

Thirty years of sediment–water science: history, trends and future directions

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Abstract. In 1976, an interdisciplinary group of international researchers met in Amsterdam to share their knowledge about sediment–water interactions, and subsequently formed the International Association for Sediment Water Science (IASWS). Since then, IASWS has met tri-annually at a variety of locations throughout the world. Over the last 30 years, over 1000 oral presentations have been presented at IASWS symposia, more than half of which have been published as books or special issues of scientific journals. As such, the publications provide an excellent record of developments in the field of sediment–water interactions over the last 30 years. This paper provides an overview of the history of the Association, and a qualitative and quantitative content analysis of the IASWS publications. Changing patterns of research in some of the dominant symposia themes, including sediment-associated nutrients, contaminants and metals as well as sediment dynamics and material cycling are presented. Temporal changes in the investigative scale of published studies and an eventual increase in papers addressing management considerations were observed. Potential directions for the future of IASWS and some directives for ensuring that future research informs aquatic ecosystem health are suggested.

Additional keywords: heavy metals, IASWS, interdisciplinary, nutrients, predictive models, remediation, restoration, sediment, sediment dynamics, sediment management.

Introduction

In 1974 at the 19th conference of the International Association of Limnology held in Winnipeg, Canada, a group of aquatic researchers planned to organise a small meeting in Amsterdam specifically to address interactions between sediment and water. They felt that the role of sediment in lake ecosystems, especially its effects on water quality, were being overlooked in the limnological community, which often considered sediment simply as a ‘sink’ (Golterman *et al.* 1977). The 1976 Amsterdam meeting, arranged to address this vacant niche, was in the end not that small, as 169 individuals attended representing 32 countries. A second meeting in Kingston, Canada (1981) resulted in the creation of the International Association for Sediment Water Science (IASWS) and since then the Association has met tri-annually at a variety of locations throughout the world. Perhaps uniquely over this time period, the IASWS conferences have involved presentations and interactions by a wide range of scientists, including geochemists, sedimentologists, hydrologists, geomorphologists, biologists, aquatic ecologists, engineers and occasionally social scientists, enabling researchers to obtain a much broader perspective on sediment–water interactions. Each of the symposia resulted in the publication of a book and/or special issues of scientific journals including *Hydrobiologia*, *Science of the Total Environment*, *Marine and Freshwater Research and Water*, *Air and Soil Pollution*. The selection of 524 papers published from these 10 meetings provides an excellent source for examining the Association’s scientific themes and approaches to the study of sediment in water. In this paper, I provide a brief history of the Association and, from a content analysis of

the 10 IASWS publications, identify the dominant themes and changing patterns of research in these three decades of contributions. In conclusion, potential directions for the future of IASWS and sediment–water research in general are suggested.

The mandate, as presented on the Association website (www.iasws.com) indicates that IASWS seeks to promote, encourage and recognise excellence in scientific research related to sediments and their interactions with water and biota in fluvial, lacustrine and marine systems and with particular reference to problems of environmental concern. As mentioned earlier, the original meeting had limnological origins, and in fact the first publication is titled ‘Interactions between sediments and fresh water’, although 2 of the 71 published papers deal with salt-water (estuarine) environments. This emphasis on freshwater continued at the second meeting in Kingston, Canada in 1981, where only 3 of the 68 publications dealt with brackish or salt water. As the Association and its mandate were created following this second meeting, explicit promotion for marine presentations was not initiated until 1984 when the symposium was held in Geneva, Switzerland. From the earliest days, the group encouraged international and multidisciplinary participation while endorsing collaborative research and dialogue between earth scientists, biologists, chemists and environmental engineers interested in sediment–water interactions. Both global and local environmental concerns had been identified as an IASWS focus and the opportunity to highlight regional issues was promoted at the fourth meeting in Melbourne, Australia in 1987. To encourage an influx of new members as well as placing global concerns in local contexts, a concerted effort

