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Systemic knowledge management in hydraulic systems: II. Application to hydraulic systems

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ABSTRACT

'Systemic knowledge management', presented in Paper I as a problem-solving methodology, is applied to hydraulic systems here in Paper II. The generic context of hydraulic systems is interrelated to a body of similar developments in science and technology through the concept of paradigms. The systemic component of this problem-solving method integrates 'holism' with 'reductionism'. Systems science approaches offer a problem-solving methodology to decompose complexities into hierarchies. The knowledge management component is implemented through (i) categorising complexities at each hierarchy for customisation of solutions, (ii) challenging the underlying assumptions; and (iii) reorganising complexities as a way of adapting to subsequent changes. This paper contributes towards the substantiation of the postulate on the formation of paradigms and their subsequent shifts. The main focus of this paper is to illustrate the potentials of applying systemic knowledge management to hydraulic systems and in particular to flood forecasting and warning.

Key words | decision-making, hydraulic systems, knowledge management, paradigm, paradigm shifts, postulate, problem-solving methodology, systemic

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INTRODUCTION

Hydraulics plays a vital role in the modern way of life. If classical hydraulics was technical and a branch of mechanics and thereby of physics, modern hydraulics encompasses social and technical dimensions and, therefore, outcomes of hydraulic engineering can even be news headlines, e.g. flood forecasting and warning. While hydraulic practitioners are at the mainstream of science and technology, there are problems yet to be solved and it is argued that 'systemic knowledge management,' as presented in Paper I (Khatibi 2003) can contribute towards their solutions. This methodology is capable of revealing that different paradigms contributing to a system may be at their different paradigmatic stages and, as such, there may be inherent inconsistencies. In particular, Paper I argues that an understanding of the treatment of components plays a crucial role in this problem-solving, as depicted in Figure 1. The term 'component' is used in the sense of a simplicity, defined in Paper I, or building block. Thus, components can be social and technical dimensions, various subsystems of a system, various hierarchies in a system, or various building blocks of a hierarchy. Admittedly the usage of component in this wider sense compromises the subtleties associated with the various terms but this is in the hope that the engineering readership is more familiar with component than the term 'simplicity', as defined in Paper I, or building block.

There are numerous cases in hydraulics for the substantiation of the 'postulate' on the formation of paradigms and their subsequent shifts through proliferating, norming and performing stages, as presented in Paper I and depicted in Figure 1. Indeed, seeking to explain the context of modern changes in these systems was the motivation for the writer to research broadly. The writer has drafted papers to substantiate the shifts on a range of paradigms in water engineering. One paper has been published outlining the paradigmatic stages on open channel

