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Developments in Economic Valuation of Hydrologic Data - Two Steps Forward, One Step Back.

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SUMMARY Techniques for the economic valuation of hydrologic data have been developed in response to the need to allocate resources to activities which will provide the most value as well as to the trend over recent years for a general reduction in the extent of hydrologic data collection networks. It is perceived that quantitative estimates of the dollar value of such data would be the most effective way of adequately representing the case for future data collection. This paper reviews the developments which have occurred in data valuation techniques with particular, though not exclusive, emphasis on Australia. It is concluded that, although many advances have been made, the ultimate goal of a practical, generally applicable and systematic methodology has not yet been attained. However, the authors remain optimistic that this goal can be reached.

1. INTRODUCTION

The importance of the collection of reliable hydrologic data for effective and efficient management, research and design has been widely recognized by practitioners and researchers in water resources (Australian Water Resources Council (AWRC), 1989; Gordon, 1993). The widespread international recognition of this importance was reviewed in a report by the Snowy Mountains Engineering Corporation (SMEC, 1988). In a report outlining the expected future trends and policy responses in management of Australian water resources (Australian Water Resources Council (AWRC), 1987), a continuing growth in the need for such data was envisaged (evidence of a realization of this growth was reviewed in the SMEC (1988) report). This was expected in response to growing needs to assess hydrologic responses to changes in land management and possible changes in the regional distribution of water resources resulting from climate change.

Despite such perceptions of the worth of collecting hydrologic data, it is apparent that there has been a general reduction in the extent and activities of hydrologic data collection networks within Australia since the early 1980's (AWRC, 1990; Doran, 1989). This has largely been the result of reviews of the networks motivated by reductions in funding and increased national and state budgetary pressures. As pointed out in the SMEC (1988) report, data collection activities are exceedingly vulnerable to such pressures as neither the benefits of additional data nor the costs of cutting data collection are easily perceived by the majority of the community. A further problem here is that these benefits and costs will be realized only in the future, thus their significance in relation to savings which can be achieved now will often be reduced in the eyes of decision makers under pressure to reduce short term expenditure.

It seems that the most effective way of adequately representing the case for increased or even sustained levels of hydrologic data collection is to demonstrate the economic benefits associated with this activity. It is not sufficient to give broad opinions stating that the value of data would outweigh their costs of collection. There is a need to place actual dollar values on these benefits in order to clearly demonstrate their significance and to allow a rational basis for allocation of resources to data collection. In response to this need, a variety of techniques have been developed to estimate the value of hydrologic data. However, despite over twenty years of research and the resulting advances which have been made, there does not appear to be any generalized and orderly methodology. This paper will review developments in and problems associated with the estimation of the worth of hydrologic data, with particular emphasis on the Australian perspective. An assessment of the current state of the art and of problems as yet unsolved is made with suggestions as to future developments.

2. DATA AND INFORMATION

When attempting to place a value on data, we must ask exactly what it is that makes data valuable? The answer is the information that they provide which can be applied to processes such as design, research, operation and management and planning. The benefits derived from these processes depend on the reliability of the relevant parameter estimates derived from data, thus it would be expected that the greater the uncertainty in these estimates the smaller would be the value of the benefits. Data collection is essentially a sampling process from an unknown population, the data being used to estimate parameters which describe this population. In general, larger amounts of data will furnish more reliable estimates and thus more information regarding the population. The value attributable to data can then be seen to be equivalent to the value of the greater amount of information they provide for application to the processes mentioned above.

Having established that the information content of data needs to be assessed, it must be able to be clearly identified in any data set. Referring to the estimation of population statistics for frequency and time series distributions of variables, Moss (1970), Dawdy et al. (1970) and Matalas (1967) defined information in terms of the reliability of the estimates, this being the reciprocal of the variance of the estimate. Matalas and Langbein (1962) pointed out that such a measure will give an indication of relative information content which can then be used to estimate *effective* record lengths and *effective* numbers of data records given that each datum in these records may share information with other data in the same record (autocorrelation) or with data in other records (cross-correlation). The measure of information content which has been used consistently in the literature relating to hydrologic data valuation focuses on the standard error in estimating population parameters, rather than on the reciprocal of the square of this error (that is, the reciprocal of the variance).