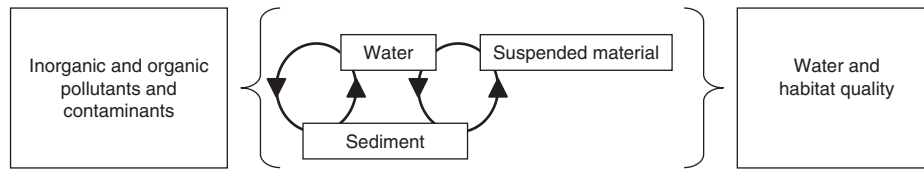


Fig. 1. An early model for physical and chemical sediment–water interactions (modified from Hart and Davies 1977).

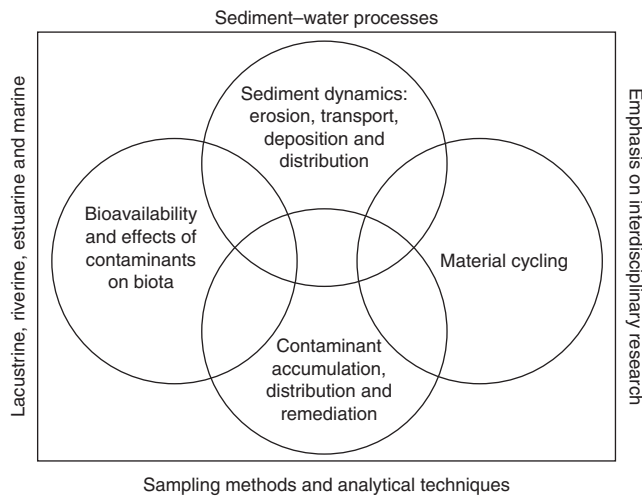


Fig. 2. The dominant themes addressed at International Association for Sediment Water Science symposia over 30 years. The inclusion of topics surrounding the box is implicit throughout all themes.

has been made to regularly move the meetings among continents, and to maintain broad international representation on the board of directors. The following six meetings were held in Uppsala, Sweden (1990), Santa Barbara, USA (1993), Baveno, Italy (1996), Beijing, China (1999), Banff, Canada (2002) and Lake Bled, Slovenia (2005). The meetings have on average hosted ~150 members with ~120 presentations. National representation at these meetings has ranged between 23 and 34 countries. These mid-sized meetings have generally been structured with three to four parallel sessions running over 3.5 days with a mid-week field trip for all registrants. The 11th symposium in 2008 was held in Esperance, Australia although the contents and structure of that meeting are not reflected in this paper.

Themes in sediment–water science

The initial recognition that a separate venue was needed for discussions of the relevance and impact of sediment–water interactions occurred in 1974 when issues of water quality and aquatic contaminant transport were beginning to be considered global concerns. While ecosystem health and management was not the terminology used at the time, there was a distinct recognition by the early organising committees that sediment played an important role in the eutrophication and pollution of aquatic habitats. In a summary of the first meeting, Golterman *et al.* (1977) stated that clarifying the physical and functional definitions of sediment was problematic, rendering them difficult to use as a logical framework for a symposium. Putting those

historical semantics aside, the group recognised that sediment in, or in contact with, the water column was a vector and/or potential source of pollutants and contaminants. Recognition that chemical, hydrodynamic and biological processes at the sediment–water interface were regulating material exchanges, and thereby habitat quality (Fig. 1), led to the interdisciplinary emphasis of the symposia. Mechanisms of sediment–water interactions and transfers, as well as the biogeochemical processes occurring at the sediment–water interface, were seen as critical in addressing these problems.

Over the 30 years of symposia, there have been several recurring themes addressed by IASWS members (Fig. 2). It is clear from the contents of the four spheres that these dominant themes are not strictly independent of each other and therefore are presented graphically as overlapping. Within each of these themes, changing sampling methodologies and analytical techniques have been presented and occasionally been given specific sessions or publication preference. Each theme applies to the full range of aquatic environments and can be addressed from several disciplinary perspectives. Therefore, running throughout the themes at all symposia is the assumption of interdisciplinary participation.