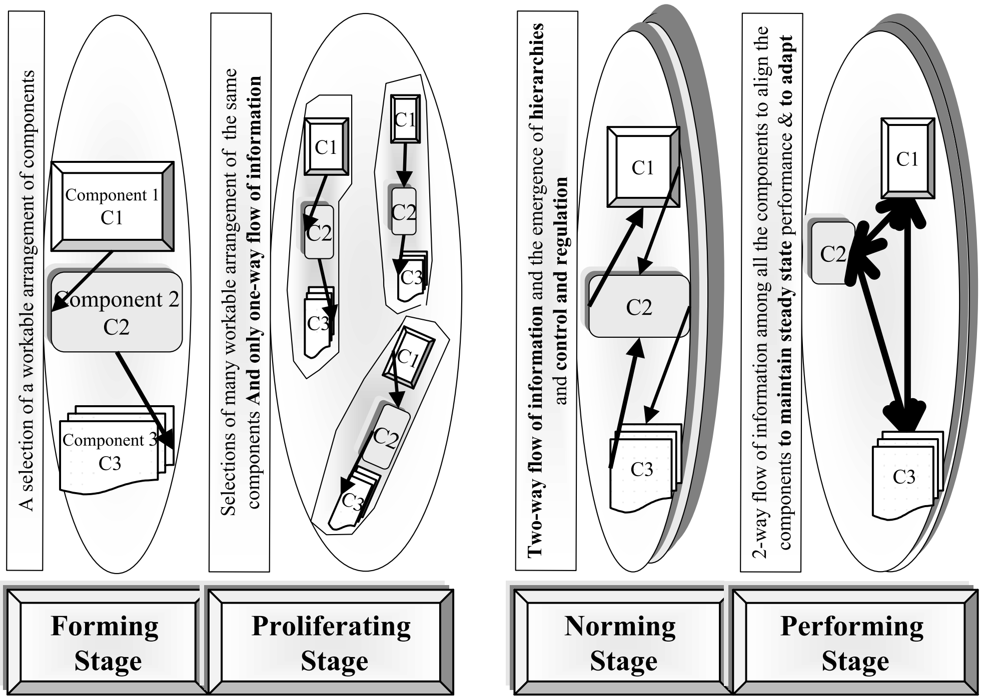

Figure 1 | The role of components in shifting paradigms.

flow modelling capabilities and these stages are reproduced in Table 1 (see Khatibi (2001)). A more comprehensive substantiation of the postulate in relation to hydraulic systems is outside the scope of one paper but this is compensated for in the following ways:

(i) outlining a number of paradigms related to hydraulics in tabular form;
(ii) selecting flood forecasting for a detailed presentation of the application of systemic problem-solving; and
(iii) presenting the application of the postulate to a number of important problem areas in more detail.

For this purpose, the following have also been drafted: (i) the paradigm of software in hydraulic modelling, (ii) the paradigm of flood risk management, and (iii) the paradigm of modelling and systems.

Many hydraulic systems have been formed since the 19th century and acquired institutional outlooks with subsequent paradigm shifts mirroring other disciplines. Rudimentary forms of some of these systems with enterprise/system outlooks existed prior to the Industrial Revolution but as *ad hoc* arrangements rather than systems. Many of these systems are products of the Industrial Revolution, which include water supply systems, irrigation and/or drainage systems, flood management systems and inland navigation systems, although their rudimentary forms may be traced to prehistory. If hydraulic systems are appraised from Kuhn's (1962) perspective, various paradigms in hydraulics have matured enough and are at their normal science stage.

The writer regards systems and modelling as two intertwined paradigms formed in science and technology. Although the contribution of these paradigms in shaping hydraulic systems is substantial, other contributions are very important too, e.g. control/regulation, information technology, incident management, risk/value management and knowledge management, and those native to hydraulic systems, e.g. flood management and flood warning. The level of understanding on these concepts is often pragmatic and the creation of transparency among these systems is long overdue. Sources creating transparency are often subtle and not embedded in pragmatic problem-solving approaches but can be revealed for example through the stages in paradigm shifts; aspects of this for open-channel flow modelling systems are discussed by Khatibi (2001).

OUTLINING PARADIGM SHIFTS FOR A NUMBER OF HYDRAULIC SYSTEMS

Paradigm shifts for modelling open-channel flows are presented in Table 1, which is a reproduction and refinement of that given by Khatibi (2001). The summary is that, prior to the 1960s, open-channel hydraulic systems were analysed by reductive approach of one-component-at-a-time building on an extensive theoretical and empirical knowledge accumulated in the late 19th and early 20th centuries. With the advent of computers, it became possible to develop system-wide modelling, a capability that made it possible to interconnect the various components to gain an insight into the interactions and the synergy among the components and to identify the potentials of the systems and their blind spots. Software tools were improved to ease the appraisal of inter-component synergies. This led to the capability of customised solutions, such that the arrangement and configuration of the various hydraulic components could be determined to assure prescribed performance requirements and this marked the emergence of foresight in modelling.

One example of foresight in science is the consensus on global climate change, which was revealed through extensive simulations. Modelling interconnected the past, present and future on a whole range of issues related to climate change. Although it is not possible to provide a black-and-white proof for climate change but science is dismissing black-and-white proofs and shifting towards risk management. Under the emerging paradigm of risk management, modelling has revealed that high risks are associated with climate change and therefore it is not tenable anymore to dismiss the risk. In relation to foresight in science, many other similar simulations on other environmental issues revealed that extensive future problems would be likely without interconnecting the present activities with their future outcomes—hence the birth of sustainable development.

