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Guessing or Assessing the World's Water Resources

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Guessing or Assessing the World's Water Resources?

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ABSTRACT

It is something of a paradox that, at this time when the global demand for water is rising faster than ever before, knowledge of the world's water resources is waning. The networks of instruments which provide the basis for this knowledge are considered, with the errors of measurements involved. Work on reducing these errors, particularly the introduction of total quality management, is discussed. The conclusion is reached that a reliable assessment of the world's water resources is some distance away. This presents problems to bodies involved in their development and management and to those organizations who wish to provide the United Nations' Commission for Sustainable Development with an assessment of global water resources for its session in 1997 – an assessment which will then be presented to a special session of the UN General Assembly.

Key words: Errors; hydrological data; total quality management; water crisis; water resources.

INTRODUCTION

Demands for water for drinking, irrigation, power and other purposes continue to rise, bringing increasing pressures on the world's freshwater resources[1]. Indeed, some regions are currently experiencing considerable shortages, principally because the margin between the finite resource and the demand is very small or non-existent. Droughts exacerbate these conditions and highlight the dangers of over-utilization of a meagre resource. This situation must worsen as the world's population grows, leading to increases in water consumption and, potentially, increased pollution of surface-waters and groundwaters – not to mention the additional threat of climatic change. There are even predictions that, with the doubling of the global population by the middle of the next century and the soaring demand for water, a world water crisis will develop[2,3] (Fig. 1). In these circumstances, the world's freshwater resources will become even more precious than today and perhaps a source of conflict in some of the globe's 200 international river basins. At the other hydrological extreme, most parts of the world are subject to floods, with the toll of death and destruction due to floods being the largest of any of the different types of disaster[4]. The rising population will be a larger target for future floods, avalanches, landslides and mudslides.

Too much or too little water can set back the progress of a developing country towards the sustainable development espoused by the UN Conference on Environment and Development (UNCED) and its report[5]. They can also hinder developed countries in the pursuit of this goal. Of course, water encapsulates the quintessential dilemma – development or environment. Every scheme to provide a better water supply, to safeguard against flooding or to meet other human needs, modifies the hydrological cycle in some way. These modifications alter the transport of materials about the earth through the natural geochemical cycles, and have an impact on the various living organisms which depend on the aquatic environment for their existence. They may also be changing the pattern of transport of energy about the globe.

Against this background, it might be assumed that reliable knowledge of freshwater resources and the use of water would be readily available on a national basis, regionally and globally. However, this is not the case. The acquisition and analysis of these data are rudimentary in many areas. The necessary institutions are lacking in a number of countries and are badly equipped in many others. In addition, there is no operational world-wide system for collecting and exchanging these data for forecasting and other purposes, as there is for meteorological data through the 'world weather watch' of the World Meteorological Organization (WMO). While a few countries have active systems for collecting data on water use, most lack such a facility and water-use figures suffer accordingly.

The consequence is that statements of world water resources (Table I) and water use (Table II) are almost certainly seriously in error. These errors concern the UN Commission for Sustainable Development and those bodies who will try to provide an assessment of global water resources to the Commission for its session in 1997 – an assessment which will subsequently be considered at a special session of the UN General Assembly.

In the face of a future water crisis, it seems imperative to improve this knowledge – at one extreme the crisis may come early next century, at the other it may never happen. Without a proper assessment of water resources[6], there can be no integrated river-basin planning and management, while the pursuit of sustainable development will remain a wild goose chase. What is required is that governments, external support agencies and international bodies embrace fully the

