deliver a program which recognises excellence in hydrography and meet the needs of employers.

Finally I would like to thank Jacquie Bellhouse for her effort as Journal Editor. Also I want to acknowledge Grant Robinson for his tremendous input and diligence as volunteer to the National Office and as Secretary, and Max Hayes for his continuing input and patience during the changeover to Xero accounting, as well as the other committee members for their continued wise input.

Regards
Bill Barratt
AHA President

AHA Member Profile - Judith Le Gresley

Describe your current role.

I am employed by the Department of Water and Environmental Regulation (DWER) and am located in the Peel region of Western Australia. I have been in this role since July 2008.

I operate and maintain a range of monitoring sites within the Peel region. Currently I operate 12 gauging stations, 9 pluvios, one water quality sites (EC) and 10 groundwater loggers.

This includes typical hydrographic works such as obtaining discharge measurements utilising various instrumentation, developing and maintaining rating curves, verify data, site visits, capital upgrades, collecting and validating groundwater logger data, calibration checks on equipment and participating within various working groups relating to the measurement field.

Recently I have had the opportunity to undertake bathymetry work on a large lake utilising ADCP and RTK technology.

What hydrographic or other qualifications — relevant to your role — do you have?

I have a Diploma in Water Operations, Bachelor of Science (Env Man), and a Cert 4 in Leadership & Management.

I love learning and am always on the lookout for further educational opportunities.

What are your major career achievements?

Successfully completing my Diploma in Water Operations.

Where has hydrography taken you in the world?

I have had the opportunity to work in other regions within WA for short periods of time such as South Coast, South West and the Pilbara.

I also got to travel to Sydney for the AHA conference in 2014 which has been a highlight of my career.

How did your career related to hydrography commence?

It was a fluke to be honest. I was looking at getting back into the workforce and there was a casual position that came up locally that I applied for.

I then was lucky enough to secure a full time permanent position and I haven’t looked back.

Was there anyone who had a major influence on your career?

Early in my career it was definitely Kevin Firth who was my manager when I started. He took the time to show me the ropes and showed a great deal of patience when trying to answer my many questions (shout out to Andrew Weatherburn for the same reasons). Paul Barton was also a major influence on my career. He was a fantastic sounding board and a tremendous support to me and was instrumental in me obtaining my Diploma.

What has been the most memorable experience in your career?

Recent high flow gaugings in February of this year. We were able to obtain quite a few of the highest gaugings ever collected at our sites in the wheatbelt. As a result we were able to improve the rating curves at these sites, being able to see the normally dry and arid wheatbelt in full flow was also amazing.

What makes hydrography interesting?

I love the variety of my job. I can be in the field one day, looking at local flora and fauna, and the next doing some value adding to the data and looking for ways to improve the way we complete our measurement work.

What do you do when you are not at work?

Home renovations, yoga, out for coffee with my lovely husband, mum’s taxi to the kids all the usual things. Mostly trying to convince the family that camping is a great idea.

What is the biggest change you foresee in Hydrography?

Doing more with less due to increasing financial constraints. Utilising new technology as it becomes available and adapting it to measurement work such as the use of the ADCP technology for practices other than obtaining discharge measurements such as bathymetry work and the use of drones to capture elevation information for models such as HECRAS.

AHA Member Profile - Ben Harrison

Describe your current role.

I'm part of a small team responsible for providing hydrometric information for use in commercial operations and flood management of SunWater's dams and weirs across Queensland.

What hydrographic or other qualifications — relevant to your role — do you have?

Bachelor of Engineering Science (Electrical).

What are your major career achievements?

Being a part of the Flood Operations team during cyclones Marcia and Debbie, overseeing the transition of our database software from Timestudio to Hydstra, and managing the rollout of Alert Data Base Stations across the state to improve SunWaters Flood Warning capabilities.

Ben during a recent trip to Vietnam.

Where has hydrography taken you in the world?

Fortunately in my current job I work across all of Queensland, from Mt Isa and Cairns to Goondiwindi and Bundaberg, as well as getting down to the ACT. There's a lot of ground to cover! I was also generously given the opportunity to spend a week working with the Hydrographers at Snowy Hydro as part of a work swap program.

How did your career related to hydrography commence?

I started at SunWater as a Cadet Electrical Draftsman, working on the Western Corridor Recycled Water Pipeline project. The Hydrographers needed an extra pair of hands on their regional trips, for which I volunteered. I found the work both challenging and interesting, and very fortunately for me I was asked to join the team permanently.

Was there anyone who had a major influence on your career?

I wouldn't be a hydrographer if it weren't for Peter Fiedler and Paul Jensen. They both taught me a lot during my time as a cadet. Peter also got me interested in programming, which plays a huge part in my current role of administering our database as well as many other areas, and has become a passion of mine.

What has been the most memorable experience in your career?

With recent cyclones such as Debbie and Marcia in mind, my biggest career achievement has been being involved SunWater's Flood Operations team both during and post events. These times presented both technical and practical challenges, whilst also highlighting the impact our work has on the greater community. I certainly learned a lot from the experience.

What makes hydrography interesting?

For me, hydrography is a constantly evolving space. There will continue to be new ways to collect process and transport information, both faster and more reliably (hopefully!) And new applications for that information begin to emerge as technology allows. I'm excited to be a part of this process and see the industry move forward.

What do you do when you are not at work?

I'm a keen Poker player and avid football (soccer) fan, although it's more watching sport than playing these days.

What is the biggest change you foresee in Hydrography?

The Cloud. I hate buzzwords, but I do think that as services develop, so too will a greater expectation of availability and transparency of information. There has already been a lot of movement in this space, and I don't expect that to slow down anytime soon.

Comparative Investigation of Canadian, US, and Australian Stage-Discharge Rating Curve Development

Stuart Hamilton, Aquatic Informatics, Vancouver, BC Canada,
Ray Maynard, DNRM[2], Bundaberg, Qld,
Terry Kenney, United States Geological Survey, Salt Lake City, UT U.S.A.

Paper presented to 18th Australian Hydrographers Association Conference Canberra. 24-27 October 2016.

Abstract

For any well-selected gauging location there is a unique relation between stage and discharge that is valid for a specified period of time. However, it is up to the stream hydrographer to discover the form of this relation, for a given epoch, by a combination of stream gauging and inference-making.

The importance of inference in rating curve development cannot be over-stated. Even if given the same data it is unlikely that any ten hydrographers would produce identical hydrographs, with the differences being primarily due to inferences made about curve form, extrapolation, and response to dynamic in-stream conditions. There are many factors that influence inference-making, including: standards, training, techniques and technologies – all of which vary between monitoring jurisdictions.

All three countries generally use the same non-linear shifted power law rating equation, $Q = a \cdot (GH - e)^m$, *where Q is discharge, GH is gauge height, and a, e, and m are calibrated parameters. They mostly also use log-log rating curve plots, although some areas in Australia use GH vs* $Q^{0.4}$ *plots, and a small subset use the more flexible GH vs* $Q^{1/m}$ *plots.*

The main difference in rating curve development is that a single height offset is used in Australia for each rating curve, presumably as a legacy of paper log-log plots. Canada and the US can use a unique height offset for up to three rating segments, which typically gives more flexible rating curves that can need less rating points to span a given range.

The three parameters of a properly-fitted shifted power law rating equation convey meaningful information about the local site hydraulics, whereas those poorly fitted using a sub-optimal height offset are hydraulically uninterpretable, due to parameter interaction in the fitting process.

Another notable difference in rating curve development is the Australian use of families of rating curves, whereas Canada and the US favour multiple base rating curves that are then modified by 3-point height shifts to account for subsequent small temporary rating changes.

Rating extrapolation methods are fairly similar in all three countries. However, some areas in Australia tend to use the $\sum ad^{1/2}$ *method or its later derivative* $\sum ad^{2/3}$.

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[2] Queensland Department of Natural Resources and Mines.

More use could be made in all three countries of prior rating information from cross section shapes and shape changes in the context of the influence of vegetation, particularly for over-bank flow. Stream channels in Australia are often of complex shape, although areas with regular high runoff tend towards simpler U-shaped channels similar to many streams in Canada and the USA.

Increased recognition that a unique stage-discharge rating is not possible at many sites is driving an increase in the number of deployments of ADVMs in North America. ADVM usage is also likely to increase in Australia because of flood access and boat gauging safety concerns.

Introduction

The perceived 'best practice' for rating curve development is not globally uniform. What is 'best' in one geographic context may not be 'best' in a different context. What may be 'best' with one set of technologies may not be 'best' with a different set of technologies. What may have been 'best' at one point in history may not be 'best' when the primary objective of monitoring changes (e.g. from after-the-fact reporting to real-time reporting of streamflow).

Stream-gauging is a place-based activity. Stream hydrographers work in-place and have little occasion to interact with hydrographers working at a different place. This relative isolation creates opportunity for place-based specialisation of practice within the broader scope of international guidance, such as WMO (2008). This diversity in practice presents an opportunity for discovery. Monitoring conditions that may be an edge-case in one region may be widely prevalent in another. Investigations of what differences exist, and why, has the potential to be instructive for the enrichment of best practice everywhere.

In a governance context, the majority of publicly accessible hydrometric data in Canada has been produced by the Water Survey of Canada (WSC) and in the U.S.A. by the United States Geological Survey (USGS). While there is also a considerable amount of hydrometric monitoring by private sector consulting and engineering firms, as well as by other government agencies, there is a lack of discoverability and accessibility of these data. Ratings for privately produced data are not part of this review, apart from a general statement that there is a wide range of rigour and sophistication applied to the rating development process in the private sector.

In general, it seems likely that both Canadian and Australian gauging and rating methods have historically been strongly influenced by the USGS, especially through their excellent series of manuals the Techniques of Water-Resources Investigations and their Water-Supply Papers (e.g. Kennedy, 1984; Rantz, 1982; Buchanan and Somers, 1969; Corbett, 1943). The Water Survey of Canada has recently added a new manual for rating curve development and maintenance (Rainville, 2016).

The majority of publicly-accessible data in Australia is produced by state water agencies, which have their own standards documents. Approaches that have been developed in Australia to help with ratings for irregular-shaped cross sections include the $\sum ad^{½}$ and $\sum ad^{2/3}$ integrated cross-section conductance methods, and the GH vs $Q^{0.4}$ and GH vs $Q^{1/m}$ rating plots.