The various approaches which have been used to value data all rely (implicitly or explicitly) on this link with the information content of data sets. The differences between approaches are due to the ways in which information content is estimated and the methods adopted to ascribe value to it. These differences have resulted from attempts to tackle different aspects of the myriad problems which present when trying to value data.

2.1 Problems in Valuing Data

One of the major difficulties in placing useful economic values (for the purposes of justifying *future* data collection) on hydrologic data is that the characteristics of data not yet collected are not known. These can be inferred from past data, but this is particularly difficult where little or no data exist. A further problem was raised by Moss (1986), this being the possibility of non-stationarities in data sets, with the form and magnitude of these being highly uncertain. All of the techniques currently used for valuing data assume stationarity of the populations sampled and thus do not take into account the value in identifying trends and shifts in hydrologic phenomena.

The SMEC (1988) report outlined more of the problems, noting particularly that benefits are difficult to define and will be shared over long periods and by many beneficiaries who may be difficult to identify. The fact that costs of collection of data and the benefits resulting from their collection will be realized at different times also presents difficulties in requiring application of complicated discounting procedures. Such discounting will tend to reduce the currently perceived significance of benefits to future generations, thus heavily biasing estimates of the value of data in favour of the current generation. It may be that greater consideration needs to be given to the value of data in the eyes of our descendants.

Brown (1980) identified the difficulties in ascribing value to the indirect and intangible benefits which are typically associated with data collection. For example, how can sensible dollar values be placed on improvements in environment and how can the improvements themselves be defined? The judgements involved are highly subjective and based on great uncertainty, thus any values estimated may be difficult to compare and assess in relation to the value of benefits derived from alternative investment of resources.

Another major problem is that specific future uses and requirements for data are not known and cannot be predicted (AWRC, 1989), thus in the long term the actual benefits which result will be expected to be much greater than would be conceived before the data are collected. For example, the value of some of the long records used for design of hydroelectric projects could not have been envisaged when collection of the records began, but this value is quite significant and real (SMEC, 1988). In addition to advances in technology, Nemec and Askew (1986) pointed out that the uncertainty regarding future data requirements depends also on future trends in socioeconomic climate. They further emphasized that any technique used to value data collection, considering all the uncertainties involved, will only be of use if the values derived are realistic and warned of the use of complicated mathematical formulations which may hide the underlying uncertainty and may be inapplicable in the real world.

2.2 Need for a General Methodology

To be truly useful for valuing data collection in a practical sense, a general methodology which can be applied to multiple purpose, multiple site real networks over a regional or even a national scale is required. Such a methodology needs to be capable of providing reasonable estimates of the value of continued and even expanded data collection in the future. It should consider specific future uses of data which can be identified as well as future uses which are uncertain and even unknown. Applications of data for research and resulting developments in technology and resource management will be important and potentially valuable benefits of data collection programs and consequently must also be allowed for. Ideally, from the point of view of actually using such a methodology, it should be as simple as possible in its application while still maintaining realistic assumptions and giving results which are more than just of theoretical interest.

Given the problems identified above and the magnitude of the task of coordinating all the requirements of a generally applicable data valuation methodology, it is not surprising that no such methodology has yet been developed. A great deal of progress has been made in specific areas, particularly in developing valuation techniques for particular uses at given sites. Even for such specific applications, significant problems are constantly encountered requiring considerable effort to resolve. For example, where the value of streamflow records is to be assessed for reservoir storage design, the difficulty of directly comparing estimates based on records of different lengths has been addressed by Cloke and Cordery (1993). This difficulty is related to the expected value of the estimates derived using many storage analysis techniques increasing with increasing length of streamflow record, where the record is analysed directly.