General patterns observed from publication content analysis

Both quantitative and qualitative content analysis of the 524 publications were undertaken for presentation here. Categorisation and enumeration of various aspects of the papers was completed to quantify the period's changing themes and research approaches. A second more subjective analysis of the content of this literature was carried out (sub-headings) to identify patterns of change observed in some of the scientific themes running throughout the period of record. Content analysis of the IASWS publications potentially presents a biased perspective on the full range of subject matter presented at the meetings as the portion of papers published varies between 24 and 85% of the oral presentations. While IASWS editors have always attempted to incorporate papers that represent significant findings as well as reflect the dominant themes of the meetings, the reduction of published papers in recent years inevitably means a loss of information, both scientific and historical. In my review of the 10 IASWS publications, I recognised the limitation of this method, but felt an analysis of the available data provided useful information and insights on the changing approaches and emphases in sediment–water science over the three decades that environmental research burgeoned.

A list of the 10 IASWS publications, the journal special issues associated with the various symposia and the number of papers included in each is provided in Table 1.

Table 1. International Association for Sediment Water Science symposia and publication details

Publication	Location (date)	No. papers
‘Interactions between Sediments and Fresh Water. Proceedings of the 1st International Symposium.’ 1977. (Ed. H. L. Golterman.) pp. 473. (Dr W. Junk: The Hague, The Netherlands.)	Amsterdam, The Netherlands (6–10 September 1976)	71
‘Sediment/Freshwater Interaction. Proceedings of the 2nd International Symposium. Developments in Hydrobiology 9.’ 1982. (Ed. P. G. Sly.) pp. 700. (Dr W. Junk: The Hague, The Netherlands.) Reprinted from <i>Hydrobiologia</i> (1982) Vol. 91/92.	Kingston, Canada (15–18 June 1981)	68
‘Sediments and Water Interactions. Proceedings of the 3rd International Symposium.’ 1986. (Ed. P. G. Sly.) pp. 521. (Springer-Verlag: New York.)	Geneva, Switzerland (27–31 August 1984)	44
‘Sediment/Water Interactions IV. Proceedings of the 4th International Symposium. Developments in Hydrobiology 50.’ 1989. (Eds P. G. Sly and B. T. Hart.) pp. 533. (Kluwer Academic Publishers: Belgium.) Reprinted from <i>Hydrobiologia</i> (1989) Vol. 176/177.	Melbourne, Australia (16–20 February 1987)	51
‘Sediment/Water Interactions V. Proceedings of the 5th International Symposium. Developments in Hydrobiology 75.’ 1992. (Eds B. T. Hart and P. G. Sly.) pp. 743. (Kluwer Academic Publishers: Belgium.) Reprinted from <i>Hydrobiologia</i> (1992) Vol. 235/236.	Uppsala, Sweden (6–9 August 1990)	66
‘Interactions between Sediments and Water. Proceedings of the 6th International Symposium.’ 1995. Special Issue of <i>Marine and Freshwater Research</i> , Vol. 46, No. 1, pp. 1–418.	Santa Barbara, USA (5–9 December 1993)	43
‘The Interactions between Sediments and Water. Proceedings of the 7th International Symposium.’ 1997. (Eds R. D. Evans, J. Wisniewski and J. R. Wisniewski.) pp. 739. (Kluwer Academic Publishers: London.) Reprinted from <i>Water, Air and Soil Pollution</i> (1997) Vol. 99, Nos. 1–4.	Baveno, Italy (22–25 September 1996)	72
‘Thematic issue: Proceedings of the 8th International Symposium on Sediment-Water Interactions.’ 2001. <i>Science of the Total Environment</i> , Vol. 266, pp. 1–326.	Beijing, China (13–17 September 1999)	35
‘The Interactions between Sediments and Water. Proceedings of the 9th International Symposium on the Interactions between Sediments and Water.’ 2003. (Ed. B. Kronvang.) pp. 325. (Kluwer Academic Press: London.) Reprinted from <i>Hydrobiologia</i> (2003) Vol. 494.	Banff, Canada (5–10 May 2002)	43
‘The Interactions between Sediment and Water. Proceedings of the 10th International Symposium.’ 2006. (Eds B. Kronvang, J. Faganeli and N. Ogrinc.) pp. 319. (Springer: Dordrecht, The Netherlands.) Reprinted from <i>Water, Air and Soil Pollution: Focus</i> (2006) Vol. 6, Nos. 5–6.	Lake Bled, Slovenia (28 August–3 September 2005)	31