Tabular information is presented in Table 2 towards the substantiation of the postulate in relation to irrigation systems, water supply systems, flood management systems and flood forecasting systems. The information presented in this table is high level and focuses on the role of components at each paradigmatic stage. Although the table is only a confirmation that the outlook of hydraulic systems has been changing continually, the roles of components and their inter-component interconnections are highlighted more clearly. In this way, a foresight emerges that can serve towards improving these systems and creating transparency for the transfer of knowledge from one system to another.

SYSTEMIC KNOWLEDGE MANAGEMENT IN FLOOD FORECASTING

The writer holds that the delivery of the flood forecasting and warning service by the Environment Agency in England and Wales is at its norming stage and this paper identifies major problems to be solved with their tentative solutions through systemic knowledge management. The background is that each Regional Office of the Environment Agency has developed its own forecasting capability, meeting its own needs. Until recently, regional autonomy was an important and common feature for the development of practices within the Agency. These developments signified a one-way flow of information and were often piecemeal and opportunistic but the various regional practices have tended to be refined by Agency sponsored research activities and a ministerial directive. In the norming stage regional autonomy with opportunistic development is regarded as counter-productive. This paper identifies some of the main issues and problems and presents tentative solutions based on systemic knowledge management. Khatibi & Haywood (2002) explain the historic context of flood forecasting and warning in England and Wales, without presenting its paradigmatic context but with the concept of paradigm and systemic knowledge management in sight.

Table 1 | Paradigmatic stages in the making of open-channel modelling

Developmental stage	Attributes
Theoretical and empirical hydraulics –1960	☐ Theoretical open-channel hydraulics had matured by the early 20th century ☐ Computational difficulties dictated the limits of applications of theoretical hydraulics ☐ Hydraulic analysis was based on simplified equations and empirical formulae with inherent uncertainties ☐ Open-channel hydraulic systems were reduced into 'one-component-at-a-time', thus: • The synergy between the components was lost; • Risks of blind spots were created between the components and • Full system potentials could not be explored. ☐ Decision-making was restricted to cost-effectiveness and hydraulic feasibility ☐ Risks of adverse effects and conflicts related to engineered solutions were overlooked ☐ Insights into the complexity of adverse effects were not possible
The forming stage of modern hydraulic modelling tools 1960–80	☐ Definitive selective advantage of computational speed over manual calculations transformed theoretical hydraulics into working computational tools ☐ Numerous project-specific codes were developed often as a customary preoccupation in many academic, research and professional organisations ☐ These codes often served as problemsolving tools offering commercial advantages to their proprietors ☐ Initial codes were inflexible and required expertise and dedication ☐ Modelling was often carried out sparingly and in reaction to major problems ☐ Code developers were often the same dedicated hydraulic modellers who hammered out coding and runtime problems
The proliferation stage of computational tools 1980–95	☐ A limited number of these tools offered selective advantage by • Being general-purpose • Data-steered • Modularly-structured • Frontend data entry, backend graphic, geographic visualisers, error trap facilities ☐ Developments were biased towards toolmaking ☐ Modelling was used to critically examine and assess impacts of adverse effects ☐ Emergence of interdisciplinary modelling culture with new roles for hydraulic modellers and software developers ☐ The paradigm of the system-wide modelling capability emerged, as a result of which entire system complexities could be taken on board by constructing models as one-to-one analogous images of real systems