The Australian methods described in this paper are based mainly on the current standard of practice in the state of Queensland, which is believed to be broadly representative of Australian practice as its rating system is widely used. However, it's inevitable that there will be some local differences that aren't documented here. Rating practices, including rating changes, have also recently been discussed for Canada by Hamilton et al. (2016), for the U.S. by Kenney (2016), and for Australia by Maynard (2016a, 2016b).

This paper decomposes the rating problem into sections about gaugings, rating equations, rating plots, rating curves, rating curve, and rating extrapolation methods. Gauging unsteady-flow adjustments haven't been discussed, as the topic warrants a whole paper by itself! The final section summarises opportunities for improvement that this investigation reveals.

Environmental Differences

There are some significant hydro-geographic differences between the three countries that may contribute to differences in the evolutionary path of development of best practice for ratings. While roughly similar in size (Canada 9,984,671 km^2, U.S.A. 9,826,675 km^2, Australia 7,686,850 km^2), they differ greatly in terrain and climate.

The landscape of Canada is shaped by ice – from the pre-Cambrian granite scraped bare of soil of the Canadian Shield, to the glacial deposits forming the Prairies, to the permafrost of the northern Taiga and Tundra, and to the U-shaped glacial valleys of the Western Cordillera.

Even today, many northern rivers are under ice for up to half the year, and many southern rivers go through several freeze-thaw cycles throughout the winter. River ice jams result in extreme flooding events, and breakup events scour the river channels.

Figure 1. Moraine Lake in the Canadian Rockies (courtesy Cameron Shaw).

Figure 2. Wade Hanna measuring streamflow in a Yukon winter (courtesy Pat Maltais).

The typical Canadian discharge hydrograph is dominated by a large snowmelt-driven peak in the early summer. The advantage of this monolithic discharge peak from a monitoring perspective is offset by the high number of remote sites and difficulty of access, adverse weather, high-energy streams (mountains), low-energy streams (prairies), unstable gauge datums (permafrost), and the limits of available technology.

There are a variety of techniques that have been developed for stage discharge ratings under an ice cover. Unfortunately, none of the available methods can account for the dynamic nature of ice. For example, when ice is actively forming the stage will rise even as discharge falls, and vice-versa while ice is decaying (Moore et al. 2002)! Measurement of discharge and computation of flow under ice is a labour-intensive activity, taking time away from the much easier task of deriving discharge rating curves for open water conditions.

The landscape of the U.S.A. is extremely diverse and is difficult to characterise. From Alaska (near-Arctic) to Utah (desert) to Washington (coastal rain forest) to Florida (tropical), all climate zones can be found. Annual rainfall varies from a low of 67 mm in Arizona to 11,684 mm in Hawaii. Temperatures vary from -62°C in Alaska to 56.7°C in California. In order to accommodate this diversity while ensuring inter-comparability of streamflow data the USGS has invested heavily in the development of standards for rating curve development.

The Australian landscape has been shaped mainly by water over the aeons. More than 60% of the continent has an annual rainfall less than 600 mm, with the majority falling in wet season rain events.

Without frequent large flows to provide the energy for systematic fluvial development, river channels tend to be incised, with insufficient cross-sectional area to contain large episodic flood events, which are conveyed by spilling out over substantial flood plains.

In contrast to North America, where the annual runoff is dominated by snowmelt and stream channels tend to be well adapted for conveyance of the full range of typical flow conditions, the runoff in Australia can literally be 'all-or-nothing' where the maximum flow can be massively greater than the median flow, hence stream channels are often much more irregular in cross section.

Figure 3. Burnett River January 2013 flood of almost 17000 cumecs in East Bundaberg (courtesy Rod Savidge).

1. Operational Gauging Considerations

1a. Gauging requirements

Gaugings are, without a doubt, the most important part of rating development. The timing, frequency, and quality of gaugings inform the shape of the curve, its period of applicability, and the magnitude of any temporary rating deviations.

Ideally, all gaugings would have uniformly small uncertainty, and be randomly distributed about the eventual rating curve. Ideally, gaugings would be distributed over the full range of stage, with uniform distribution within each and every segment of the rating curve. Ideally, gaugings would be timed so every change in the hydraulic properties of the control reach can be accurately identified.

While the ideal for gaugings is easy to identify, it is next to impossible to fully achieve. There are many operational constraints affecting the timing, frequency, and quality of gaugings.

If we had sufficient gaugings of low uncertainty measured across every rating curve segment, and timed to accurately identify every influence on the various hydraulic controls, then rating curve development and maintenance would not be difficult.

However, the operational environment in all three countries results in sub-optimal gaugings that must be compensated for by making inferences about the form of the curve(s) and how it changes over time. The basis for evaluation of the rating curve form is the rating equation, discussed in section 2.

1b. Gauging site access

Canada has a very low number of stream hydrographers per unit area compared to either the U.S.A. or Australia. There is also a very poorly developed transportation network over vast regions, resulting in a large proportion of gauges that must be reached by helicopter or by fixed-wing aircraft.

The high cost of flying means that field trips must be kept to an absolute minimum to stay within allocated budgets. The timing of trips is usually fairly straightforward, with high-water trips scheduled to coincide with the snowmelt runoff peak in early summer. However, a large proportion of gaugings are under ice conditions, reducing the number of gaugings available to develop an open-water rating curve in any given water year.

Figure 4. Stream gauging the Otter Pup River in northern Ontario (courtesy Keith Hryciw).

The USGS has 33 Water Science Centres, well-distributed around the United States, ensuring that hydrographers are located relatively close to their gauges. Within the contiguous United States there is a well-developed transportation infrastructure, so it's usually only the last few kilometres of gauge access that may be problematic. The hydrology in the United States is more diverse than in Canada, but the USGS has the advantage of very good forecasts for weather and flood events that assist with their timing of field trips.

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Australia is also a large country, and water is not evenly distributed over the land mass. Extensive areas of inland Australia have few gauging stations.

However, there are relatively high numbers of gauging stations in the humid parts of Australia, which are also the regions with the best developed transportation infrastructure.

Access to Australian gauges is often limited during high flows, due to extensive over-bank flooding and boggy dirt roads and tracks. Many streams are ephemeral and only need gauging during the wet season. The frequency of field visits is mostly a function of monitoring budgets, which may allow for only a few gaugings per year, and often these will only be zero-flow observations.

Figure 5. Remote area flood gauging at a section more than 2.6 km wide on the Flinders River at Walkers Bend (GH 12.00 m, Q 3618 cumecs).

1c. Gauging safety

Working in and around fast flowing water, in adverse conditions, from boats or cableways or bridges can be a risky endeavour. The history of hydrometric surveys all over the world is full of heroic efforts to obtain extreme discharge measurements under improbable conditions. However, there are risks even for 'normal' conditions.

Many locations require access by fixed wing aircraft on floats or skis, helicopter, snowmobile, quad-bike, jet boat, 4-wheel drive vehicle, or on foot. Almost all locations require some highway travel.

All forms of transportation have a risk and that risk is elevated during the extreme weather that, unfortunately, is strongly correlated with extreme flow conditions. Snow, ice, mud, and washed-out culverts and bridges are all variables that can stand between a hydrographer and a good gauging.

The weather itself is a risk, from hyperthermia at one end of the scale to hypothermia at the other. Megafauna such as Grizzly and Black Bears in North America and Saltwater Crocodiles and Bull sharks in Australia are risk factors to be considered at many gauge locations. Venomous snakes and spiders are rare in North America but prevalent in Australia.

It is increasingly the case that for Occupational Safety and Health reasons an opportunity to obtain that once-in-a-lifetime measurement will not be taken. Stream hydrographers are taught, and rightly so, that no measurement is worth a human life.

Figure 6. Grizzly Bear (courtesy Cameron Shaw).

Figure 7. Saltwater crocodile in the Burdekin River, North Queensland.

However, risk assessment is a difficult thing to learn. How much risk is too much risk? Without clear answers to that question there is an increasing trend toward risk aversion at the expense of valuable gaugings.

1d. Gauging methods

Historically, the techniques and technologies used for mechanical current meter area-velocity measurements were a bit different in the three countries. In Canada and the U.S.A. the vertical axis Price current meter was historically dominant, whereas in Australia the horizontal axis Ott and Oss meters were preferred. All mechanical current meters have frictional resistance that needs to be overcome, and that can affect their performance in very slow velocities. In very turbulent flow, vertical axis meters may over-register (Fulford *et al.* 1994).

All three nations have almost exclusively used the mid-section method to calculate current-meter gauging discharges. The influence of differences in gauging techniques and technologies on rating curve development has not been investigated for this paper, but it is expected that it is unlikely that any differences in gaugings would systematically influence the rating process.

The widespread recent adoption of hydro-acoustics is bringing gauging technology and methods in all three countries fairly closely into line. The USGS and WSC collaborated very closely in the development of standards for the use of Acoustic Doppler Current Profilers (ADCPs) (e.g. Mueller *et al*., 2013). Australian agencies have extensively used them for operational guidance, and also during the development of their own national standards, done under the aegis of the Australian Bureau of Meteorology (2013a, 2013b, 2013c).

1e. Hydrographer training

Stream hydrographer training and accreditation is quite rigorous in all three countries. Both the WSC and the USGS have developed their own in-house training and apprenticeship programs.

In Australia significant training is also provided in-house, and historically most hydrographers did the hydrography course provided by the then Snowy Mountains Hydro-electric Authority or a TAFE college, and lately do the Hydrography Basics course run by the Australian Hydrographers Association.

2. Rating Curve Equations

The three countries use rating curve equations for operational flow rating calculations. However, it's common practice to produce an expanded numeric rating table from the rating equation for sharing ratings amongst agencies. In fact, the Open Geospatial Consortium WaterML 2.0 standard for ratings is based on rating tables, not on equations (Taylor, 2015). The source equation(s) are then treated merely as metadata.

2a. Shifted power-law rating curve equation

The Water Survey of Canada, the USGS, and Australian water agencies all use the same shifted power-law rating curve equation to represent rating segments. It relates discharge (Q), gauge height (GH), and a height offset (e) that notionally converts stage to hydraulic head:

$$Q=a\cdot(GH-e)^m$$

The shifted power-law rating curve equation is extremely flexible, and is clearly superior for fitting rating curves, as its parameters contain meaningful information about the site hydraulics. See subsection 2g for typical parameter values.

2b. Linear rating curve equation

North America and Australia historically used linear rating curve equations for interpolation between points in a rating table manually digitised from a rating curve, and they're still used in Queensland for dam storage volume rating curves:

$$Q=a+b\cdot GH$$

A rating curve shouldn't have piece-wise linear segments unless each height span is quite small, as the rating won't have a continuously-smooth first differential (rate of discharge change with height). The existence of the linear equation is a legacy from when all curves were drawn on paper and represented as numeric rating tables.