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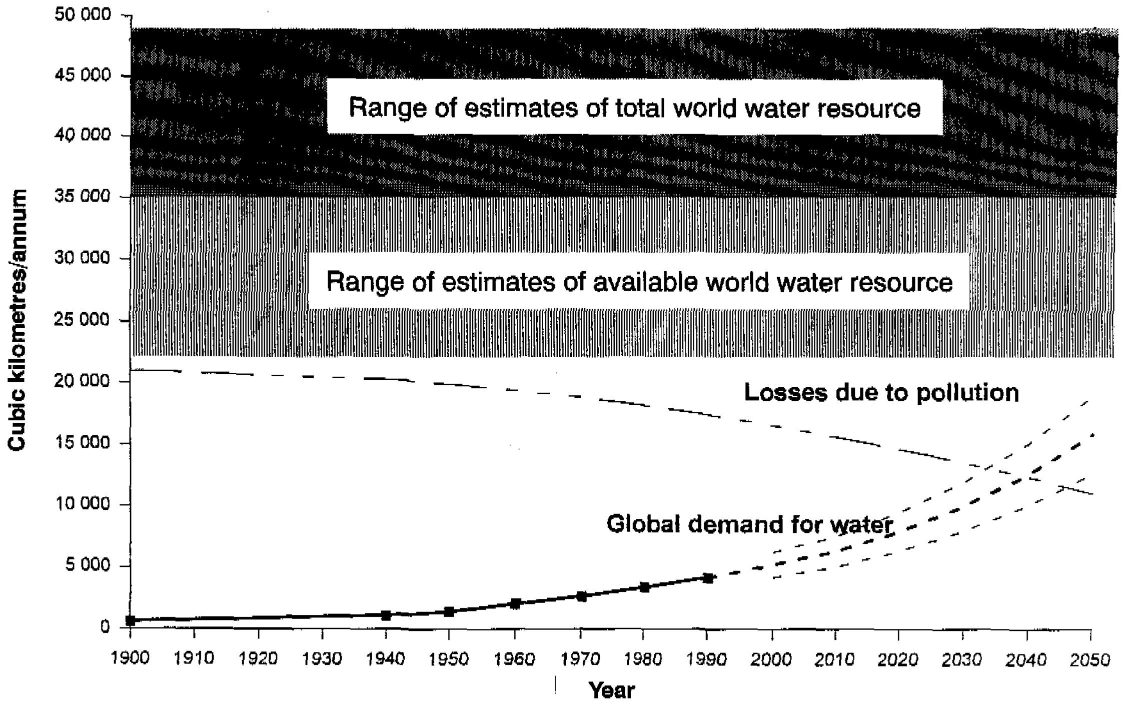

Fig. 1. Scenarios for world water resources and demands

holistic approach to freshwater which they supported at the International Conference on Water and the Environment[7] and at UNCED. The luxury of an 'à la carte' approach to water is no longer tenable[8], and the full menu of integrated river-basin management must be taken.

GATHERING KNOWLEDGE OF HYDROLOGICAL CYCLE

A number of theories are to be found in the early literature explaining how springs rise and rain forms. However, with the birth of scientific hydrology[9] in

TABLE I. Approximate Quantities of Water in Various Parts of Hydrological Cycle with Replacement Periods (Taken from Ref. 60)

Category	Total volume ($km^3 \times 10^3$)	% of total	% of fresh	Annual volume recycled (km^3)	Replacement period
Oceans	1 338 000	96.5		505 000	2 654 years
Groundwater to 2000 m	23 400	1.7		16 700	1 400 years
Predominantly fresh groundwater	10 530	0.76	30.1	—	—
Soil moisture	16.5	0.001	0.005	16 500	1 year
Glaciers and permanent snow	24 064.1	1.74	68.7	—	—
Antartica	21 600	1.56	61.7	—	—
Greenland	2 340	0.17	6.68	2 477	9 700 years
Arctic Islands	83.5	0.006	0.24	—	—
Other Mountain areas	40.6	0.003	0.12	25	1 600 years
Ground ice (permafrost)	300	0.022	0.86	30	10 000 years
Lakes	176.4	0.013		10 376	17 years
Freshwater	91	0.007	0.26	—	—
Salt water	85.4	0.006		—	—
Marshes	11.5	0.0008	0.03	2 294	5 years
Rivers	2.1	0.0002	0.006	49 400	16 days
Biological water	1.1	0.0001	0.003	—	—
Atmospheric water	12.9	0.001	0.04	600 000	8 days
Total water	1 385 984.6	100[a]			
Total freshwater	35 029.2	2.53	100[a]		

[a] Some duplication in categories and sub-categories.