Table 1 | *Continued*

Developmental stage	Attributes
The norming stage of developing computational tools 1990–	☐ The monolithic ties between modellers and toolmaker have been breaking off and being transformed into partnering relationships
	☐ Commercial software applications gain a competitive edge by offering (i) intuitive model building tools (ii) facilities to problemsolve/customise engineering solutions
	☐ Users' expectations by greater user-friendliness, improved editors, error-traps, visualisers and by tabular/graphic facilities
	☐ Modelling has become a proactive tool to investigate the system compliance with a wide range of technical/management constraints imposed against multipurpose utilitarian river functions
	☐ Customised engineering solutions are possible
The performing stage of developing computational tools	☐ 'Total modelling' practices to serve 'sustainable development' for finding compromises to conflicting issues
	☐ 'Conscientious' practice is needed for a risk-based defensible practice, treating uncertainties and refined methodologies and modelling tools
Model usage	☐ Proactive practices for identification of system blind spots/potentials/bottlenecks
	☐ Assessment of impacts of proposed developments on river-basin systems or their interactions with the environment through a comparison of the performances of baseline and design systems by assessing 'levels of service', taking account of land use and flood frequencies
	☐ Customised solutions for rehabilitation/mitigation of the system and its components
	☐ Important decision-making tools for conflict resolution/flood warning

Some of the fundamental problems to be solved on flood forecasting and warning include: (i) enhancing the level of confidence on forecasting results, (ii) interconnecting technical drivers with other drivers, (iii) selecting a modelling solution, (iv) interconnecting the service with other flood management measures, (v) creating systemic arrangement within the service, and (vi) promoting open architecture in software development towards 'user-designed software systems'. Thus, there are many gaps but these can be solved through systemic knowledge management by (a) categorising complexities at each hierarchy towards customising solutions, (b) challenging the underlying assumptions and (c) fostering cultural reorganisations to adapt to new changes.

(i) Enhancing the level of confidence on forecasting results

The growing wealth of international experience on modelling the various catchment processes suggests that there is no single modelling technique to outperform others for delivering a prescribed accuracy with minimal costs. Yet the various models do not produce identical results. This contrast signifies that there are gaps and arguably they can be bridged through knowledge management. The fundamental problems to be solved are: categorising the modelling techniques and categorising physical systems vulnerable to flooding and then transforming a wealth of tacit knowledge already accrued into

Table 2 |

The case	Paradigms before and after forming	Proliferation stage	Norming stage	Towards the performing stage
Irrigation systems Transfer water from where available but often not needed to where needed but often not available See Khatibi 2002*a*	• Traceable to the settled way of life • Traditional systems were: —Integrated to local market patterns —Restricted to a subsistence economy —Unable when demand/supply vary —Exploited gravity with no significant hydraulic structures • Irrigation enterprises emerged as large-scale plantation agricultural schemes through colonial powers—since 17th/18th centuries	• Distributing stored water through large canals without significant control structures • Incorporation of some hydraulics/technology since 19th century • Early 20th century systems emphasised on technological innovations • Social impacts were ignored in privately owned early large schemes and in nationalised enterprises of the 20th century • Technical local components emerged in early 20th century, e.g. weir, gate, offtake	• Frequent reports of poor performances • The need for problem-solving/remodelling • The emergence of following issues (1980): —Holistic approaches —Integration of technical/social dimensions —Remodelling for steady deliveries through efficiency, equitability, flexibility, water conservation, workability and integrity • Chambers (1988) criticises the manner of application of holistic approaches in the 1980s, holding them to be descriptive	• A framework is emerging to regard these systems as business enterprises placing in Management, Operations and Maintenance (MOM) models • An increasing emphasis on sustainability of these systems through studying their interdisciplinary interfaces and identifying their blind spots both in technical and social dimensions • Holistic problemsolving methodologies widespread
Municipal water supply High-technology enterprises delivering wholesome water to meet random demands within acceptable pressure ranges	• Prior to industrialisation coexistence among man, nature and water resources • Urbanisation upset the balance and required reliable supplies—the 19th century • The delivery of wholesome water needed the development a specific technology • Driven by individual entrepreneurs, a technology was developed by the early 19th century but on ad hoc basis	• Improved flexibility by pumping but overall labour intensive up to the 1950s • Improved efficiency by semiautomatic, local, remote and fully automatic control for backwashing/chlorination and other processes in 1950–1970 • The total system: sequence of abstraction, storage reservoirs, stored water supply, water treatment works, delivery and reticulation systems, consumption, drainage and disposal.	• Intensive agricultural techniques and deterioration of the quality of raw source-waters since the 1980s • Public perception and green philosophies—1980s and 1990s • New stringent directives on water quality • Novel treatment processes on taste, odour, colour, pesticides and nitrite concentrations • Regarding water as a trading commodity and regulated water industries and enforced by agencies since the 1980s and 90s	• Remodelling: uprating for capacity, upgrading for improved water quality and automating for reliable operations • Pre-ozonation: inactivate algae, partially disinfect and improve micro-flocculation; • Post-ozonation and granular activated carbon beds to remove pesticides; • Dissolved air floatation counter current: remove algae/improve on taste and odour • Reliable operations: automatic operations • Cost savings/ management/directives