2c. Visual fitting of rating equations

North American hydrographers prefer to visually fit rating equations via rating points manually inserted on gauging plots. This gives the hydrographer full control by mentally weighting the influence of gaugings in terms of their perceived relevance. For example, older gaugings may help constrain the curve fitting process, even if they have a predictable bias.

It is often the case that the hydraulic factors controlling the relation between stage and discharge change through time. Careful consideration of the sequence and magnitude of deviations from a base curve, in the context of supplementary field observations, is required to develop a conceptual understanding of the dynamic nature of the control conditions.

The USGS and WSC develop rating curves, which may have multiple offsets, by segments where data plot as straight lines when the log scale of stage is adjusted by the offset and plotted against log discharge. Gaugings are evaluated on the basis of the hydraulic control that was in effect at the time of the measurement. For each hydraulic control segment, a scale offset is determined. The height offset (e) for the rating curve segment associated with the section (riffle) control is first approximated from a measured cease-to-flow (CTF) gauge height, termed *gage [sic] height of zero flow* in the U.S.

Offsets for channel and over-bank controls are determined iteratively through a trial and error process of increasing or decreasing the offset value. The offset is selected that produces a linear relation in log space of the gaugings associated with a single hydraulic control. This is done for each of the hydraulic controls that are experienced at a station. The transitions between segments are then smoothed by the addition of extra rating points at hydraulic control transitions.

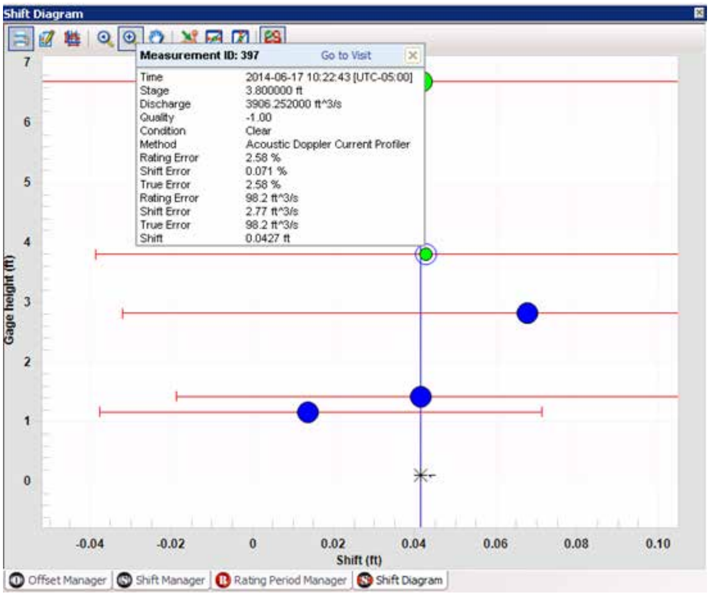
Australian hydrographers have traditionally similarly used visually-selected rating points, but are less likely or even unlikely to fine-tune the height offset for each rating segment.

2d. Regression fitting of rating equations

Least squares fitting is supported by the graphical rating editor used by both the WSC and USGS in North America, but it isn't recommended for use because the underlying Independent and Identically Distributed (IID) assumption is almost never true for gauging uncertainty.

In addition, the model structure, in terms of segmentation break points, is often not readily apparent from gaugings alone. However, it can readily be identified from cross section data, which is easy for a hydrographer to interpret, but not possible to include in statistical regression unless it's done on individual rating segments. In addition to the hard data of the gaugings there are also lots of soft data that are relevant to the curve fitting process.

Some Australian hydrographers have used least squares regression, with good results if sufficient gaugings are available, notwithstanding the IID limitation mentioned above. To avoid rating curve bias though it's necessary that regressions are done only within hydraulically-defined rating segments, and unsteady-flow gauging discharges should first be adjusted to their quasi-steady flow equivalents.



Measurement ID: 397

Time	2014-06-17 10:22:43 [UTC-05:00]
Stage	3.800000 ft
Discharge	3906.252000 ft^3/s
Quality	-1.00
Condition	Clear
Method	Acoustic Doppler Current Profiler
Rating Error	2.58 %
Shift Error	0.071 %
True Error	2.58 %
Rating Error	98.2 ft^3/s
Shift Error	2.77 ft^3/s
True Error	98.2 ft^3/s
Shift	0.0427 ft

Figure 8a. Gauge Height versus Stage Deviation plot from USGS/WSC rating editor.

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Unadjusted unsteady-flow gaugings cause locally-increased discharge and height data variance (heteroscedasticity) if gaugings are done at similar rising and falling stages, or bias if they're done on only the rising or the falling stage.

Heteroscedastic data causes biased fit statistics, and the fitted trendline might not be the best estimator, although it'll still be unbiased in the sense that the objective function is always minimised (e.g. the sums of the squares of y deviations).

It's thus desirable that the data variance and the equation fit be evaluated by visual inspection of the pattern of the residuals, which should appear random about the trendline, with no significant curved patterns that would indicate local biases.

In North American practice, the deviations are plotted in units of stage, hence the magnitude of each deviation provides a direct measure of the rating shift that needs to be applied to correct the departure.

In Australia the evaluation is more likely to be done using discharge percentage deviations and by plotting gauge height versus gauging discharge, or versus the ratio of gauging discharge to rating discharge.

Many of the Australian rating curves fitted by regression were entered into their rating table database as conventional rating points. The most popular Australian rating system allows the direct entry of rating equations, but only five flow rating equations have been entered by Qld DNRM hydrographers.

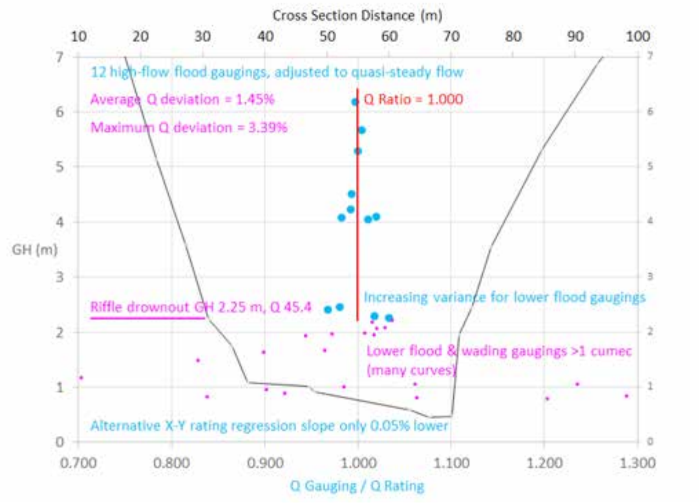

Figure 9b. Flood rating equation fitting check using a Gauge Height versus Discharge Ratio plot for Reid Creek at Mungy.

2e. Probabilistic fitting of rating equations

Rating equations can also be fitted by probabilistic methods, but as far as we know that isn't being done operationally by the major water authorities in the three countries. Mason *et al.* (2016) document a recent USGS trial aimed at characterising the uncertainty of rating curves, which used the Bayesian inference fitting method reported by Le Coz *et al.* (2014). The method has also been extended by Le Coz *et al.* (2016) to the fitting of rating curves at twin gauging stations subject to variable backwater.

The fitting process starts with estimated Prior Probability Density Functions (PDFs) for each of the three rating equation parameters, determined by approximately representing the stream cross section by a few fundamental hydraulic shapes such as rectangles and triangles. More accurate Posterior PDFs are then explored for the most likely range of rating equation parameter values, via 10^4-10^5 Monte Carlo random trials using gauging data to calculate the fitted parameter values and their PDFs. These are then used to generate an ensemble of many possible rating curves, from which their PDFs can be calculated, with the most likely rating curve being the one with the Maximum Posterior probability.

Gauging uncertainty can be easily incorporated into the model, and the uncertainty of the output rating curve is given as a by-product of the numerous trials. Our caveats are that quasi-steady flow gauging data are required to give the uncertainty of the rating curve, which always notionally represents steady flow, but the calculated steady-flow uncertainty of the rated discharges will always be substantially lower than the actual uncertainty relative to the unsteady flow during floods.

2f. Multiple power-law height offsets in rating table databases

WSC and USGS hydrographers are able to use a unique height offset (e) for each rating curve segment, as mentioned above in subsection 2c. This gives them great flexibility, as they can easily develop and use rating curves that are hydraulically optimal for each rating segment.

The rating table database used by most Australian hydrographers only allows the use of a single height offset for each rating curve. Multiple height offsets could still be used, by directly inputting multiple rating equations, but at the expense of complexity compared to the traditional and convenient input of rating points.

Multiple height offsets enable hydrographers to define rating curves of minimal curvature that are based on relatively few gaugings. The coefficients and exponents of all well-calibrated rating segments make ‘sense’, and fall within conventional wisdom once an appropriate offset is selected.

2g. Typical power-law equation parameter values

The shifted power-law rating equation’s parameters contain meaningful information about the site hydraulics, but only if they’re properly fitted. If they’re not, the parameters are hydraulically meaningless, due to parameter interaction in the fitting process.

Coefficient a is a linear growth factor that is equal to the discharge when GH - e = 1.00. Its value is larger for larger channel widths for that head, for channel shapes that tend most towards the rectangular shape limit, for higher slopes (via $S^{0.5}$), and for lower Manning n (via 1/n). As S & n are usually correlated with width to some degree, width is the most influential.

Height Offset e converts stage to hydraulic head, the maximum height of the water column available to drive flow. For a section (riffle) control, offset e is the physical cease-to-flow gauge height. For channel and floodplain controls though, the offset (e) only represents a conversion of stage to effective static pressure head, as it’s not a physical feature. Its value thus should increase with each successive channel or floodplain width expansion, as a lower head is required to grow the discharge to the same value given by the adjacent lower curve where their equations intercept.

Exponent m is a non-linear growth factor that depends mainly on channel width and shape, including bank side-slopes and curvature, and whether the flow is sub-critical (e.g. channel flow) or super-critical (e.g. spillway flow). In the U.S. the exponent m is usually >2 for section (riffle) control, and <2 for channel (i.e. flood-flow) control, according to Kennedy (1984). However, Queensland channel control exponents can be >2 (e.g. 2.17 for the large parabolic Walla channel).