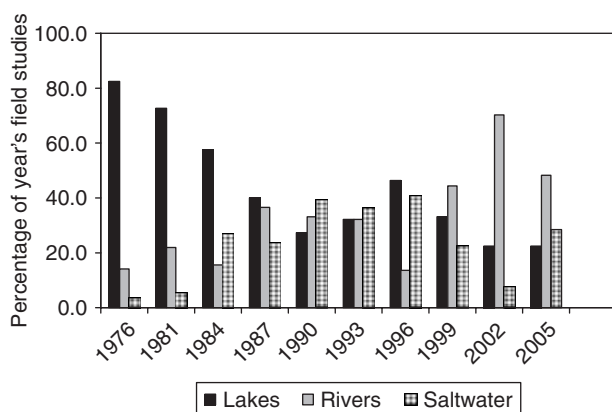


Fig. 3. Relative proportions of field-based lake, fluvial and saltwater research publications from each International Association for Sediment Water Science symposium.

Characterisation of the 524 published papers as field, laboratory, modelling or review studies shows that the majority of research has been field based, ranging from 58 to 81% over the 30-year period. Within this category, the aquatic environment studied reflects the historical break-away from limnology. At the first two symposia, >80% of the field studies were lacustrine,

while fluvial research represented only 14–22% (Fig. 3). Recall that the original emphasis of this Association was on freshwater so only a few marine studies were included initially. At the Melbourne (1987), Uppsala (1990) and Santa Barbara (1993) meetings, each of the three categories was well represented, suggesting the explicit inclusion of the marine component was a success. In 1996, a resurgence of lake studies (46%) occurred, likely reflecting the location of the meeting in Baveno, in the famous lake district of Italy. Recently, fluvial studies dominate the publications (70% in 2002 – Banff and 48% in 2005 – Lake Bled). This change reflects the inclusion of a specific emphasis on catchment-scale disturbances, both natural and anthropogenic. In the context of these aquatic categories, it appears that the location of the symposia reflects to some degree the research interests of the organising committee, which directly affects the selected sub-themes and thereby the contributions to symposia sessions.

The proportion of laboratory-based and modelling studies (Fig. 4) represents the smaller component of the publications (each maximum 20%). An interesting periodicity is exhibited in the proportion of modelling papers. They appear to have a 6–9-year cycle potentially reflecting either the use of laboratory and field-generated data to inform modelling of natural systems and/or temporal changes in research funding, which can restrict more expensive field programs.