Table 2 | *Continued*

The case	Paradigms before and after forming	Proliferation stage	Norming stage	Towards the performing stage
Flood drainage systems Primary function: land drainage, navigation, fishing, power/mills, leisure/abstraction/ waste disposal	• Prior to the industrial revolution: • Floodplains/washlands/flood marshes were often habitats • Biodiversity and geomorphologic forces were in balance • But at a limited scale, riparian owners were in balance with natural forces along river courses and coastlines	• Encroachment of floodplains/washlands/flood marshes since industrial revolution • A network emerged of tree-like and/or looped channels, complex floodplains, regulatory structures e.g. weirs/sluice/barrier, navigation, detention/ retention structures, features for flood defences, low flow, aquatic life	• Govern mental policies evolved on flood-plains and coastlines through localised to strategic engineering measures, • Adverse effects accumulated since industrial revolution until the late 1980s • Realisation for sustainable development and restoration of environmental and ecological balances since the 1990s	• Environmental movements in the 1980/90s aligned conscientious professionals with environmental goals. • Institutional setting in the USA served as a model to set up agency-type organisations for regulation/enforcement in water services • Customisation in drainage systems towards knowledge management
	• Risks are high frequency low impact	• Risks are low frequency high impact	• A risk-based culture emerges	• Risks should be low frequency low impact

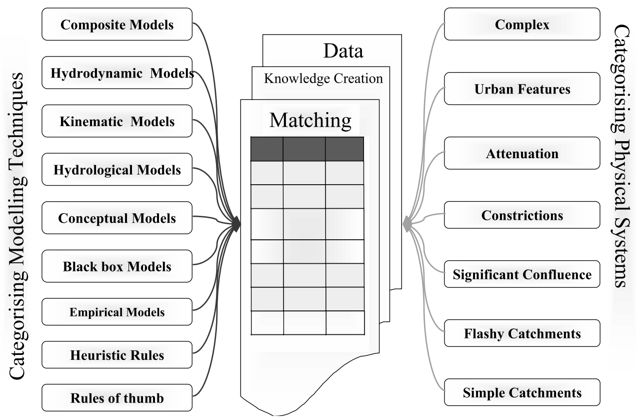

Figure 2 | Categorising modelling techniques and fluvial systems.

explicit knowledge and guidelines by matching each category of techniques to each category of systems.

Already there are a number of R&D projects commissioned by the National Flood Warning Centre of the Environment Agency to lay down a framework for such knowledge creation, see Figure 2. Categorisation will play a key role and the writer uses the concept of control volume to categorise flood-modelling approaches (Khatibi *et al*. 2002). Control volume is a microcosm of the whole system so that flow state in the prototype system is rendered by replicating the control volumes side by side to describe the propagation of flood waves. It is composed of (a) a physical building block characterised by the selected spatiotemporal resolution, where resolution is the smallest level of detail, and (b) a conceptual building block normally described by mathematical equations expressing conservation laws of nature or empirical relationships.