3. Rating Curve Plots

3a. Evaluation of rating curves using plotted gaugings

It is common practice in all three countries to plot gaugings with an overlaid rating curve(s) to visually evaluate the curve fit. The choice of plotting method can influence the interpretation of the stage-discharge relation.

All three countries plot stage on the vertical ordinate (y) axis and discharge on the horizontal abscissa (x) axis, which is against the mathematical convention of having the dependent variable on the vertical ordinate (y) axis. In some other regions of the world discharge is plotted on the ordinate axis, but the rationale for this choice in Canada, the U.S.A, and Australia is not explicitly known.

It seems likely though that it was done to better visualise stage as a variable that goes up and down rather than sideways, although it may have been to better fit plots on conventional plotting paper, so that the variable with the greatest range is on the long axis. Stuart Hamilton speculates that — in a physical sense — discharge really should be the independent (x) variable anyway because when there is a change in control conditions, it is stage that is responsive to the change (i.e. changing the control has no effect on the catchment-scale processes generating discharge).

3b. Arithmetic plots

Arithmetic scale plotting on paper was historically widely preferred in all three countries, but now log-log plots are mostly preferred.

The arithmetic scale has a significant advantage for manual plotting in that it is easy to visually interpret precise plotting positions and deviations. French curve templates of varying radii, suitable for most parabolas, are used to manually fit curve segments through the plotted gaugings.

3c. Log-log plots

Log-log scale plots are widely used in the three countries. They have a significant advantage for curve fitting in that when the optimal rating height offset (e in the shifted power-law equation) is subtracted from the gauge height, then the rating will plot as a straight line.

This requires that the offset be known at the outset of any manual plotting process. However, usually the optimal offset isn't explicitly known a priori, or the offset may change over time, or there might be multiple controls (e.g. section, channel, over-bank), each with a unique offset. In these cases the advantage of manual log-log plotting for linearisation of the rating is defeated by the choice of a single chart-scale offset.

An unfortunate consequence of the logarithmic scale is that zero and negative numbers are undefined. This means that it is impossible to directly plot the cease-to-flow point or gaugings below the height offset level.

To overcome these difficulties both the WSC and USGS in North America have adopted the use of a graphical rating editor for curve fitting (see Figure 9, below). On-screen plotting allows for the use of up to three height offsets per rating curve (notionally section, channel and over-bank curve segments), with the choice of adding zero, one, two, or all height offsets to the plot scaling. The user is able to incrementally 'fine-tune' the height offset to linearise a desired segment.

The rating editor allows a compound rating curve to be created that has a lower linear segment for intersection with the point of zero flow, but has upper power-law segments for fitting through the gaugings. This allows any zero and negative heights to be plotted. Widespread adoption of this rating editor has all but eliminated the use of paper curve plots.

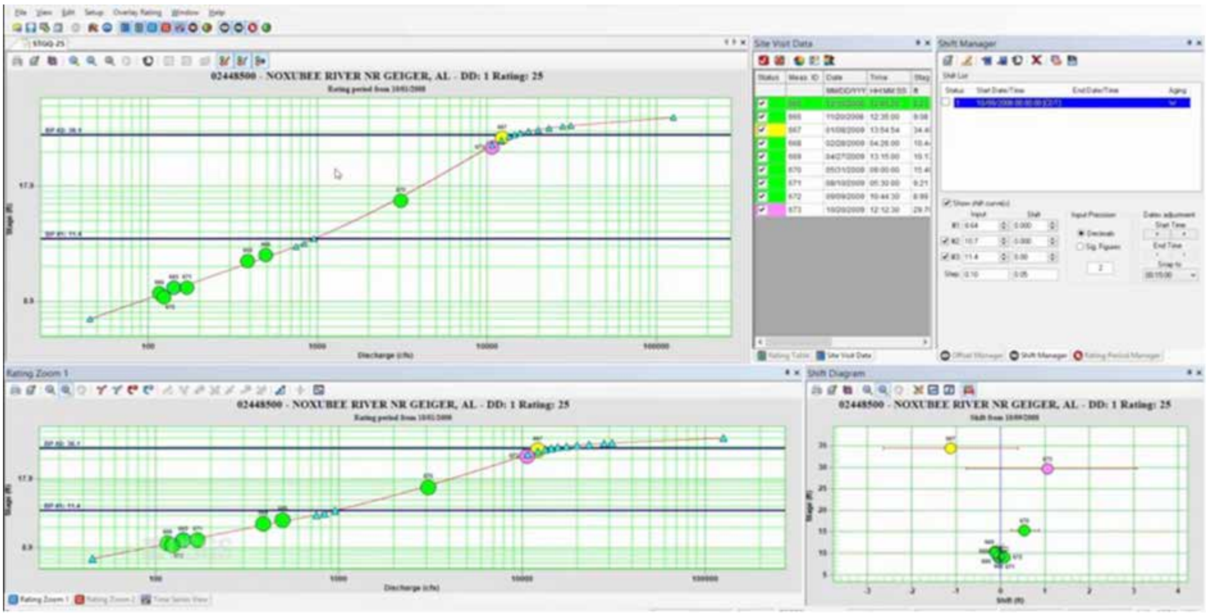

Figure 9. USGS and WSC rating editor.

Queensland practice is to plot all or most rating curves on one or more large paper log-log sheet(s), which almost always necessitates using a sub-optimal height offset. For unstable gravel riffles or sandy beds, the lowest curve in the family might typically only start at a plot height (GH – e) of about 0.10-0.15 m, to leave room to subsequently draw some lower curves.

If subsequent scour is enough that a lower height offset has to be used, a new paper plot sheet is used. The changed offset also has the usually-unrecognised but undesirable side-effect of slightly changing the interpolation of the upper rating curves between the fixed rating points.

3d. GH-$Q^{0.4}$ plots

West Australian hydrographer Brian Chester (1986) proposed a novel approach for overcoming the difficulties with log-log plotting of ratings. Among the advantages of these plots are the linear height scale, the ability to directly plot cease-to-flow levels, and the easy inclusion of gaugings below the offset level when fitting trendlines.

The GH-$Q^{0.4}$ plots are an option in the most popular Australian rating system. A similar derivative of GH-$Q^{0.5}$ proposed by Fenton (2001) and Fenton & Keller (2001) has had little if any operational use, but better suits the channel control of flood rating segments.

3e. GH-$Q^{1/m}$ plots

GH-$Q^{1/m}$ plots are a more flexible variant of the previous fixed Q-exponent plots, and were originally briefly mentioned by Kolupaila (1963) in his discussion of a paper by Sittner (1963).

Their Queensland reincarnation in a spreadsheet occurred in October 2007, and has been described by Maynard (2007, 2014, 2016a). Trendlines are only fitted within hydraulically-identified rating segments, and the exponent 1/m is manually optimised by tweaking its value in a single spreadsheet cell. The optimal linear trendline fit is determined mainly by maximising the coefficient of determination R^2, but the goodness of fit is also visually assessed on the gauging plot.

The parameters of the shifted power-law rating equation are calculated from the trendline equation.

The height offset (e) is easily recognisable as the trendline intercept value, but the coefficient (a) has to be calculated from the trendline coefficient and the optimised exponent.

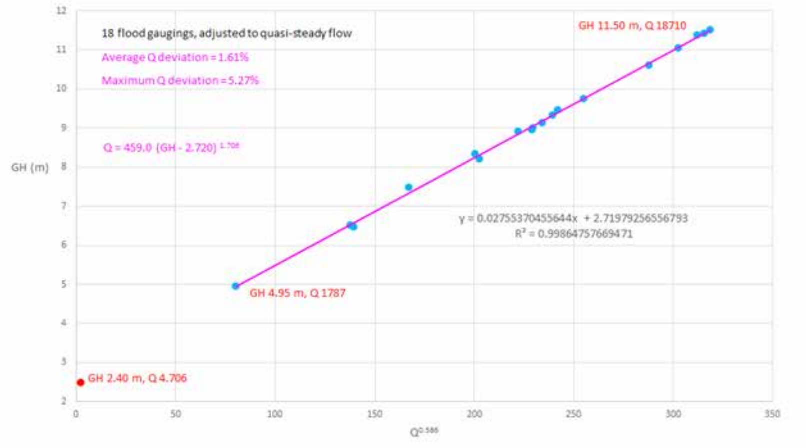

Figure 10. GH-$Q^{1/m}$ plot of the high-flow rating curve for the main channel of the Burdekin River at Home Hill.

The exponent 1/m is the inverse of the exponent in the shifted power-law rating equation, so the trendlines are properly hydraulically founded, and are thus much easier to extrapolate & interpolate across large spans between gaugings.

4. Rating Curves

4a. Rating segments

U.S. rating curves are often comprised of three segments, each associated with a unique hydraulic control and joined by relatively short transition curves, according to Kennedy (1984):

1. Low-water (section control)
2. Medium-water (channel control)
3. High-water (overbank control)

Some Queensland rating curves for high-rainfall streams also have those three segments. However, some other lower-rainfall coastal and sub-coastal streams have more complex channels, some with relatively-large medium-flow channels embedded within very large high-flow main channels. These streams tend to have low runoff for long periods, but sporadically have extremely high run off after torrential rain from tropical cyclones or tropical lows (e.g. up to 1372 mm in 72 hrs in the often-dry Burnett catchment).

Many Queensland streams thus need rating curves with four or more segments, typically:
1. Low-flow (riffle)
2. Medium-flow (embedded channel)
3. High-flow (main channel)
4. Floodplain flow

Cross sections surveyed in gauge height datum at the gaugeline and at the low-water control provide information that can readily be used in the development of rating curves, particularly the gauge heights where hydraulic control transitions occur. These gauge heights, together with gaugings and related hydraulic control observations assist in developing physically accurate stage-discharge relations.

4b. Rating curve transitions

The USGS pays careful attention to rating curve transitions between rating segments, such as when a weir or rockbar drowns out, or when over-bank flow starts. This is a manual process, especially important when there is a change in offset, where they limit the decrease in difference in discharge per 0.1 ft (0.03 m) of stage to less than 3%.

The WSC policy is to use 3 to 5 rating points within the transition range to smoothly join consecutive rating segments, while fitting any gaugings in the transition zone (Rainville, 2016).

Australian hydrographers mostly don’t put that much effort into smoothing the transitions. However, some manually add one or more rating points to smooth-out sharp bumps at curve intersections, especially in the drownout zone for weir spillways. In the absence of sufficient gaugings though, it’s sometimes difficult to know exactly where to position the transition curve, although the start and end points for channel-control transitions are often easy to discern from cross section plots.