TABLE. II. DYNAMICS OF WATER CONSUMPTION (km^3/year) IN WORLD ACCORDING TO VARIOUS KINDS OF HUMAN ACTIVITY (TAKEN FROM REF. 23)

Water uses	1900	1940	1950	1960	1970	1975	1980	1990	2000
Irrigated lands (Mha)	47.3	75.8	101	142	173	192	217	272	347
Agriculture									
A	525	893	1130	1550	1850	2050	2290 (68.9)	2680	3250 (62.6)
B	409	679	859	1180	1400	1570	1730 (88.7)	2050	2500 (86.2)
Industry									
A	37.2	124	178	330	540	612	710 (21.4)	973	1280 (4.7)
B	3.5	9.7	14.5	24.9	38.0	47.2	61.9 (3.1)	88.5	117 (4.0)
Municipal supply									
A	16.1	36.3	52.0	82.0	130	161	200 (6.1)	300	441 (8.5)
B	4.0	9.0	14	20.3	29.2	4.2	41.1 (2.1)	52.4	64.5 (2.2)
Reservoirs									
A	0.3	3.7	6.5	23.0	66.0	103	120 (3.6)	170	220 (4.2)
B	0.3	3.7	6.5	23.0	66.0	103	120 (6.1)	170	220 (7.6)
TOTALS (rounded)									
A	579	1060	1360	1990	2590	2930	3320 (100)	4130	5190 (100)
B	417	701	894	1250	1540	1760	1950 (100)	2360	2900 (100)

Note: A: Total water consumption B: Irretrievable water losses Percentage figures in parentheses.

1674, following the publication of 'De l'origine des fontaines' by Pierre Perrault[10], there was the first experimental evidence that atmospheric transport provides precipitation in sufficient quantities to cause rivers to flow. Perrault's study of the Coquille at Aignay le Duc, a headwater tributary of the River Seine, and the contemporary work of Mariotte, on the basin of the Seine to Paris[11], are the earliest assessments of the water balance of any basin. Doubts which lingered during the remainder of the eighteenth century over the ability of the atmosphere to transport sufficient moisture were finally scotched by Dalton[12].

The nineteenth century saw (i) an increase in the ability to measure and analyse the different hydrological variables, (ii) a gradual expansion of countrywide instrument networks, and (iii) the organization of the earliest national hydrological and meteorological services. Some of these analyses were for purely scientific purposes, but an increasing number were aimed at the design and operation of various structures and schemes to cope with the increasing demand for water, to provide drainage and to alleviate floods. Water-balance studies were important to a number of these purposes and to questions being asked about the impact of human activities on water resources. These studies involved a range of scales[13]: at one extreme, studies of the global water balance; at the other, studies of experimental plots and small basins.

ASSESSING RESOURCES THROUGH WATER BALANCE

One of the earliest examples of a small water-balance study commenced in the 1890s in the basins of the Sperbelgraben and Rappengraben in the Emmental, Switzerland[14]. This investigation into the hydrological differences between forest and pasture was the first in a long series of paired basin studies[15,16], such as Waggon Wheel Gap (USA), Coweeta (USA), Valdai (Russia), Hupselse Beek (Netherlands), and Plynlimon (UK) aimed primarily at determining the hydrological impact of land-use differences and changes. These studies were stimulated in the 'international hydrological decade' (IHD) and in UNESCO's subsequent 'international hydrological programme' (IHP), some of the results being employed to assist the development of the comparative approach to hydrology[17]. More recently, these basin studies and the application of the results from them have been promoted in Europe by the IHP FRIEND project[18] and in several other parts of the world by the series of similar projects which the FRIEND concept has fostered.