A paper has been prepared by the writer on categorising modelling techniques based on control volume, an outline of which is presented by Khatibi *et al*. (2002*a*) and Khatibi & Haywood (2002); the latter also outlines possible approaches for the categorisation of physical systems. Some possible options for matching categories of modelling techniques with categories of physical systems include: (a) fit-for-purpose approaches if data availability is poor, (b) rules of thumb based on transforming observations to guidelines, (c) guidelines based on articulating tacit knowledge, (d) homologous approaches, and (e) semi-empirical approaches by developing a rough model for a cyclic improvement. For instance, if no information is available to design a modelling solution for a particular physical problem, the modeller can select a simple solution fit for the problem. However, a site visit and a review of past records can reveal a great deal about the modelling requirement and such tacit knowledge can be transformed into guidelines, e.g. for a long river without tributary and upstream reservoirs, level-to-level correlation can be an adequate method of flood forecasting. The homologous approach may be described as the selection of a modelling solution for a problem by comparing it with similar problems for which known good modelling solutions have been documented.

(ii) Interconnecting technical drivers with other drivers

The Environment Agency has a lead role in providing flood forecasting and warning services. There are a number of important drivers to continually refine the service to meet customers' needs through targeting flood warning messages and customising flood forecasting solutions to local requirements. The problems to be solved include (a) interconnecting the technical driver with the social dimension, discussed here, (b) interconnecting the service with the social dimension, and (c) interconnecting technical and economical drivers.

(a) Interconnecting the technical driver with the social dimension

Flood forecasting and warning is not a monolithic service. An early model of breaking down this service into subsystems was given by Haimes *et al*. (1989). These concepts are evolving until an insight into the optimum solutions of interconnection among the subsystems is identified. There are two problems here: to modularise the system into components and interconnect them through performance criteria in terms of accuracy, timeliness and reliability, even though there are no agreed definitions for these criteria yet. One solution is depicted in Figure 3, comprising the insertion of interfaces in amongst detection, flood

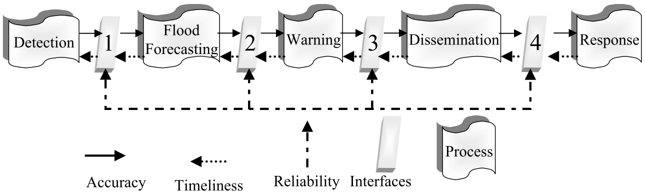

Figure 3 | Interconnecting technical drivers with other drivers.

forecasting, warning, dissemination and responses as follows:

- Interface 1 between Detection–Flood Forecasting
- Interface 2 between Flood Forecasting–Warning (decision-making)
- Interface 3 between Warning–Dissemination
- Interface 4 between Dissemination–Response
- Accuracy reflects the modellers/forecasters mathematical view of these sequences at interfaces, i.e. Interfaces 1–2–3–4–the forward direction; similarly timeliness represents the flood forecasting and warning requirements at each interface to serve the population at risk of flooding.

(b) Interconnecting the service with the social dimension

The criterion of timeliness is a social driver and evolves through the same interfaces, i.e. Interfaces 4–3–2–1–the reverse direction. The criteria at both of these forward and reverse directions describe the performance during an incident but these performances in, a statistical sense, reflect the reliability criterion. With such an approach in place, the reliability of a particular forecasting solution can be prescribed and monitored. The point to be emphasised here is that the various systems are interconnected in this systemic approach and in addition the technical drivers (the forward direction) are interconnected with the social drivers (the reverse direction).