Most Qld rating transitions could be reasonably defined just by adding one more rating curve segment. However, large floodplains that often initially have lateral water level slopes need two transition segments, the first effectively convex-upwards, but the second concave upwards as it becomes asymptotic to the floodplain rating when the water finally levels out across the floodplain.

4c. Rating curve families

Australian hydrographers use families of rating curves. Rating curve changes are normally made at the peaks of floods higher than the convergence height(s) of the low-flow curves, when the low flow hydraulic control has notionally been drowned out by backwater from the downstream channel. Where there is a rating curve change during a period with lower or even no freshes (e.g. from weed growth), the rating is pro-rated with time from one curve to the next, locally called a phased rating change.

Unfortunately, most gauging stations have numerous rating curves, so it's a tedious job to update all their top end rating points after flood rating changes. It would be so much simpler if low-flow rating curves could be linked to only one or at most a few flood-flow curves! Alternatively, a single historic base rating curve could be modified by shift ratings, thus replacing the multiple curves and their associated overheads.

Queensland doesn't have a policy on rating curve spacing. One rule-of-thumb is that low-flow curves should be spaced no closer than 0.01 m, and 0.02 m might be justifiable. It was determined by assuming that gauging uncertainty can be represented by an elliptical 95 percentile bound with uncertainty in both dimensions (e.g. H ±0.007 m, Q ±7%). If the rating curves spacing was such that at worst they just touched the ellipse, then the curve spacing ΔH should be >0.014 m and ΔQ should be >14%.

Queensland policy is that gauging discharge deviations from rating curves should be <10% for unstable controls, but <5% for stable controls. Unfortunately, their rating system only reports discharge percentage errors, although practical hydrographers realise that for low flows the gauging height errors are actually the more important.

Another rule-of-thumb is that for heads of <0.25 m at a riffle, rating curve spacing should be controlled by height errors, rather than by the specified discharge errors. It was determined by differentiating rating curves and calculating ΔH & ΔQ errors for different water heads. As an example, for a head of 0.05 m at Dakiel, a 10% Q increase equates to only a 0.002 m H increase, according to Maynard (2015b).

4d. Rating curve shifts

North American hydrographers use rating curve shifts whenever gaugings indicate only a temporary change to the stage discharge relation, such as minor scour or the presence of algae on a section control. An adjustment defined by a shift curve is made to effectively shift gauge height data during flow rating calculations, so it can be rated by the active base rating curve. A shift curve is defined by up to three shift points that each consist of a stage value and a shift value. The shift value is simply the stage adjustment needed to effectively adjust a gauging or logger height onto the existing base rating curve, at specified gage heights.

Shift curves typically merge back into the existing rating curve at a gauge height associated with a transition from one hydraulic control to another, thus also at transitions between rating curve segments. Thus, a shift curve is analogous to a one-off temporary rating curve that shares portions of the stage discharge relation with the active base rating curve.

Shift curves can be abrupt to accommodate a sudden change such as debris catching on the control, or gradual to allow the existing rating curve and defined shift curve to prorate between each other. Proration can be between any rating curves, whether base rating curves or temporary rating curves defined by shifts, and allows the stage discharge relation to be applied dynamically over a hydrologic event that is interpreted to have caused the change to the existing relation. During such a proration, the stage discharge relation is effectively changing with every time step.

Two-point and three-point shift curves are often described as varying by both stage and time, whereas single-point shift curves can only vary with time. The choices amongst these behaviours give the hydrographer the ability to represent the hydraulic changes to a control due to ongoing hydraulic processes. As indicated above, shifts are used to handle temporary changes to the stage discharge relation. When a more permanent change or an extensive change to the stage discharge relation is identified, based upon a number of gaugings, a new base rating curve is developed. Shift curves can also be used to transition from one rating curve to another.

Australian hydrographers don't use shift ratings to our knowledge, even though support for them is built into their most popular rating system, but a few Qld hydrographers like the concept. Shift ratings can make the rating process quicker and more flexible compared to using discrete rating curves. There would be a short learning curve to adjust to the concept and understand when shifting is advantageous over creating a new rating curve.

5. Rating Curve Extrapolation Methods

5a. Manning resistance equation

Hydrographers on both continents favour the Manning resistance equation for rating extrapolation calculations:

$$Q = \frac{1}{n} AR^{2/3} S^{1/2}$$

The Manning equation is also used in the 1-D and 2-D hydraulic models that have sometimes been used on both continents to extrapolate rating curves. USGS 1-D step backwater methods were detailed by Bailey and Ray (1966) and Shearman (1976), and 2-D methods were mentioned by Kenney and Freeman (2011). Some West Australian 1-D rating extrapolations have been documented by Doherty (2010) and Harris and Bowyer (2010), and Queensland modelling has been documented in various departmental and consultant reports.

5b. Manning's n resistance factors

All hydraulic models, whether simple or complex, have a large and common problem —Manning's n is usually the largest source of uncertainty unless the model is well-calibrated to flood gaugings! Estimating Manning's n resistance factors is an art on both continents, but has been assisted by photographic guides to Manning's n in the U.S. by Barnes (1967), in New Zealand by Hicks and Mason (1998), and in Victoria by Ladson *et al*. (2013).

Attempts to make it more of a science have seen the development in the U.S. of various simplified slope-area equations, from Riggs (1976), Dingman and Sharma (1997), Bjerklie *et al*. (2003, 2005), and Dingman (2007). A study by Lopez *et al*. (2007) used a larger dataset, and also conveniently listed the earlier equations.

Queensland tests of many of those equations after the large 2011 floods gave Manning's n values that were seemingly too low, presumably because of vegetation on both the beds and banks of channels.

Queensland flood gaugings indicate that Manning's n values often initially reduce substantially with increasing discharge, as fringing Bottlebrush etc. drowns out and stream power increases.

However, many 2-D flood modellers use fixed Manning's n values for convenience, often without calibration to flood gaugings. The n values for 2-D models should be lower than for other models because 2-D models internally calculate bend losses, which can be quite significant in large high-velocity floods (e.g. Burnett River).

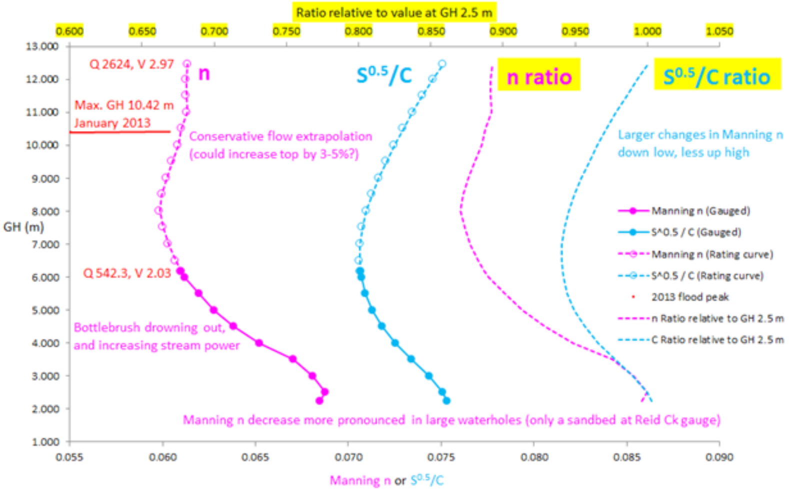

Figure 11. Resistance changes due to vegetation in the sand-bed channel at Reid Creek at Mungy.

5c. $\sum ad^{1/2}$ method

Some Australian hydrographers extrapolate rating curves using the $\sum ad^{1/2}$ integrated conductance method proposed by Chester (1979, 1986, 2007), as it is an option in the Hydstra rating system:

$$Q = C \cdot \sum ad^{1/2}$$

The $\sum ad^{1/2}$ term is calculated by an integration of the local area (a) and the local hydraulic depth (d) effects across a cross section, which implicitly assumes that at each vertical the local mean velocity is proportional to $d^{1/2}$.

The method is well suited to analysing super-critical flow over dam and weir spillways, especially if their crests are uneven, but isn't as well suited to sub-critical flood flows. For free-flow over spillways, the value of the coefficient C should be roughly similar to that for a rectangular horizontal spillway, about 1.705, usually increasing with increasing spillway head.

5d. $\sum ad^{2/3}$ method

The $\sum ad^{2/3}$ method was in essence originally proposed by Dolega (1959, 1962), who integrated across the channel width the $d^{1.7}$ term from the Matekiewicz equation, according to Kolupaila (1963). The near-identical $\sum ad^{2/3}$ method is effectively an Australian sub-critical flow derivative of the $\sum ad^{1/2}$ integrated conductance method, but has only been sparingly and independently used in Western Australia and Queensland, as it is not an option in the Hydstra rating system:

$$Q = C \cdot \sum ad^{2/3}$$

The $d^{2/3}$ velocity proxy term implies that there's a 1/6 exponent point-velocity profile at each vertical. West Australian hydrographer Brian Chester started using $\sum ad^{2/3}$ sometime in the 1990s according to Russell Marks (email to Ray Maynard, 20/04/2016). The $\sum ad^{2/3}$ method was later incorporated into Chester's prototype rating program, for the channel control range, according to Brian Chester (email to Ray Maynard, 30/03/2006). Brian Chester also mentioned the earlier Dolega variant.

This method is well suited to analysing sub-critical flow in open channels, and allows easy bridging across multiple rating segments and their intervening transitions. The value of coefficient C should be roughly similar to but not identical to the Manning $S^{1/2}/n$ term value.

5e. Mean velocity method

Plots of gauge height versus mean velocity were one of the traditional rating extrapolation and validation methods in all three countries. Although simple, they remain an effective tool for experienced hydrographers, even if only to confirm that a more sophisticated rating extrapolation gives mean velocities that intuitively seem about right.

When channels have a width expansion at a rating segment transition, the mean velocity should reduce somewhat compared to its previous trend. Above the transition, it should resume its steady monotonic increase, but with lower mean velocity values than the previous trend.

Mean velocity is a useful indicator because it has such a relatively narrow range at a site compared to the other hydraulic parameters such as depth, width, area, and discharge. Similarly, bankfull mean velocity is often relatively invariant within some Australian drainage basins, even though the bankfull depths may typically increase markedly in a downstream direction.