Pretto *et al.* (1994) have shown that even more complex dependencies on the length of streamflow sequence may exist where behaviour analysis is used to estimate required storage. Figure 1 illustrates this with a plot (adapted from the study) showing expected values of storage estimates against length of sequence analysed. Given that in many cases streamflow records may be analysed directly such that the sequence length in Figure 1 will equate to record length, a problem similar to that identified by Cloke and Cordery can be seen to exist. Direct comparisons between estimates derived from different record lengths will be most difficult for the purposes of valuing longer data records.

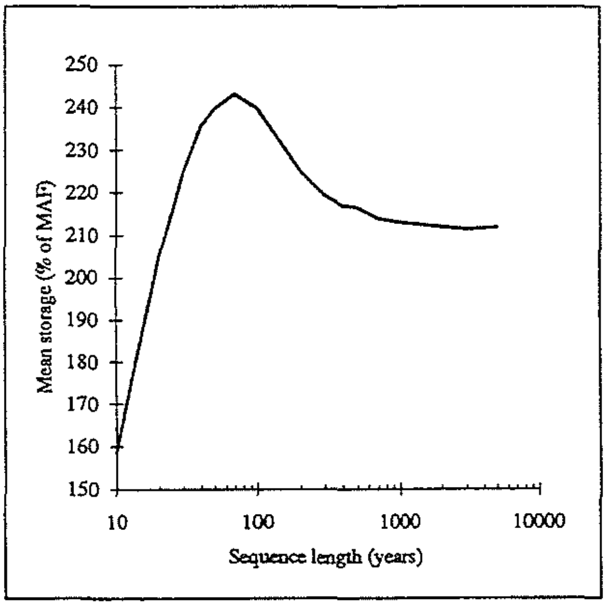

Figure 1 Plot of mean storage estimates (over k replicates) against length of streamflow sequence (n) for log-normally distributed annual flows (C_v = 0.7) for draft of 90% of mean annual flow (MAF), satisfying conditions for overyear storage design (with kn = 5,000,000).

Many such difficulties arise in developing approaches to valuation of data for specific situations. As they are solved, we move closer to deriving useful estimates of the value of data for these situations, for example the approach used by Cloke and Cordery (1993) to deal with the problem just outlined. However, many problems, particularly that of coordinating all the advances made into a universally applicable methodology, remain and new ones are constantly encountered. Thus, although much progress has been made, it has been significantly slowed, with the ultimate goal of being able to derive consistent, complete and realistic estimates of the value of all hydrologic data not yet having been achieved. There may also be a need to reassess exactly what is implied by economic valuation as opposed to financial valuation.

3. EXISTING APPROACHES TO DATA VALUATION

Techniques to measure the information content of data records, as outlined above, were available by the 1960's. These can provide some measure of the relative worth of different amounts of data (sampling in space and time), but are limited in that they are specific to certain statistical parameters of the data such as mean and variance rather than directly to actual outcomes of uses of the data. Watson (1976) developed related techniques such that standard errors of estimates of some statistical *and* design parameters could be calculated and related to lengths and number (taking into account cross correlation between records from different sites) of data records in a data collection network. Design and/or operation of networks could then be carried out on the basis of the achievement of set accuracy goals. This philosophy has, until recently, been adopted for the assessment of the New South Wales (N.S.W.) hydrologic data collection network (Watson *et al.*, 1978). These techniques, however, do not provide estimates of economic value derived from the data.

Haimes *et al.* (1979) looked at the value of a reduction in the standard deviation of storage yield estimates for water resource planning as record lengths increase. They generated a penalty matrix for each combination of high and low yield estimates for six projects based on expected capital costs and water shortages. However, dollar values were only ascribed to the potential savings in capital costs associated with data, the effects of water shortages not strictly being assessed in economic terms. Thus absolute economic values were not derived.

Techniques which derive actual estimates of the economic value of data in terms of monetary units (dollars) have been classified in a number of ways. Considering the classifications proposed in reviews by Simpson and Cordery (1987), SMEC (1988) and Brown (1980), methods developed for economic valuation of hydrologic data will be discussed here under four types of approach. These approaches and the studies included in each are shown in Figure 2.