(c) Interconnecting technical and economical drivers

The principle is part of designing a modelling solution, as explained in the next subsection and depicted in Box 1 of Figure 4. The economic driver signifies that, if the damage to be avoided by a flood forecasting solution is high, there is a justification for costly high-resolution models, else

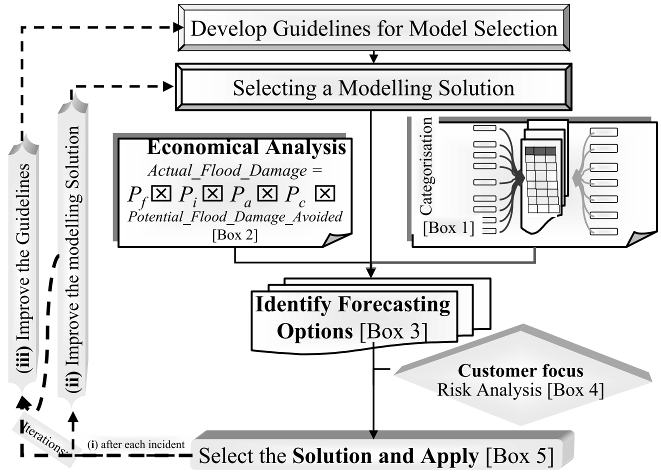

Figure 4 | The procedure for the selection of a forecasting solution.

credible solutions have to be found to mitigate low-level damage risks through low-resolution models. The inherent principles are explained by Khatibi & Haywood (2002).

(iii) Selecting a modelling solution

Traditionally, selecting a modelling technique for a particular application in an office does not involve an exhaustive search of all the techniques but rely on the past experience and continued capability. The culture of civil engineering design on selecting a structural member is yet to be transferred to selecting a modelling technique for a particular problem. The systemic knowledge management is capable of creating the new culture of selecting a 'modelling solutions' from whole range of modelling techniques.

The principles are shown in Figure 4 and may be outlined as follows. A number of feasible 'modelling options' can be identified through matching economical drivers with technical drivers (Box 3) and therefore a risk evaluation is necessary for the selection of a defensible modelling solution (Box 4). Thus, it is realised that there may be more than one modelling category meeting more than one category of physical systems in need of flood forecasting and warning. Hence, there is a need to distinguish between modelling options and a selection of a modelling solution. The selection procedure above compounds the interconnections of technical and economical drivers with each other in a risk-based decision-making environment, where technical drivers are interconnected with social drivers, as depicted in Figure 4.

(iv) Interconnecting flood forecasting and warning with other flood management measures

The flood forecasting and warning service in current practices is a discrete measure accounting for residual risks associated with the performance of preventive measures. In a system with a host of other measures to mitigate flood risks, it is not quite possible to assess the contribution of flood forecasting and warning as a mitigation measure, because of methodological problems. Thus, presently there is no lateral holism among some of its flood mitigation measures but the measures presented above on selecting a modelling solution with prescribed confidence enables the flood forecasting and warning service to be integrated to the body of other measures in a quantitative manner. For an outline, see Khatibi & Haywood (2002).

(v) Creating systemic arrangement within the service

The ultimate solution for this service will be the delivery of 'safe systems', where a report defines it as a strategy to demonstrate that steps are taken to ensure that all hazards in all locations are identified, quantified and assessed (R&D Note 106 1992). Such a strategy also includes the folowing:

- Approaches for each class of hazards in each location, commensurate with existing technical capability and within reasonable cost-effectiveness parameters.
- Awareness of risks inside and outside the organisation.
- A safety case for each situation where a hazard is identified.

Where business requirements are contrary to safe systems strategy, conscious decisions must be made. The delivery of safe systems is a formidable task and requires a higher level of insight into the complexity of the system. It depends on the following:

- the capability to deliver customised solutions,
- developing partnership among the stakeholder groups, and
- determining the systemic arrangement in the technical and social dimensions and among the stakeholders.

This subject is vast and beyond the scope of one paper, let alone this paper. The overview is that knowledge is required for an understanding of the synergy between the components within a hierarchy or among the hierarchies and interactions at the interfaces of different subsystems. Such knowledge is often tacit and due to be transformed to explicit knowledge. It is difficult to see if there are gaps or inconsistencies at this stage. For instance, the commendable culture of partnership can be at risk without owners, which can be significant when conflicts prevail. One solution is that systems scientists own the partnership at a generic level through a risk-based culture, where the systemic arrangement can play a determining role. Before solving these complex problems, arguably the delivery of safe systems can only be a goal.