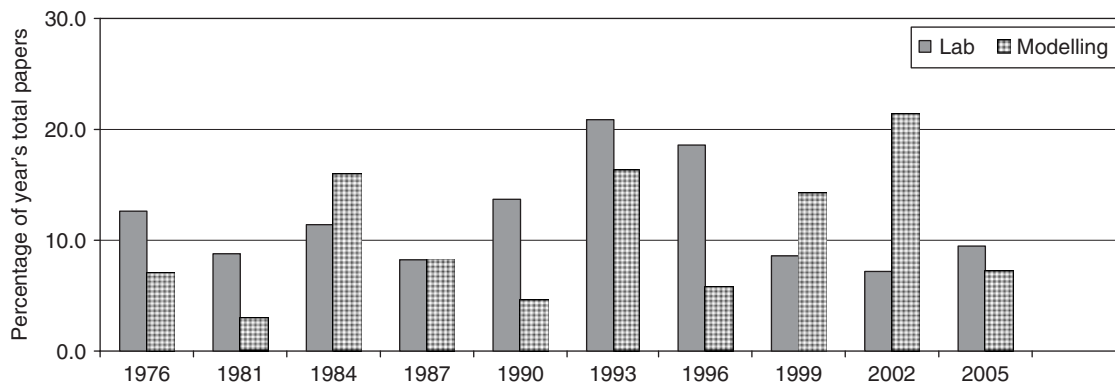


Fig. 4. Changing pattern in the proportion of modelling and laboratory-based studies from each year of International Association for Sediment Water Science publications.

Nutrients

Given the limnological associations of most of the early symposia organisers, one of the original topics of interest was the cycling of nutrients, specifically phosphorus (P). At the first meeting, 30% of the papers dealt with P dynamics, reflecting the global concern at the time about lake eutrophication (e.g. DiGiano and Snow 1977; Lee *et al.* 1977). Over the next 30 years, research reporting on both nitrogen (N) and P continued, but recently there has been a renewed focus on P and N loadings and transfers, due in part to regulations initiated via the European Water Framework Directive (e.g. Owens and Walling 2003; Hejzlar *et al.* 2006). The original process-based research has informed the direction of government programs, but now the concern is about regulation and reporting of nutrient movement and storage in targeted environments. The 30-year period of IASWS reportage reflects these temporal trends in environmental concern and subsequent governmental focus and funding.

Metals and contaminants

A prevalence of case studies of metal and contaminant distribution in the early publications (e.g. Vernet *et al.* 1977; Gavens *et al.* 1982) indicates the initial need for countries to document the scale and severity of that recently acknowledged environmental problem. The IASWS publications show that concomitant with early case studies and for the remainder of the 30 years, contributions continued to address methodological improvements and *in situ* mechanistic experiments. A review of the series of papers Ulrich Förstner presented over the years reflects a changing perspective in heavy metal research. An initial paper (Förstner 1977) presents the spatial variation in natural and anthropogenic heavy metal concentrations in lake sediment from a wide range of geological, climatic and hydrological locations. The importance of various extraction methods and the role of sediment grain size influences on resultant metal levels were stressed. An invited paper at the second symposium was a review of the mechanisms of metal enrichment on sediment (Förstner 1982). Methods of metal extraction and concentration are reviewed and warnings are provided about the difficulty in using these techniques to characterise bioavailable metals. It is interesting to note that these two papers are written from a geochemical perspective

and reiterate caution about interpreting data directly for biologically driven systems. Förstner was invited as a plenary speaker at the Lake Bled symposium, and he spoke about the historic changes in sediment–metal research via a focus on studies his research group has been associated with on the Rhine River. The publication of this material by Heise and Förstner (2006) focuses on the management of the Rhine Basin to reduce risks from historically contaminated sediment. This change in emphasis again shows that over the 30-year period we have developed sufficient technical and background knowledge to allow us to address management issues. The move away from case study reporting to large scale management approaches again reflects not only the interests of the researchers, but also the involvement of government agencies and the sustained concern by both groups about contaminants in our ecosystems.

Sediment dynamics

Another central theme over the 30 years has been sediment dynamics. Aspects of erosion, deposition, entrainment and transport have all been considered. The emphasis on the movement and fate of fine-grained sediment (<63 μm) was a major concern in the early days of IASWS when most of the other literature dealt predominantly with predictions for sand and gravel material in rivers and lakes. Clarifying the role of silts and clays allowed for the prediction of transfers and storage of sediment-associated pollutants (e.g. Sly 1989; Blom *et al.* 1992). The added concern that aggregated and/or flocculated particles, composed of fine-grained sediment and organic material, behave differently from their individual particles has generated an emphasis on characterising the size, structure and composition of composite aquatic particles (e.g. Droppo *et al.* 1997; Petticrew and Arocena 2003).