3.1 Case Study Approach

The most direct way to calculate the value of benefits attributable to hydrologic data is to analyse the results of past data collection for specific projects. Appendix B in the SMEC (1988) report presents a large number of case histories from around Australia covering a very wide range of projects and activities which depend on the provision of water resources data. In some cases dollar benefits were estimated for projects already completed, but in general the cases illustrated the worth of data only in a semi-quantitative way. No generally applicable approach was used which would be capable of estimating value for future data collection.

A similar case study was outlined by Simpson and Cordery (1987), in which it was found that the costs of operating the

N.S.W. streamgauging network were only about 10% of the mean annual flood damage estimates in N.S.W. Given that flood estimation and management practices depend to some extent on the data collected, this was used as an indication of the potential benefits of continued data collection. However, this approach does not allow an actual value to be estimated for the data as it is not known what effect more data would have on the expected flood damage estimates. A further problem which is associated with a case study approach is that any values determined, even if well representative of the value of data for actual cases, can only show that resources have or have not been employed well in the past. Extrapolation to future data collection and to other projects will not necessarily be relevant.

3.2 Bayesian Approach

Davis *et al.* (1972) used a Bayesian decision theory approach to flood levee design. The emphasis in this approach is on how decisions affect the expected costs of the project, including costs of building and operating flood protection systems and expected costs of flood damage less miscellaneous benefits. The analysis incorporates calculating expected opportunity losses (increases in project costs associated with non-optimal decisions) associated with a range of decisions, these decisions being based on uncertain information represented by an assumed probability distribution function. This function is updated using Bayes' theorem to simulate incorporation of new information due to increments in the data record. The expected decrease in expected opportunity loss is then calculated as a measure of the value of the extra data and an expected net gain is calculated considering costs of data collection and of delaying a project. A major problem is that the value calculated is not absolute, being comparable only in terms of the specific project to which the analysis is applied. The approach is therefore not particularly useful from the point of view of demonstrating the value of investment in data collection compared with alternative investments. Further, as pointed out by Brown (1980), the technique is computationally too complex for any general practical application.

3.3 Empirical Approach to Assessing Benefits

Acres Consulting Services Ltd (1977) carried out an economic evaluation of the entire Canadian streamgauging network. The benefits derived from each data application were assumed to be a fixed percentage of total expenditure in that area of application. These percentages were based on the opinions expressed in a survey of data users. In this way a benefit-cost ratio of 9.3 was estimated for the entire