Studies of the world water balance also seem to have commenced in the late nineteenth century, a series of examples being listed by Lvovitch[19,20] and Baumgartner and Richel[21]. More recently, Korzun[22] and Shiklomanov[23] have assessed in detail the global budget and its regional patterns, while the variations of its components have been summarized by Street-Perrott *et al*[24]. Knowledge of the processes that determine the water balance has been improving because of process studies within basin studies and because of the series of large-scale experiments on land/atmosphere interactions being conducted in different parts of the world[25,26]. Some of these experiments come under the 'international geosphere biosphere programme' (IGBP) core project on the biological aspects of the hydrological cycle[27]. Others fall within the World Climate Research Programme's 'global energy and water cycle experiment' (GEWEX)[28] and its 'continental scale international project', focusing on the Mississippi Basin[29].

Because the hydrological cycle provides most of the power to transport materials in the different geochemical cycles, measurements of the fluxes in the water balance globally and basin-wide are essential in determining the budgets of these different materials. Consequently, knowledge of runoff is needed to estimate the transported loads of sediment[30], carbon [31,32] and other determinands[33]. In addition to dry deposition, precipitation amounts must be known in order to determine the loads being deposited from the atmosphere[33]. A summary of global movement of water and material was made by Berner and Berner[34].

ACQUIRING HYDROLOGICAL DATA

Data on the water balance and water resources on a global scale, or for the smallest headwater basin, must be determined by measurements. Traditionally these measurements have been derived from networks of ground-based instruments, but now data are available in an increasing volume from weather radar networks and satellite imagery. However, these data are used routinely in assessments of water resources in only a few countries.

Table III provides a summary of the statistics for the global instrument network, compiled from information on national networks[35], including networks employed for research purposes. These instruments and methods of observation are operated on a routine basis by the world's Hydrological Services who collect, analyze and apply the data from them. There are contrasts between the 'data rich' and 'data poor' areas of the world, but these rarely feature as commentaries on published global water budgets. Error, accuracy and precision are words that seem to be absent from most of these discussions; however, they appear more frequently in the results of small basin studies. They are, of course, the concern of those who operate these instrument networks and manage the data obtained from them on a regular basis. Agency-wide, national and international programmes aid this effort to assure quality. Certain initiatives on the international level aim to assist in quality assurance, as well as in making international data sets more readily available. There are, for example, the World Glacier Monitoring Service in Zurich, the Global Runoff Data Centre (GRDC) in Koblenz, the Global Precipitation Climatology Centre at Offenbach and the GEMS Collaborating Centre for Surface and Groundwater Quality at Burlington, Ontario. Each of these global centres controls the data which it acquires before archiving them and, in addition, the GEMS Water Quality Programme[36] provides help to national services to improve and maintain the standards of their analytical services for water quality. Unfortunately, the data held by these centres do not cover all countries. The most recent are frequently 2–3 years old, and time series are often short and incomplete.

The absence of a readily accessible and reliable body of hydrological data for the globe has led the WMO to propose the establishment of a 'world hydrological cycle observing system' (WHYCOS), which would consist of about 1000 stations world-wide, sited on the major rivers[37]. It is recognized that WHYCOS by itself would not provide the answer to this problem, but it would stimulate the process of finding a solu-

TABLE III. Global Hydrological Network (Taken from Ref. 35)