Material cycling at the sediment–water interface

Throughout the full 30 years, the IASWS publications have emphasised basic research on sediment-related processes. An example of a body of work, and steady progress, is that of material exchange at the sediment–water interface. Early methodological studies for analysing interstitial water from river sediment (e.g. Hart and Davies 1977) and lake sediment (e.g. Brinkman *et al.* 1982) provided techniques and a knowledge base

allowing later flux determinations of nutrients and contaminants (e.g. Ciceri *et al.* 1992; Barbanti *et al.* 1995). Later work at the sediment–water interface incorporated hydrodynamic effects on the flux and dissipation of materials (Huettel *et al.* 2003) and linked the role of microbial activity to these interface processes (Hines 2006). Modelling material flux at the sediment–water interface, using this basic research information, is a major objective of a group of IASWS researchers that has spanned the full publication time period.

Biological impacts and influences

The bioavailability of nutrients and/or contaminants as well as the effect of these pollutants on biota has been a recurring theme at IASWS symposia although it was not dominant in the earliest years. In Fig. 1, which is modified from Hart and Davies (1977), only the physico-chemical aspects of the sediment–water system are portrayed; the biological component is not included. This diagram is representative of the major concerns at the first meeting where only a few of the 71 papers address biological involvement in sediment–water processes. This likely reflects the initial IASWS concern to study sediment as a geochemically dynamic component of aquatic systems as well as the breaking away of this group of scientists from the limnological community where there had always been a biological emphasis. Due to the obvious connection of IASWS research and general concern regarding the effects of pollutants on aquatic organisms and habitats, the third publication (1986) from the Geneva meeting includes a sub-theme, which includes ‘transfers to the biosystem’ and includes papers addressing bioavailability and bio-toxicity of pollutants (Morrison *et al.* 1986; Munawar *et al.* 1986). While this interest continued through to later meetings, more recent biological emphasis has been in the opposite direction, focusing on the role of organisms modifying the sediment and benthic environment. The influence of microbes (Hines 2006), algae (Kozerski 2003), benthic organisms (Mugnai *et al.* 2003) and aquatic macrophytes (Clarke *et al.* 2006) on sediment structure, chemistry and composition have been reported. An amendment to Fig. 1 to reflect current perspectives of sediment–water interactions should include these biological implications and impacts.

Scale of research investigations

The scale of the reported research investigations has tended to increase over time. While the titles of some papers seem to indicate large scale field studies in the early years, for example Plumb and Lee (1977) investigating the effect of mine tailings in Lake Superior, often the work was focussed on a small portion of a larger system. A few early papers are very large scale such as Ongley’s (1986) summary of the effects of phosphate reductions on Great Lakes water quality and Håkanson’s (1986) characterisation of sediment types in the Swedish coastal zone. Catchment-wide projects and catchment comparisons, where spatial sampling is broadly distributed, are reported more frequently in later years (e.g. Ankers *et al.* 2003; Lauridsen *et al.* 2006). While Ongley (1986) had access to several extensive government databases allowing an analysis of temporal changes on a large scale, the current availability of computerised databases and geographic information systems suggests that we would

expect to see more of these types of projects recently and into the future. Douglas *et al.* (2003), Huang *et al.* (2003) and van der Perk *et al.* (2006) are good examples of using catchment scale databases for modelling the source and controls on aquatic sediment.

Land use impacts

Anthropogenically induced land use change, and its effects on sediment delivery to aquatic systems were introduced in the early papers (e.g. Slaymaker 1982) and have seen a resurgence in the publications since 1996. This revisitation coincides with the scientific interest in whole-system or ecosystem approaches, which began to receive attention from the organisers for the 1990 Uppsala symposium who introduced a sub-theme titled ‘Sediment and water movement in rivers and their catchments’. At the Banff symposium, two sub-themes ‘Assessing and restoring disturbed watersheds’ and ‘Sediment–water linkages in terrestrial and aquatic environments’ drew a number of papers addressing land use impacts on sediment transfers (e.g. Heywood and Walling 2003; Nishimune *et al.* 2003). While the dominant research themes of IASWS (Fig. 2) have been maintained over the 30-year period, the symposium sub-themes advertised for the individual meetings clearly influences the attendee registration and the content of the publications. These sub-themes are identified by the symposium organising committee and presumably reflect their awareness of new issues and their scientific concerns and interests. While this thread of land-use change weaves through the IASWS publications for the last 30 years, we have not seen publications addressing impacts of climate change scenarios on sediment transfers and/or sediment–contaminant interactions. Given the extent of this problem and the recent funding associated with climate change research, some reporting on this topic is likely to appear in future symposia.