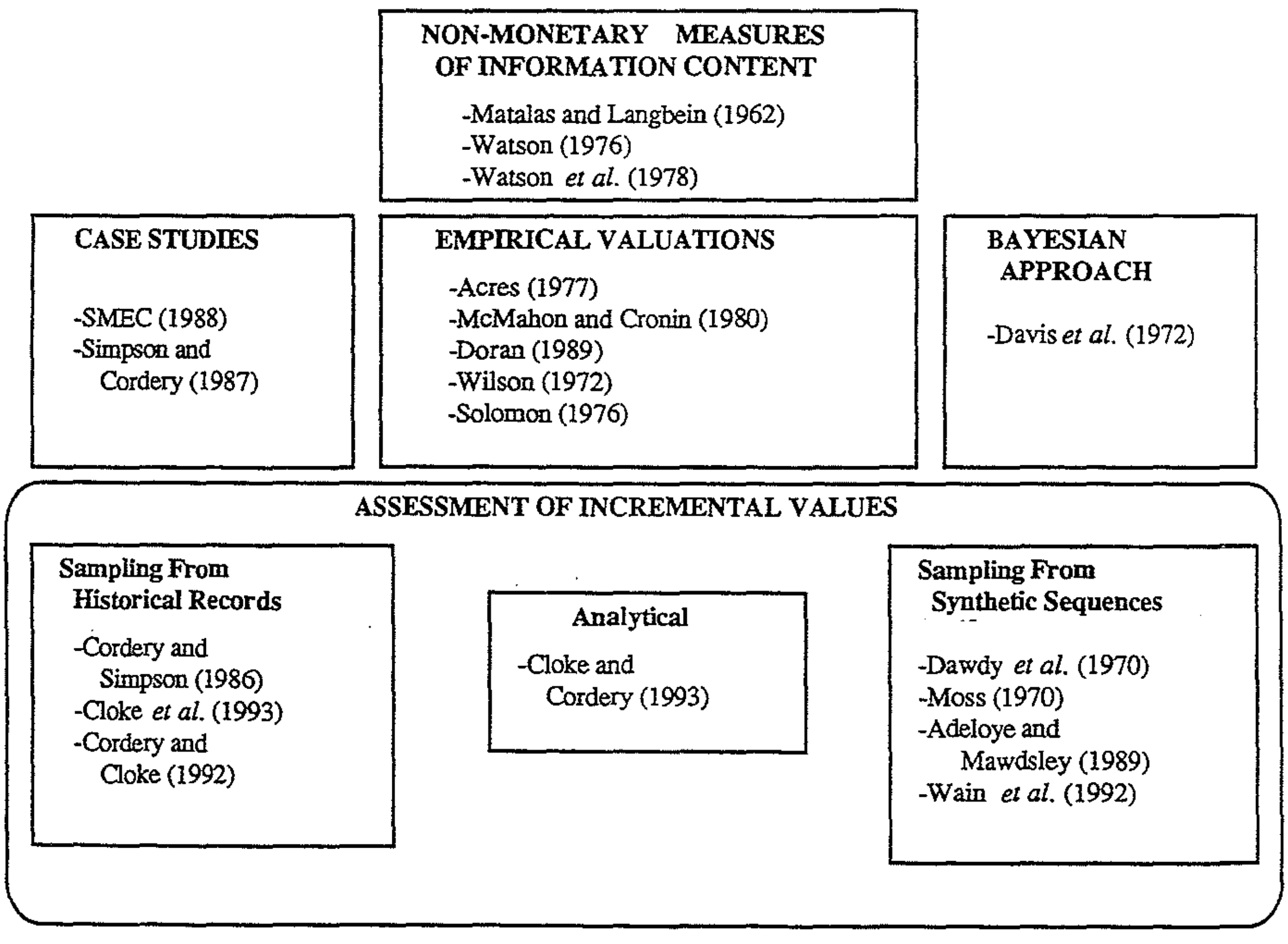

***Figure 2** A classification of theoretical approaches to valuation of the worth and economic value of hydrologic data.*

Canadian network. Although this approach implicitly includes the knowledge, experience and judgement of practitioners who actually use data and would be expected to have an appreciation of their worth, it provides no generally applicable methodology for deriving economic valuations of data. The validity of the opinions on which the estimates are based in this approach would be difficult to establish. Further, as the opinions would most likely be based on past experience rather than a statistical appreciation of the value of further sampling, it is quite likely that they would not be relevant for the assessment of future data collection.

Although large values for benefit-cost ratios estimated for the collection of hydrologic data may appear, on the surface, to represent compelling evidence of the need to continue data collection, Doran (1989) points out that such ratios will be of little interest to those making decisions regarding allocation of resources. Instead *marginal* benefit-cost ratios, indicating the value of benefits over costs for increments in expenditure on data collection, are of much greater importance. This is the approach which was adopted by McMahon and Cronin (1980), reporting the marginal economic analysis carried out in the project by Acres (1977). The analysis was based on developing relationships between overall error (uncertainty) in parameters estimated from data and the characteristics and extent of the data collection network, as well as on relating incremental increases in these errors to increased costs due to overdesign of capital works. Application to three types of hydraulic structures was accomplished by empirically estimating the relationships for each type. These relationships were then applied to each province in Canada for a 20% increase and a 20% decrease in gauge density. A marginal benefit-cost ratio of about 1.3 for the entire Canadian network was found, but it was recognized that many benefits other than savings in capital costs were not analysed. Thus, although the approach outlines a methodology which can be used to estimate marginal benefits (and thus value) of collecting more data, its unsuitability for other benefits restricts its general applicability.