Variable	Type of station	Number of stations						
		Africa (RA I) (1)	Asia (RA II) (2)	S. America (RA III) (3)	N. & C. America (RA IV) (4)	S. W. Pacific (RA V) (5)	Europe (RA VI) (6)	Global Total
Precipitation	Non-recording	17 036	39 456	19 247	19 973	15 276	40 367	151 355
	Recording	2 639	18 864	4 124	5 280	3 332	8 422	46 661
	Telemetry	8	1 916	211	1 023	515	459	4 132
	Radar	9	56	3	82	8	35	193
Evaporation	Pan	1 508	3 686	2 031	2 716	1 120	1 499	12 560
	Indirect method	374	7	40	11	1 049	488	1 969
Discharge	Total[a]	5 703	11 543	7 924	13 211	5 838	19 798	64 017
	Non-recording	3 045	8 479	5 691	2 080	2 043	6 137	27 475
	Recording	1 856	3 064	2 233	11 128	3 795	13 661	35 737
	Telemetry	39	2 033	158	3 613	1 075	2 561	9 479
Stage	Total[a]	3 410	6 405	5 872	11 274	1 167	10 474	38 602
(water level)	Non-recording	2 244	3 800	4 244	1 725	522	5 826	18 361
	Recording	877	2 300	1 628	9 549	642	4 599	19 595
	Telemetry	15	1 257	194	1 734	192	1 768	5 160
Sediment discharge	Suspended	859	3 820	1 561	5 217	619	3 712	15 788
	Bedload	6	685	505	0	1	549	1 746
Water quality		5 297	5 045	2 752	31 462	1 690	55 379	101 625
Groundwater	Water level							
	- Observational wells	4 884	16 657	1 133	19 818	18 585	85 075	146 152
	- Production wells	31 804	63 705	14 150	14 099	13 504	38 452	175 714
	Temperature							
	- Observation wells	287	2 541	5 200	21 097	4 888	18 967	52 980
	- Production wells	243	88	5 539	21 501	888	1 641	29 900
	Water quality							
	- Observation wells	4 898	1 964	320	13 757	7 935	14 889	43 763
	- Production wells	5 674	45 187	3 416	14 825	3 172	23 711	95 985

[a] The total includes stations not distinguished as 'recording' and 'non-recording'

tion. Each WHYCOS station would monitor 15 or more variables, including flow and physico-chemical determinands of water quality, which would be transmitted via a geostationary satellite, such as Meteosat, to national, regional and global centres. At these centres, archives of data would be built up over the period of operation of WHYCOS of at least twenty years, and processed to create tools for decision making, as well as for science. These archives could be extensions to existing national archives and to those compiled for FRIEND purposes, as well as to those in existing global data centres, such as the GRDC. WHYCOS would also contribute to the 'global climate observing system' (GCOS), and the 'global terrestrial observing system' (GTOS) initiatives, which WMO is sharing with a number of international bodies concerned with identifying global change. More importantly, WHYCOS would seek to build up the capabilities of the hydrological services in those countries where networks, staff levels and facilities are in decline. Such a decline has been revealed in a number of recent studies – particularly in Africa[38,39]. With this decline, an increase in the errors surrounding water-balance estimates is to be expected; and it is something of a paradox that, at this time when global demand for water is rising faster than ever before, the errors in assessing just how much water is available for use are generally increasing.

For research on the water balance of small basins and for the process studies within them, the instrument systems are normally more advanced and more complete than for countrywide networks. Toebes and Ouryvaev[40] provided an overview of observational and other practices for representative and experimental basins, and there are many more recent reviews of experience in individual basin studies[41,42,43]. Large-scale studies of hydrological processes such as FIFE, HAPEX-MOBILHY and BOREAS have a much shorter history than studies of the global water balance. Basically, they try to couple simultaneous measurements of a number of variables on different scales in intensive field campaigns, which may have been approached previously through different disciplines. These studies are described extensively in the literature, such as by Dozier[44] who considers their experimental design using ground-based measurements, aircraft and satellites.

ERRORS, UNCERTAINTIES AND ACCURACIES

Determining water resources requires measurements to be made mostly in the natural environment where conditions are continually changing with time, and now human activities impose further modifications. To sample these changes, and particularly the extremes which they contain, the measurements are best made over long time periods; the presence of the sensor should not alter the variable being observed and the instruments should be located at sites which are properly representative of the area or basin being sampled. Table IV indicates some of the problems of point precipitation measurement. For out-of-river variables, the problem of representatives has been eased somewhat by the advent of weather radars and satellites, through the images they provide of the fields of several variables. However, these images need measurements from strategically placed ground-based instruments for their calibration and interpretation. In other areas, for example in measuring soil water content and water quality, the representativeness problem remains. Concentrations of constituents vary vertically and horizontally in a water body, and of course in time. Depth-integrated samples tend to overcome these difficulties, and obviously the more samples taken the more nearly they represent the whole[45]. These difficulties have often led to dense networks being developed, which are later reduced as hydrological patterns become established.