5f. ADVMs – an emerging alternative to conventional rating extrapolation methods

The USGS and WSC use Acoustic Doppler Velocity Meter (ADVM) technology and Index-Velocity ratings almost exclusively for locations where the stage-discharge relation is non-unique due to unsteady flow or variable backwater effects. The most-complete current reference is the U.S. Geological Survey Techniques and Methods 3–A23 of Levesque and Oberg (2012). The USGS does not favour theoretical ADVM rating curves, so it has placed emphasis on advancing technologies that will potentially make measurement of extreme stream flows safer and easier.

Mark Randall of Qld DNRM's Mareeba office is also investigating the use of remote-controlled gauging boats for flood gaugings, and the possible use of flood video images taken from Unmanned Aerial Vehicles (UAV). The video could later by analysed by Large-Scale Particle Image Velocimetry (LSPIV) or Space-Time Image Velocimetry (STIV) techniques. Experts Jerome Le Coz of France and Ichiro Fujita of Japan will be running a training course on LSPIV in North Queensland in late-November 2016.

Most Australian ADVM usage thus far has been similar to that in North America. Victorian and NSW hydrographers use Index-Velocity ratings for all their ADVM sites. The Victorians tend to use uplooker ADVMs at temporary project sites, probably about 20 in all over the years. The NSW hydrographers operate a few ADVMs, both sidelookers and uplookers, in irrigation channels and a few regulated natural streams. Northern Territory hydrographers have operated some sidelooker ADVMs. Queensland DSITI uses Index-Velocity ratings for some near-coastal ADVMs it operates as part of the Great Barrier Reef Loads Program.

However, a chronic lack of high-flow gaugings at many remote Queensland sites has resulted in investigations into the use of ADVM data for extrapolating flood rating curves. Queensland DNRM operates 10 ADVMs solely to ascertain high-flow ratings.

There is a steep learning curve, as Qld has experienced many ADVM failures when operating them in both extreme floods and extreme heat and sunlight, especially when streams were dry. Northern Territory hydrographers were also frustrated by failures probably related to extreme heat and radiation.

Figure 12. ADVM on Wide Bay Creek at Brooyar knocked over by a record flood GH 13.35 m in January 2013).

A standardised method of rating Qld flood ADVM data has yet to be decided, but the preferred Index-Velocity rating method rating often will not be practicable, as it requires each site to be calibrated using simultaneous ADVM data and gaugings. From limited enquiries, it seems that the other Australian states haven’t tested theoretical ADVM ratings in natural channels. The View Argonaut program has been used to generate a theoretical channel ADVM rating curve for Queensland’s remote Cloncurry River at Canobie.

A deficiency though of simple theoretical ADVM rating curve extrapolation models is that they don’t take into account bank & vegetal effects, asymmetrical cross-stream velocity distributions caused by helical flow from upstream bends, or variations in point-velocity profiles in the vertical from the standard 1/6 power-law velocity profile. Further insights into local variations of the lumped hydraulic parameters might be gained if the large number of historic flood gaugings were properly analysed – Qld alone has 13791 gaugings over 30 cumecs. The ultimate theoretical ADVM rating model might be a 2-D hydraulic model of the local reach, with no 1-D approximations in the main channel, calibrated against measured ADVM point velocity patterns.

5g. Integrated-conductance ADVM rating curve extrapolation method

An Australian theoretical ADVM rating extrapolation approach was devised by Maynard (2015a), who for a range of desired water levels used the $\sum ad^{2/3}$ method to calculate the channel conductance, and a 1/6 power-law velocity profile to calculate theoretical point velocities vy at the centroid of each ADVM cell. The velocity profile exponent can easily be tweaked to other values via a single spreadsheet cell, and the model also includes a multiplier to notionally reduce the calculated conductance through thickly-vegetated stream banks (relative to open water = 1.00).

A test of the model on GS 134002A Oyster Creek gave a fairly constant theoretical $k_{ADVM\,V}$ multiplier, which multiplies a range-averaged ADVM velocity datapoint to give the calculated channel mean velocity datapoint.

Similarly the theoretical $k_{ADVM\,Q}$ multiplier multiplies a range-averaged ADVM velocity datapoint to give a calculated channel discharge datapoint.

It was extremely well fitted by only one shifted power-law rating equation segment over a height span of more than 6 m.

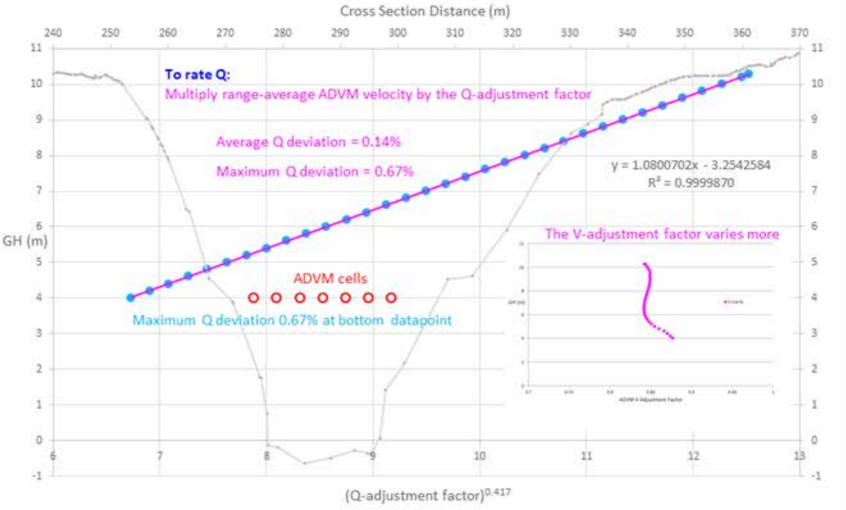

Figure 13. ADVM Integrated-conductance Q-adjustment multiplier plot for Oyster Creek.

[3] DSITI Queensland Department of Science, Technology and Innovation.

This surprisingly consistent behaviour was partly due to a fairly symmetrical cross-section shape. Another factor is that ADVMs only measure the fastest streamlines, so as flow increases the small additional edge areas have relatively lower velocities that retard the growth of the V-multiplier factor. When the cross-section widens a bit, the V-multiplier factor theoretically falls, but that's compensated for by an increase in area so the discharge just keeps increasing monotonically!

Conclusions

This comparison and contrast of rating development in three different countries provides a perspective on how diverse the practice of hydrometry can be, when at the end of the day everyone is dealing with water flowing downhill.

While all three countries base their rating methodology on the same rating equation, differences in interpretation of the equation has created divergence in approaches to solving rating problems. The main difference is the great limitation placed on Australian hydrographers by their rating system's use of only a single height offset (e) for each rating curve.

This deeply entrenched conceptual system difference unfortunately influences the interpretation of ratings and the solutions developed for fitting ratings. In North America a rating editor has been developed that allows for up to three different height offsets to be used to represent three different control regimes (notionally section, channel and over-bank).

As a result, when rating segments are developed in Australia using a sub-optimal choice of the height offset value, it tends to interact with the fitting of the exponent in the rating equation, resulting in rating equations that make no sense hydraulically (e.g. out-of-range exponent values).

In contrast, in North America careful attention is paid to the relationship between the hydraulic control, the observed condition of that control and the rating curve, to ensure that any change in the rating curve is physically reasonable (e.g. channel scour or fill events should result in a commensurate change in height offset value).

A graphical rating editor that uses multiple height offsets has resolved the problems inherent in conventional log-log plotting of ratings, while exploiting the inherent advantages of linearising ratings. Frustration with the conceptual constraint of a single height offset has resulted in a different Australian approach. The GH-$Q^{1/m}$ method has not yet been widely adopted, but addresses the problems inherent with conventional log-log plotting.

Another significant difference that was found is in the way that temporal changes of control conditions are handled. In Canada and the U.S.A. the three-point shift corrections have been found to be an efficient and effective way of dealing with transient or ephemeral influences on the control. In Australia temporary departures from an otherwise well-defined curve are handled with discrete rating curves, often necessitating new curves.

Recommendations

Supplemental information such as cross section surveys (for control features) and notes photos and sketches of control conditions should be a component of every monitoring plan. This 'soft data' — when used in conjunction with the 'hard data' of stage-discharge point data — supports defensible inference-making for determination of segment break-points, offset value(s), time-phase for curve transitions and curve extrapolations.

Rating curve editors should be extremely flexible and easily cater for the full range of individual hydrographer preferences, such as any combination of variables, any height range (e.g. for a rating segment), easily-tweaked height offsets or exponents, and any combination of plot x & y scaling. Suspect gaugings should be easily quarantined from analyses. Such an editor would make it easy for individuals to work using their preferences, but also to easily explore other options.

Rating table databases should allow the entry of a height offset for each rating segment, however many. They should also calculate and display all the parameters of the shifted power-law equations for each rating segment, to enhance hydrographer understanding of the underlying hydraulics.