Doran (1989) applied McMahon and Cronin's marginal benefit-cost ratio method to the Australian streamgauging network and found that investment in expansion of the network was economically viable. However a problem here is that, when applied only on a nationwide scale, such an analysis cannot identify the specific areas within the network which would provide benefits and those which would not if expansion were carried out. Thus, the need to allocate resources to streamgauging in general may be identified, but allocation of these resources *within* the network could not. This problem does not apply to the Acres (1977) study, as the analysis for the Canadian network was carried out at a regional level, thus allowing identification of particular areas from which greater value could be derived from further investment.

Wilson (1972) and Solomon (1976) related the economic value of benefits to errors in statistical parameter estimates in a similar way to the studies outlined above. However, Solomon pointed out the difficulty in realistically estimating the empirical relationships involved. Adeloye (1990) reinforced this point, arguing that combining the large number of parameters which actually influence the outcome of many water resources design applications into an analytical form presents often intractable problems. Nemec and Askew (1986) also warned of the lack of practical application of such procedures where assumptions may be based on little or no real world experience.

3.4 Assessment of Incremental Values

These techniques rely on sampling from either existing data records or from synthetically generated data records, or on analytical approaches to determine the sampling properties of design and management parameters, the value of increments in data records being related to the decreased uncertainty as more data are acquired. The sampling techniques avoid the intractability which often occurs with analytical approaches.

3.4.1 Analytical Approach

Cloke and Cordery (1993) used estimates of the sampling properties of the rescaled adjusted range derived from analytical techniques to investigate the reduced uncertainty associated with storage design using longer data records. The value attributable to increments in data was equated to the decrease in range of the dollar value of estimated expected capital costs of construction associated with longer records. Although this provides a simple technique to value data for storage design, it is not applicable to any other data uses. A particular problem with such techniques is likely to be the difficulty of deriving appropriate analytical expressions, as for the empirical approaches.

3.4.2 Sampling from Historical Record

Cordery and Simpson (1986) derived cost-benefit ratios for the use of data for design of a flood mitigation scheme. The available record at the site considered was 91 years in length. This record was used as a finite population representing flows, smaller non-overlapping samples of different lengths being taken from this to determine the decrease in the 90% confidence interval for flow magnitudes with a set probability of exceedance associated with longer records. In association with flood damage data for the area, expected damage averted was calculated for each case by integrating damage values over probability of occurrence. The decrease in uncertainty of expected damage averted as the record length was increased was equated to the value of additional data.

Cloke *et al.* (1993) calculated the benefits resulting from reductions in both underdesign (less obstruction to traffic and damage to structures) and overdesign (savings in capital costs) associated with improved flood estimates from an updated regional flood estimation technique. It was considered reasonable to assume that the improved flood estimates were due to incorporation of additional data in the updated technique and thus the benefits could be attributed to increments in data. In terms of searching for generally applicable methodologies, the problem with this approach is the availability of such regional techniques and their relevance to calculating the effects of increments in data in each case. Any analysis would be specific only to a particular region and in reality probably only demonstrates value from collecting past data.

Cordery and Cloke (1992) assessed the value of data for use in hydraulic design associated with both high and low flow hydrology. The analyses discussed above in this section were used, along with estimates of the value of data for large hydraulic structures similar to those used in Acres (1977), to calculate an overall benefit-cost ratio for hydrologic data collection in N.S.W. of about 9.

The particular usefulness of the techniques discussed in this section is that they provide some guide as to estimation of the value of data for a number of *different* uses. However, as pointed out by Cloke *et al.* (1993), all these benefits are calculated after the data have been collected, similar to the situation for case studies. This results from sampling from a finite population of existing historical data. Thus the value of the collection of *additional* data in the future is not resolved.