TABLE IV. PROBLEMS OF ASSESSING WATER BALANCE FROM POINT PRECIPITATION MEASUREMENTS

1	Spatial coverage is often incomplete
2	Temporal coverage is often incomplete
3	There are at least 54 different types of standard gauge in use in 136 countries covering about 90% of the land area of the globe and in addition a large number of different types of rain recorders. No measurements are made over the oceans
4	Errors of measurement have not been determined for each gauge type
5	Installation of gauges and their sites may not meet the required practice
6	Changes have occurred in gauge exposure
7	Gauges have been moved
8	New types of gauge have been introduced without comparisons with old models
9	Observer practice has altered
10	Station histories are not documented

These problems and others, such as those concerned with the storage and analysis of data captured from the field, introduce errors into the measurements of the hydrological variables. The error is strictly the difference between the result of a measurement and the true value of the quantity being measured[46]; however, for most hydrological variables, the true value is unknown and even a best approximation (such as might be obtained in the laboratory from a series of repeated measurements) is not usually available. This has led to a preference for the use of the term 'uncertainty', i.e. the interval about the measurement within which the true value of the quantity can be expected to be with a stated probability[46]. There are many sources of error, and Fig. 2 shows how these may arise in flow measurement with a weir or a flume. The overall uncertainty of measurement X_Q[47] depends upon (a) the standard of construction of the gauging structure, (b) the correct application of the design specifications, and (c) a number of other factors; X_Q will also vary with discharge for a given structure. Herschy[48,49] discussed the errors of the various methods of flow measurement, drawing on material published by the