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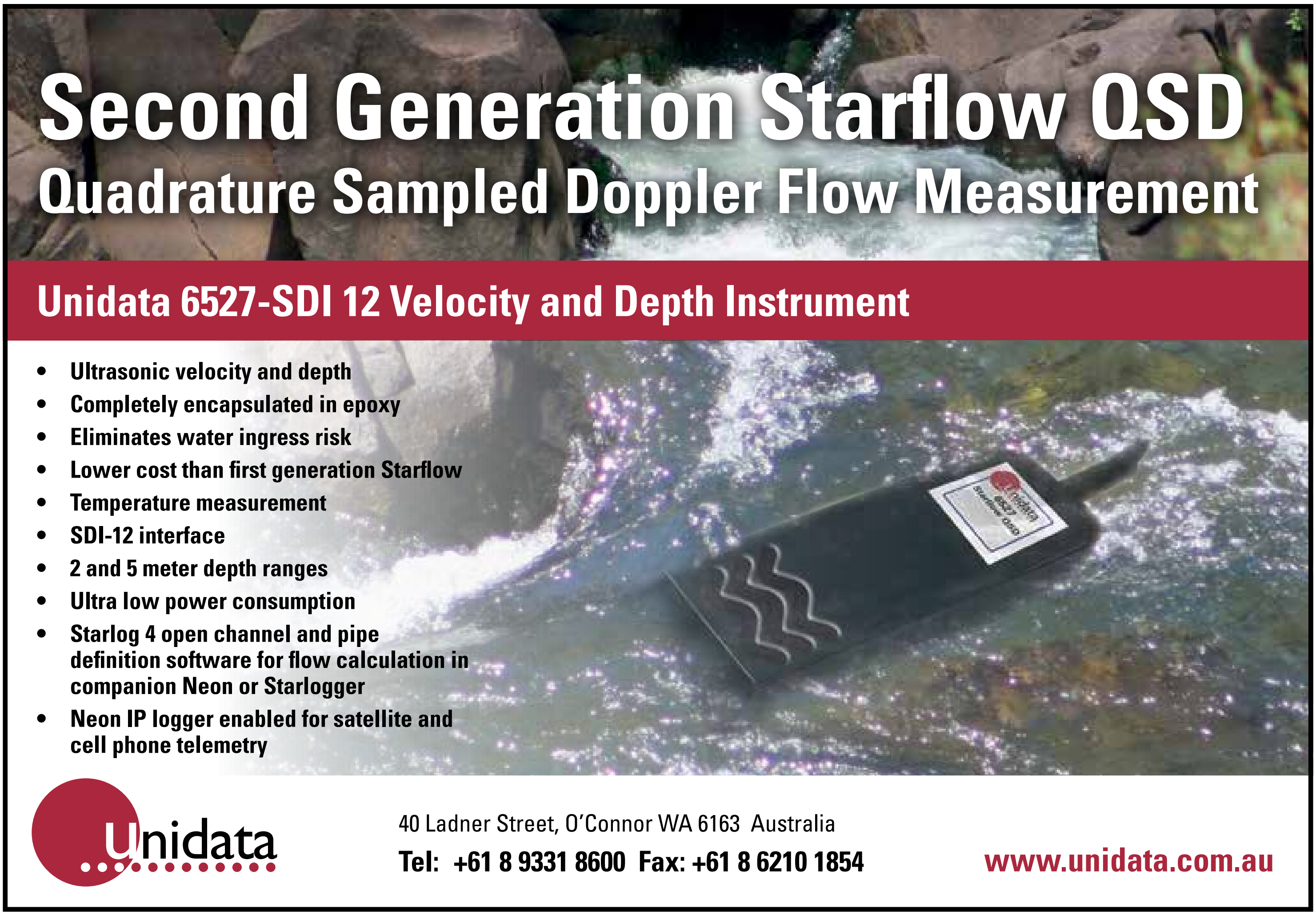

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Application of Hydrographic Data

Todd Lovell, Bureau of Meteorology, Canberra, ACT

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Abstract

The Bureau of Meteorology (the Bureau) is responsible for the compiling and disseminating comprehensive water information across Australia. The Bureau collects data from approximately 200 organisations with more than 15,000 raw files received per day from organisations named in the Water Regulations. This data is stored, collated and managed in the Bureau's systems and used to produce water information products and systems including:

- *Australian Groundwater Explorer;*
- *Australian Hydrological Geospatial Fabric (Geofabric);*
- *Australian Water Resources Assessment Modelling System;*
- *Flood Forecasting and Warning Service;*
- *Groundwater Dependent Ecosystems Atlas;*
- *Hydrologic Reference Stations;*
- *Intensity–Frequency–Duration Design Rainfalls;*
- *Monthly Water Data;*
- *National Ground Water Information Systems;*
- *National Water Account;*
- *Seasonal Streamflow Forecasting Service;*
- *Water Data Online;*
- *Water in Australia;*
- *Water Market Information Portal;*
- *Water Restrictions; and*
- *Water Storages.*

This paper will investigate the use of hydrometric data at the national level exploring the publication of the data through value added products and examine how this data is utilised by stakeholders. One example that will be discussed is how water managers and key water users use seasonal stream flow forecasts to improve their water management and decision making capability.

Introduction

The Improving Water Information Program was designed to enhance the quality of water information in Australia. The program provided for the collection, collation, analysis and dissemination of information about Australia's water resources (Bureau of Meteorology, 2017). The Water Act (Cwlth) and associated Regulations came into effect on the 30th of June 2008. The Bureau of Meteorology (the Bureau) was given responsibility for administrating the Improving Water Information Program. The program funding was used to support the Bureau in the collection and harmonisation of water data from approximately 200 organisations named in the regulations and to produce new water-related products and improved forecasting services. The program was initially funded for 10 years until the 30th of June 2017. The Bureau is in the process of putting in a new bid to the government so funding for the program can continue after this date. To fulfil its requirements under the Act, the Bureau is dependent on the provision of hydrographic data collected by state and territory agencies, local government and their contractors. Under the 10 year program the Bureau has released a range of new water information products and services. This paper will discuss the application of hydrographic data in some of those products and discuss how hydrographic data is being produced and utilised by a number of disparate stakeholders.

Data Collection and Harmonisation

The Bureau faced a significant challenge to fulfil its objective of compiling and disseminating comprehensive water information across Australia (Commonwealth of Australia, 2017), the data had to be translated from a large number of sources and formats. In the program's early years the Bureau focused on developing consistent definitions, data formats and processes to ensure water information could be comparable across the country (Bureau of Meteorology, 2015b). There are more than 200 organisations involved in the collection and reporting of water information. These organisations collect data for their own business needs. It has been difficult historically to get a national picture of the water situation at any point in time. Hydrological data has not been easily discoverable or accessible. This has made it difficult to utilise the data for analytical and reporting purposes other than those intended by the collecting agency (Vertessy, 2013).

To meet the challenge the Bureau and the Commonwealth Scientific and Industrial Research Organisation (CSIRO) jointly developed the Water Data Transfer Format (WDTF) — a national standard for the representation and transfer of water data. The ability to deliver data to the Bureau in a standard format improved water data management nationally (Walker, et al., 2009). The Bureau receives approximately 15,000 new data files every day. These time series files cover 105 parameters and 10 categories from thousands of hydrologic monitoring sites across Australia. The WDTF is used to deliver more than 80 per cent of all water data to the Bureau, with around 100 organisations providing data in the latest version (Bureau of Meteorology, 2015b). Delivery of data in the WDTF has been a key factor in the Bureau's ability to ingest and interpret information from the multitude of different sources, and to present a nationally consistent dataset (Johnston, 2014). Nationally consistent information is one of the key achievements identified under the Water Program by information stakeholders in a survey conducted in December 2015 (Bureau of Meteorology, 2016a).

Application of Hydrographic Data in Bureau Products and Services

The Commonwealth Government's core vision for the Improving Water Information Program was that water information gathered by the Bureau would be delivered back to stakeholders as "services" to meet their needs in areas such as: infrastructure design and planning; policy advice; emergency management; education and research; flood mitigation; water supply forecasting; and river management and environmental flows (Bureau of Meteorology, 2015b). The general public would also benefit by having access to better and more timely water information, delivered via reliable and enduring services from a trusted and authoritative source (Vertessy, 2013).

The Bureau has developed a range of water information products and services. The information products give greater visibility of the status of surface water, ground water and alternative water sources around the country.

Some of these products include:

1. Australian Groundwater Explorer.
2. Australian Hydrological Geospatial Fabric (Geofabric).
3. Australian Water Resources Assessment Modelling System.
4. Flood Forecasting and Warning Service.
5. Groundwater Dependent Ecosystems Atlas.
6. Hydrologic Reference Stations.
7. Intensity–Frequency–Duration Design Rainfalls.
8. Monthly Water Data.
9. National Ground Water Information Systems.
10. National Water Account.
11. Seasonal Streamflow Forecasting Service.
12. Water Data Online.
13. Water in Australia.
14. Water Market Information Portal.
15. Water Restrictions.
16. Water Storage.

Some Examples of the Application of Hydrographic Data in Products

Water Data Online

Overview

Water Data Online provides free access to nationally consistent current and historical water information. It allows users to view and download standardised data and reports from 3,500 water monitoring stations from around Australia. More stations and additional parameters to will be added soon (Bureau of Meteorology, 2015d). The system provides a single point of access to the most extensive streamflow dataset for Australia combining historical and recent monitoring information (Bureau of Meteorology, 2015b). The time period over which data is available varies according to how long the stations have been operating. The period of record for some locations starts in the late 19th century.

Benefit

This is the first time that current and historical water monitoring data from across Australia is available from a single website. Water monitoring data is a critical input into the analysis, reporting, modelling and forecasting tools used by water managers, policymakers, researchers and industry professionals. Information about watercourse levels and discharge are used to monitor water use and environmental conditions over time, improving the understanding and management of our valuable water resources (Bureau of Meteorology, 2015e).

Examples of a stakeholders using Water Data Online

JBA Risk Management, a consultancy company, uses daily watercourse discharge data for the purpose of calibrating rainfall-runoff models for commercial purposes. They have clients in the insurance and property industries and the data is used to manage natural peril risk.

Researchers at the University of Queensland use the watercourse discharge data for a project on bird distribution across the Australian continent in relation to wetlands and the hydrological characteristics of landscapes.

National Water Account

Overview

The National Water Account provides a detailed insight into the management of Australia’s water resources at the national and regional scale. It is Australia’s most comprehensive water information report, disclosing information about water stores and flows, water rights and water use. It reports on the volumes of water traded, extracted and managed for economic, social, cultural and environmental benefit (Bureau of Meteorology, NWAA). The National Water Account provides information that has previously been difficult to access or has been unavailable to general users. The Bureau acknowledges the many partners who directly contribute to the production of the National Water Account. The Committee’s membership includes representatives from each State and Territory’s lead water agency, urban and rural peak industry bodies and Australian Government agencies (Bureau of Meteorology, NWAC).

Benefit

The National Water Account informs policy, planning and decision-making by governments and industry by providing detailed insight into the management of Australia’s water resources at a national and regional level (Vertessy, 2013). The data is presented in a standardised form and highlights gaps and inconsistencies, allowing improvements to be made to our national water information base (Bureau of Meteorology, NWAA). The account provides a set of water accounting reports for ten nationally significant water resource management regions: Adelaide, Burdekin, Canberra, Daly, Melbourne, Murray–Darling Basin, Ord, Perth, South East Queensland and Sydney. The national overview highlights broad trends and findings across the ten National Water Account regions (Bureau of Meteorology, 2015c). Water accounting is a relatively new concept in water resources management, and Australia is leading the world in this discipline (Bureau of Meteorology, NWAA).

Example of a stakeholder using the National Water Account

The National Sustainability Council’s Sustainable Australia Report highlights trends in Australia and the world that are set to have a significant impact on the next generation of Australians. The Council used the closing Net Water Asset and Water Use information from the National Water Account as an indicator of sustainability. The National Water Account’s standardised approach to reporting across regions meant that the information could be used to draw comparisons of the adequacy of water availability to meet demand across the country. One question addressed in the report is whether there is enough water available in regions of Australia to meet demand. The council argued that water storage levels are only part of the picture and the more complete story is found by tracking water allocation and use within a region as provided by the National Water Account (Bureau of Meteorology, 2014).