3.4.3 Sampling from Synthetic Sequences

Dawdy *et al.* (1970) assessed the effect of sampling error on the value of data for reservoir design by sampling from a 500 year long synthetic streamflow record generated using a model based on the available historical record. This 500 year synthetic record was then assumed to represent the streamflow population. In this way, the sampling was used to simulate the effects of adding to the data record beyond the length of record already available, allowing a determination of the sampling properties of storage estimates for data collected in the future. A shortage index was developed from which a relationship between storage size and the value of direct benefits was derived. By including a relationship between storage size and capital construction costs, the net benefit was maximized to give a design storage for each length of record sampled from the assumed population. As the length of sample records increased (simulating an increase in the length of the historical record) it was found that the maximized net benefits increased, this representing the value of the extra data.

Moss (1970) applied this approach to the determination of optimum operating procedures for a single gauging station with a single use for data. A marginal benefit marginal cost analysis was performed allowing assessment of optimum lengths and timing of collection of streamflow records specific to two different design cases. Although it would seem that this provides a framework for practical application of the approach of Dawdy *et al.*, problems were identified for its application to situations where a data record already exists, it being more suited to analysing the value of data at sites currently ungauged. The technique is further limited in application to a single site and single use for the data.

Adeloye and Mawdsley (1989) developed the use of an opportunity loss model in which the expected economic losses suffered as a result of the uncertainty in design due to inadequate data can be quantified. This was applied to a hypothetical direct supply reservoir design case, the value due to increments in data being estimated as the associated reduction in opportunity loss. The expected opportunity losses were calculated by integrating benefit and loss as functions of total data errors over the distribution of these errors determined by reservoir simulation using synthetically generated data. This approach is similar in some respects to the Bayesian approach (but avoids its computational complexity) and allows value to be estimated for future data collection.

Wain *et al.* (1992) also applied the opportunity loss model just described for reservoir storage design. A hypothetical framework was proposed incorporating this model to value the benefits of hydrologic data collection for multiple uses of the data. Also included was a model of the feedback of these valuations to the data collection process allowing maximization of expected future net benefits to be used as a guide to more efficient resource allocation within data collection networks. However, this framework was not developed past the hypothetical stage and no application of the opportunity loss model other than to storage design was attempted. Although the opportunity loss model offers some promise in the search for a general methodology, a great deal of development is still required, particularly in terms of estimation of realistic benefit and loss functions for each application of data. Unfortunately the constraining factor in this sense is, once again, availability of relevant real world information. Extension to a general multiple site data collection network is also yet to be achieved.

4. CURRENT PRACTICE FOR ASSESSING VALUE IN AUSTRALIA

Given that a number of techniques do exist (although currently limited in application to real networks) which can be used to value the collection of hydrologic data, the various state and territory water authorities in Australia were contacted to give an indication of how the value of data is assessed in practice in relation to network planning and operation. It was found that none of the formal methods for quantifying actual dollar values are currently used. Network operation is currently driven, in general, by an increasingly commercial approach in which funding cuts have required network rationalization. Analyses have been carried out assessing the relative (not absolute) value of the data collected at different sites within networks so that losses in value associated with rationalization can be minimized. Allocation of resources appears to be becoming driven more by the needs of paying clients for specific projects. The danger here is that the resulting allocation of resources may not adequately represent the value of hydrologic data to society (both current and future) as a whole.

5. SUMMARY AND CONCLUSIONS

This paper has reviewed the development of techniques to estimate economic values for the collection of hydrologic data. Although many significant developments have occurred, these have been specific to particular aspects of data valuation and do not provide a generally applicable and simple systematic methodology. This is apparent especially when it is considered that explicit dollar values of the benefits of data are not currently estimated by hydrologic data collection agencies in Australia, even though these agencies are most interested in demonstrating the worth of the data they collect. However, given the advances which have been made, there is promise that such a methodology will be developed. This may involve reformulation and integration of existing techniques, thus building further on the developments described above. Decisions concerning resource allocation for hydrologic data collection will ultimately be made on the basis of the subjectively assessed relative importance of assumptions regarding the value of data. The contribution of a general methodology would be in providing a consistent approach to data valuation in which all such assumptions would be explicitly identified.

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