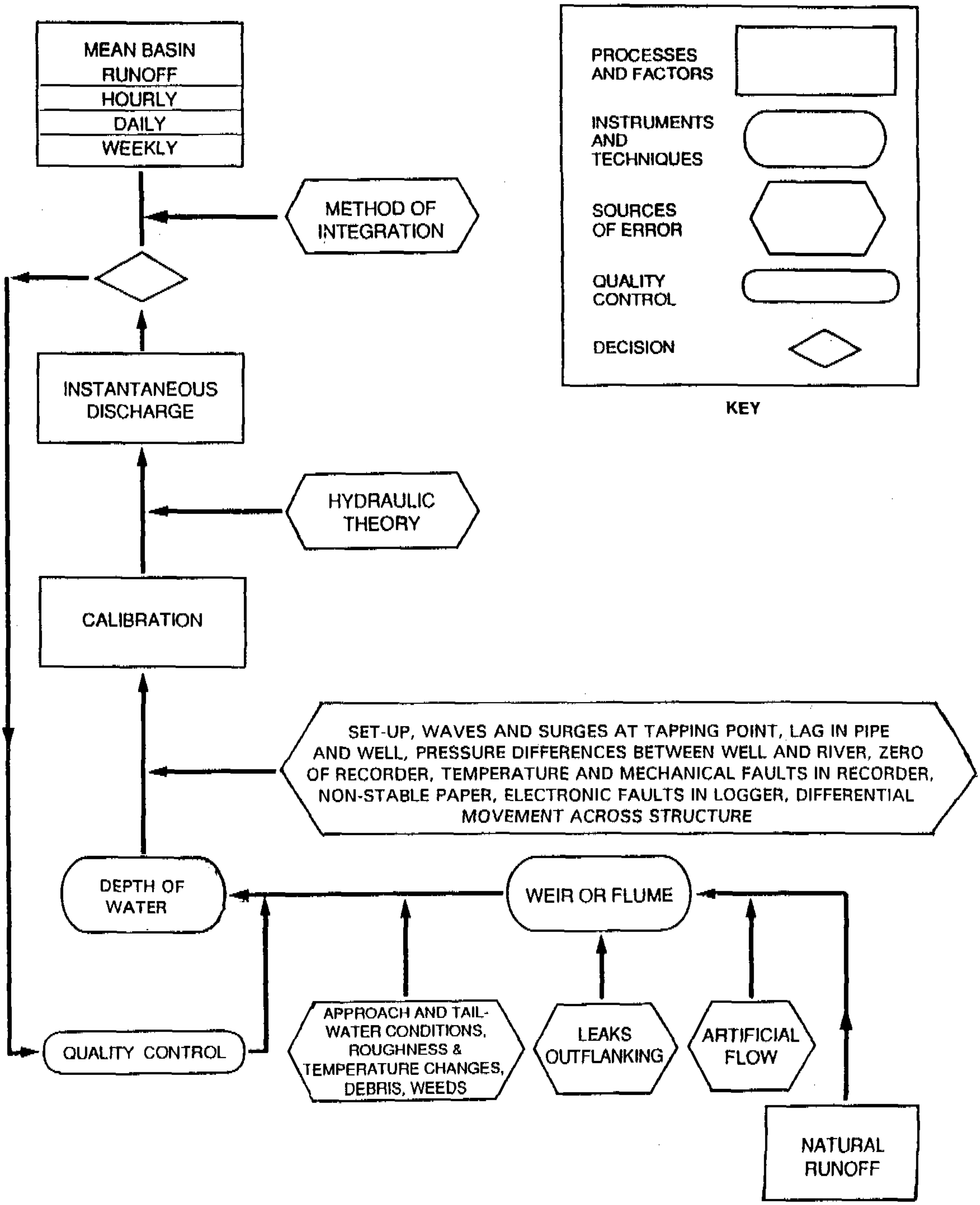

Fig. 2. Source of errors in measurement of flow by weir or flume

International Organization for Standardization (ISO) and also by WMO. He concluded that if ISO standards are followed, flow measurements made at a single gauge are expected to have the following upper limits of uncertainties at the 95% confidence limits:

Single determination of discharge	±7%
15 min average of discharge	±5%
Daily mean, monthly mean or annual discharge	±5%

Understandably, it would be unwise to assume that river flows are normally measured to these limits:

many countries are not able to meet ISO Standards[50], nor the requirements of WMO[51]; neither do the measurements of the other variables often satisfy the WMO recommendations for accuracy (Table V). Unfortunately, these are accuracies to aim at rather than those being presently achieved. Take precipitation as an example: errors can range from 5 to 30% for rain and from 10 to 80% for snow – depending on gauge type, site, wind speed and other factors.

TABLE V. Recommended Accuracies (Uncertainty Levels) Expressed at 95% Confidence Interval for Different Variables (Taken from Ref. 46)

Variable	Recommended accuracy
Precipitation (amount and form)	3–7%
Rainfall intensity	1 mm/h
Snow depth (point)	10 mm below 200 mm or 10% above 200 mm
Water content of snow	2.5–10%
Evaporation (point)	2–5%, 0.5 mm
Wind speed	0.5 m/s
Water level	10–20 mm
Wave height	10%
Water depth	0.1 m, 2%
Width of water surface	0.5%
Velocity of flow	2.5%
Discharge	5%
Suspended sediment concentration	10%
Suspended sediment transport	10%
Bed-load transport	25%
Water temperature	0.1–0.5°C
Dissolved oxygen (water temperature is more than 10°C)	3%
Turbidity	5–10%
Colour	5%
pH	0.05–0.1 pH unit
Electrical conductivity	5%
Ice thickness	12 mm, 5%
Ice coverage	5% for ≥ 20 kg/m³
Soil moisture	1 kg/m³ ≥ 20 kg/m³

*When a range of accuracy levels is recommended, the lower value is applicable to measurements under relatively good conditions and the higher value is applicable to measurements in a difficult situation

WORK OF WMO TO REDUCE ERRORS

The Secretariat of WMO and the member countries of the organization have been working in various ways to combat errors in instrument practice and in the errors which can occur at later stages in data management. One of the main vehicles for this work has been the series of instrument intercomparisons which cover the measurement of the main hydrological variables.