Sediment management and risk analysis

Sediment management is another sub-theme that develops over the 30-year period. It has been mentioned that in the early papers researchers were leery of extrapolating data to evaluate untested environments. As environmental management continues to be one of the main drivers of sediment–water research, it is pleasing to note the eventual increase in papers on management (e.g. Mattice *et al.* 1997), remediation (e.g. Leppard and Droppo 2003) and restoration (e.g. Shields *et al.* 2003). Considering the past need for knowledge on remediation and restoration, it is surprising that so few papers are included on these topics. A bias against applied papers by researchers may be the explanation for this earlier situation, and future appreciation and inclusion of regulatory research, which provides scientific background for regulatory decisions, is needed. There has been a concerted effort since the Baveno meeting (1996) to incorporate a sub-theme addressing sediment risk management. Expanding the emphasis of the science-based IASWS membership to include individuals who straddle the social, economic and scientific arenas of risk assessment has been slow, although there are a few publications addressing risk in sediment management scattered throughout the years (Cullen 1989; Förstner 1995; Haag *et al.* 2001; Senior *et al.* 2003; Heise and Förstner 2006).

Future directions

Future research and symposia addressing sediment–water science are expected to continue to provide high quality basic research and process knowledge. Forthcoming improvements in laboratory and field technologies and therefore methods will allow more detailed characterisation of environmental conditions. This new knowledge production combined with what we have already documented needs to be used to (i) improve our quantitative predictive ability across the full range of investigative scales (clay particle to open ocean), (ii) develop models that are useful and appropriate for managers, policymakers and stakeholders involved in governing aquatic resources and (iii) inform regulatory agencies who identify and require information on issues of strategic environmental importance.

Current environmental concerns suggest the IASWS literature of the past and the future will be critical for use in aquatic remediation and habitat restoration. Multiple use environments from urban ponds to global ports demand a sharing and maintenance of resources at healthy levels of water and sediment quality. IASWS can and should be informing and supporting these requirements. If funding to individuals and research institutions continues to be associated with specific environmental concerns, knowledge sharing with government and/or funding agencies will be required to ensure both our awareness of and influence upon their research agendas. Given the history of the Association and the composition of the recent meetings, most researchers should readily be able to generate interdisciplinary research networks that reflect the scientific requirements of many calls for proposals. Addressing the social and economic aspects of these problems will be necessary, but will require different approaches and team members. As a means of achieving these ends, IASWS could (i) encourage a transdisciplinary emphasis (this surpasses multidisciplinary approaches in that rather than incorporating several disciplines in problem solving, it brings together disciplinary expertise but attempts to diminish disciplinary boundaries and set perspectives in addressing real-world problems), (ii) incorporate both researchers and practicing professionals at the symposia, (iii) return to the use of post-symposia workshops with specific problems or research planning in mind (as was done at the first meeting in Amsterdam) and (iv) initiate training workshops pre- or post-symposia to support membership knowledge sharing and breadth of student participation.

Much of the past research reported here emphasises transport and interaction mechanisms of sediment and associated pollutants in aquatic environments. This body of literature fits easily within a ‘Catchment to Coast’ concept that in the future could be used as a broader organising theme to promote our research’s interdisciplinarity and societal value. If we are serious about providing useful, transferable knowledge we should, as individuals, be stating how our research results can directly inform questions of aquatic ecosystem health.

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