Hydrologic Reference Stations

Overview

The Hydrologic Reference Stations provides access to a wealth of information for 222 high quality streamflow data series. These sites were selected on the basis that they had 30 years or more years of record, are regularly rated, affected by minimal river regulation and have had little land use change or other factors that influence the hydrological data quality. These stations are highly regarded by stakeholders for assessing long-term variability and trend (Turner, et al., 2015).

Benefit

The data at these sites assist in detecting long-term variability in streamflow and can be used for a number of purposes including: planning the location of new storages; researching the impact of different climate stressors on water resources; developing irrigation areas; sharing water between basins; developing new hydrologic tools and models; and identifying the need for new sources of water. The Hydrologic Reference Stations are available via a public web portal. Typical users include national and international research communities, government agencies, water managers and utilities (Bureau of Meteorology, HRS).

Example of a stakeholder using the Hydrologic Reference Stations

One example of a stakeholder using the Hydrological Reference stations was Mark Thyer, Director of Research School of Civil Environmental and Mining Engineering University of Adelaide. He used the Hydrologic Reference Stations to determine long-term streamflow trends, revealing some distinct patterns around the country. His findings were that since 1975, in general flows are decreasing in southern Australia but increasing in the northern tropics. More specifically, moderate to low flows are more likely to show an increasing trend in the north, while moderate to high flows are decreasing in the south. He commented that the dataset was a vital resource for undertaking high quality hydrological research. The research team plan to use the dataset in honours, PhD and postdoctoral research projects that undertake hydrological modelling. Such research will improve understanding of the Australian hydrological regime and the ability to predict future droughts and floods, ultimately leading to better use of Australia's limited water resources. This dataset forms an important legacy that will enable significant advances in our ability to understand, predict and manage Australia's water resources (Bureau of Meteorology, 2015b).

Intensity–Frequency–Duration Design Rainfalls

Overview

Design rainfalls are based on the statistical analysis of historical rainfall data to determine the design rainfall depth (mm) or design intensity (mm/hr) corresponding to selected durations and frequencies (Bureau of Meteorology, 2010). In mid-2013 the Bureau released updated design rainfall estimates for frequent and infrequent rainfall events, known as Intensity-Frequency-Duration design. The previous Intensity-Frequency-Duration designs were primarily based on Bureau collected data, the new design rainfalls are based on the Bureau's rainfall database along with data from rainfall recording networks operated by the many urban water utilities across the country, such as Melbourne Water and Water NSW. In addition to 30 years of extra rainfall data an additional 2300 rainfall stations were used. The new design rainfall estimates also use contemporary statistical analysis and techniques to provide more accurate estimates for Australia (Bureau of Meteorology, IFD).

Benefit

The Intensity-Frequency-Duration Design Rainfalls are used primarily by engineers, hydrologists and planners but are also of interest to the insurance industry, emergency management personnel, and the general public. They are used by engineers in the design of infrastructure—such as gutters, culverts, stormwater drains, flood mitigation levees and retarding basins—to determine the flood capacity and water level to meet the required levels of safety such as a 100 year flood (Bureau of Meteorology, 2015d). Design rainfall estimates are a vital tool in every engineer's toolkit. The design rainfall estimates have been developed at either end of the spectrum of rainfall frequencies with estimates for very frequent rainfall events like those likely to occur between 2 and 12 times every year for water-sensitive urban design and rare rainfall events statistically likely to occur less than once every 100 years used for designing bridges and assessing the adequacy of dam spillways (Bureau of Meteorology, 2015b).


Email collected data using a mobile phone as a hotspot wireless device
Or
CMCbt
Or
CMCsp
Wireless Bluetooth
HydroTab
Or
PVD100
Or
PVD200 or MAG
Mechanical Current Meter

Example of a stakeholder using Intensity–Frequency–Duration Design Rainfalls
In the Rowallan Dam Upgrade project (by Hydro Tasmania), the Bureau was engaged to provide a special service on extreme rainfall forecasts and to give detailed briefings to develop an understanding of potential major rain events. This provided the principal engineer with confidence that flood risk could be managed through the construction, including the excavation of two portions of the dam right down to bedrock (Bureau of Meteorology, 2015b).

Seasonal Streamflow Forecasting Service

Overview
Each month, the Bureau produces forecasts for the likely streamflow volumes for the next three months. The forecasts are based on probabilities, for example the likelihood or chance of a given volume of water flowing into a stream, based on the recent climate and catchment conditions. The service delivers forecasts via a public website for 147 locations covering every state and territory around the country, with a further 87 locations available to registered users (Bureau of Meteorology, 2016b). The service applies a statistical approach, using the relationship between climate indicators, past catchment conditions and historical rainfall and streamflow at a location to forecast its total streamflow volume for the following three-month period (Bureau of Meteorology, 2016b).

Benefit
The forecasts provide an estimate of seasonal flow volumes and provide users with more certainty in their decision making. They are available to everyone via the Bureau's web page. The forecasts support Irrigators, farmers and local government and recreational users around water allocation, cropping strategies, water storage operations, irrigation scheduling, risk management, environmental watering and the potential for flooding (Bureau of Meteorology, 2016b)(19).

Examples of stakeholders using the Seasonal Streamflow forecast
Melbourne Water is the wholesale supplier of Melbourne's drinking water responsible for managing the catchments, treating water and transferring it to water retailers, who then distribute it to users. Melbourne Water uses the Bureau's Seasonal Streamflow Forecasts to guide water supply planning and operations and to manage environmental water resources. They also use it as an input to develop the annual 'Water Outlook for Melbourne', which guides water security management and drought-response planning.

The Bureau and Melbourne Water work together to deliver forecasts at the five major inflow locations in the Melbourne water supply network. By the third day of each month, Melbourne Water provides net inflow data from the previous month at each location. The Bureau feeds the inflow data into its forecast model and issues a seasonal forecast for each location. The Bureau also provides additional information to demonstrate how often a forecast matches observed streamflow, giving Melbourne Water and other industry users valuable guidance on forecast performance at different times of the year (Bureau of Meteorology, 2015b).

In spring 2010, ACTEW Water was considering whether water storage levels had increased enough to remove temporary water restrictions before summer. However, due to the large variability in historical climate data, a small but significant number of scenarios indicated that water storages would remain below the level needed to keep restrictions in place during the summer of 2010–11. To assist ACTEW Water, the Bureau converted some experimental seasonal streamflow forecasts into water storage forecasts and overlaid them onto the historic reference period. The new forecast was less variable than the historical reference period. Importantly, the forecast storage outcomes showed a high chance of increased water storage which provided ACTEW with the confidence to remove temporary water restrictions in October 2010 (Bureau of Meteorology, 2013).

7-day Streamflow forecasting service

Overview
The 7-day streamflow forecasts cover more than 100 sites around Australia combining near real-time rainfall and streamflow observations with rainfall forecasts. Calculations are carried out to determine how much runoff and flow is likely to be added to the down the stream network. A forecast is generated for each of the next seven days (Bureau of Meteorology, 2016b). These forecasts indicate whether rivers are likely to rise or fall in the coming week.

Benefit
The 7-day forecast can be used to: reduce water wastage in managed irrigation systems when natural flows are expected; support on-farm water management decisions; and support recreational users planning water-based activities such as camping, fishing, and boating (Bureau of Meteorology, 2015a). A more advanced service is available for registered users, providing hourly forecasts out to seven days to help dam and river operators plan water releases around expected rainfall.

One example of stakeholders using the 7-day Seasonal Streamflow forecast
River operators at the Murray Darling Basin Authority manage the River Murray System including water releases from Hume Reservoir in the upper reaches of the Murray. The water runs into Lake Mulwala, which supplies major irrigation districts in northern Victoria and southern New South Wales. Flows continuing downstream of Lake Mulwala are managed to meet many other uses, including supporting the riverine environment at sites such as the Barmah–Millewa Forest and along the length of river to the Murray mouth in South Australia. River operators must take account of natural inflows from tributaries of the Murray such as the Kiewa and Ovens rivers in northern Victoria. This is where the 7-day streamflow forecasting service is of great benefit. Having the 7-day forecast allows the operators to more accurately estimate what the natural inflows would be. This means they can better meet the Lake Mulwala objectives with more precise decisions on how much to release upstream. They can also plan for releases in conjunction with natural flows to improve environmental outcomes downstream (Bureau of Meteorology, 2015b).

Water Storage Data

Overview
The Water Storage website and iPhone app contain daily time series level and volume information on more than 300 major storages across Australia (Bureau of Meteorology, 2015b). The data is received from 28 data providers. The storages included on the site account for over 96% of the capacity of Australia's public water storages (Vertessy, 2013). In a recent Water Information Program stakeholders survey 82% of respondents stated that they used the Water Storage product (Bureau of Meteorology, 2016a). There were almost 300 000 unique visits to the website in 2015.

Benefit
One of the biggest users of the Water Storages website is the general community. The information it provides regarding where reservoirs are located, water storage volumes and trends over time increases the public's awareness of water resources in their local area and across the nation. It assists in fostering a transparent and open relationship between the government and the community and facilitates co-operation when behavioural changes are required to enable water management measures—such as water restrictions or rebate and incentive schemes. The information provided also helps the community to understand the requirement for some major infrastructure investment decisions (Bureau of Meteorology, 2015d).

One example of stakeholders using Water Storage Data
The Department of Agriculture use water storage data across the nation as a key descriptor of seasonal conditions and water availability for the Australian water market report (Aither Pty Ltd, 2015). They present the data and discuss the trends for all of Australia and for specific areas of interest. The latest report discusses how Australian storage volumes declined by 11 per cent relative to the previous year and the overall trend has been declining since the flood events of 2011 and 2012.

Summary

Under the National Water Initiative the Bureau is receiving hydrographic data from a large number of sources across the country. Since the beginning of the Water Information Program, the Bureau has been progressively improving its products and services. Although data collected by organisations and hydrographers is primarily to meet their own specific business needs. The data sent to the Bureau is being collated, standardised and made available via services to meet much broader purposes. The Bureau services support a large range of stakeholders for water policy development, planning, operations, public enquiry, emergency services, education and research. There are also an increasing number of other users leveraging from the access to the data collected by hydrographers to create additional services adding further value. The hydrographic data collected by hydrographers is being used for national significant products and services today, and may form part of new services delivered in the future.

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