For the first comparison of liquid precipitation measurements undertaken in the 1950s, one particular reference gauge was selected. When the faults of this gauge were recognized, a different reference was chosen for the second intercomparison made in the 1970s[52]. For the third intercomparison, which is of devices for measuring solid precipitation (and is just concluding), a different interim reference was employed[53]. These reference instruments were installed at a large number of different sites around the world for comparisons with the various national gauges. The results of the different intercomparisons show how national gauges performed against the reference. For the comparison of methods of evaporation measurement and estimation which was conducted in the 1960s[54], a substantial amount of data was collected from national tests and by means of a questionnaire. For phase 1 of the intercomparison of water-level recorders and current meters, tests were conducted nation by nation of their own instruments, and several other instruments were tested against detailed test specifications which had been agreed previously[55]. For phase 2 of this intercomparison, which was broadened to include data loggers, suspended-sediment samplers and several categories of water level and velocity sensors, the US Geological Survey additionally made available a number of US P61 sediment samplers to participating countries for tests against national samplers[56]. The other results of these intercomparisons show how different instruments performed against the test specifications, but no clear preferences for devices of particular types are stated in the conclusions. A statement of the errors of measurement for the variables concerned is not included. However, the tests themselves, through the transfer of technology which they promote, help to raise the standard of performance of the hydrological services involved, which (in turn) assists in error reduction in the long term. The same applies to the transfer of technology facilitated by the 'hydrological operational multipurpose system' (HOMS)[57], i.e. the WMO technology transfer system which has achieved more than 3000 exchanges of components between hydrologists in developed and developing countries since it was launched in 1981. However, neither as a result of these comparisons, nor in HOMS does WMO, nor any other international organization, advocate the use of a particular type of instrument, so that observations might be made in a uniform way world-wide. If this was the case, and if all the subsequent data-management procedures were also harmonized, there would be few difficulties in ascribing errors to the estimates of water resources. This type of observational homogeneity is what the GEMS water quality programme[36] aims to achieve. It is what has been achieved by certain national programmes in water quality, for example, in the United States Water Information System[45].

TOTAL QUALITY MANAGEMENT

Perhaps the time is opportune to adopt similar initiatives globally and to embrace the concept of total quality management which is embodied in the ISO 9000 series of standards[58]. These offer an integrated global system for optimizing the quality effectiveness of a company organization. By adhering to defined standards, an organization ensures that its product is 'fit for the purpose for which it is intended', a hydrometeorological data set being one such product. This approach has been adopted by New Zealand's National Institute for Water and Atmosphere (NIWA)[59] for its environmental data activities, including hydrological data. The reasons given were:

(i) To eliminate the costs of poor quality control;
(ii) To ensure that the product meets the user's needs – that the data are confidently usable; and
(iii) To demonstrate to users that the organization is meeting and anticipating their needs.

The approach incorporates adherence to manuals and procedures, and includes certification by an independent body accredited to carry out the inspection work. NIWA implemented new procedures and upgraded instruments and equipment to meet the necessary requirements and to achieve the standards of quality claimed for them.

CONCLUSIONS

1. There are considerable errors in the majority of assessments of water resources, at virtually every scale; errors which are usually disregarded.
2. The sizes of these errors are unknown for most national and global assessments, New Zealand being an exception due to the adoption of total quality management.
3. The establishment of WHYCOS is an obvious method for the propagation of quality assurance for hydrological data globally, with the operation of stations and the use of procedures to meet ISO and WMO requirements and recommendations within the framework of total quality management.
4. Without such an approach, it will be impossible to determine the known errors to the volumes of water stored and in motion about the surface of the earth and the loads of material which they transport.
5. At present, despite the forthcoming water crisis, only educated guesses can be made about the dimensions of the world's water resources.
6. In 1997, the United Nations Commission for Sustainable Development and the General Assembly of the United Nations have the possibility of rectifying this situation and ensuring that the development and management of water resources will become sustainable.

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