(vi) Promoting open architecture in software development towards 'user-designed software systems'

This subject has been outlined by Khatibi *et al*. (2001) but a comprehensive treatment of the subject is compiled under the concept of paradigm shifts (Khatibi *et al*. in press). An outline is that models in the form of assembled datasets are currently system dependent. Thus, if the hydrodynamic or conceptual model dataset of a fluvial flow system is developed using Software A, the same model dataset is normally useless in the environment of Software B developed for the same set of equations with minor differences. This is unacceptable and Khatibi *et al*. (in press) reflect on the consensus view among practitioners, model developers, software producers and academics to move away from this position through open architecture. This is defined in terms of assembling together a variety of off-the-shelf components from different producers without the need for any producers' intervention.

Challenging the assumptions

Reductive science places in a mechanism for challenging assumptions through the comparison of scientifically predicted and physically observed values; systems science introduces feedback loops for controlling or regulating the inherent entropy; and knowledge management uses high-level knowledge creation to challenge inherent assumptions. Following the culture of fuzzy logic, there is a realisation that deterministic modelling alone is not tenable anymore and subsequent results are bound to suffer from a whole range of shortfalls. Thus, there is a need for the integration of deterministic and stochastic approaches. Obviously various challenging mechanisms are valid and can be incorporated into the practice. For instance, Figure 4 depicts a number of mechanisms to challenge assumptions. These include (a) risk analysis for the selection of a particular solution, (b) monitoring the performance of a solution after each flood incident, (c) monitoring the performance after a number of incidents to revise the selected solution, if necessary; and (d) monitoring the long-term performance to improve on the guidelines.

Reorganisations

Reorganisation is a modern feature in dynamic organisations. The writer believes that these reorganisations are ultimately driving an organisation towards a capability to deliver customised solutions. This has reflected itself in the reorganisation of the flood forecasting and warning service in the Environment Agency. A detailed account of the historic context of this service in relation to flood management is presented by Khatibi & Haywood (2002) but without their paradigmatic context. The writer is preparing a paper regarding flood management as a paradigm and outlines its paradigm shifts from pre-paradigm periods to the performing stage.

An overview is that a provision for flood forecasting and warning emerged in a number of industrialised countries in reaction to high impacts of floods, stemming from encroachments onto floodplains and coastlines since the industrial revolution. Prior to encroachments, floods were still regarded as hazards but posed low-consequence risks, whereas the Industrial Revolution transformed the situation to low frequency but high consequence risks. In response to such high consequences, the risks had to be managed and the flood forecasting and warning service was a solution. At the initial stages, this service was formed as a paradigm often out of duty of care and proliferated among different authorities implicated with this duty of care—a one-way flow of information. Gradually, institutional arrangements were defined for this service defining lines of responsibilities and various tools of forecasting and dissemination were developed. The outcome in the experience of the Environment Agency was that there were eight regions with eight rather different practices. There are many drivers in recent years to align these regional differences towards best practice. Arguably the activities now correspond to the norming stages of this service—to foster a two-way flow of information.

The current organisational arrangement within the Environment Agency recognises the importance of the delivery of the service, for which the 26 Area Offices are better placed to provide a local focus. However, the creation of information for the operation of the service during each flood incident is a complex process and is the responsibility of Regional Offices. The national Flood Warning Centre is overarching these organisational arrangements on policy matters. The direction of research and development activities is sharply focused towards science-based and risk-based customers' needs. Best practice has not been fully defined but this is in the process of being realised. Despite a recent reorganisation, other waves of refinements cannot be ruled out.

COMMENTS

There are many other examples illustrating the need for the application of systemic knowledge management in hydraulic systems. For instance, there are some 13 different methods recommended for calculating the conveyance of compound channels (see Knight 2001) and yet a survey in Britain showed that these were not used by practitioners in Britain. The Environment Agency has initiated a large research program to consolidate these approaches and transform them into working tools. It is argued that, by regarding friction modelling as a paradigm, a better picture emerges on the various shifts. For instance, the development of some 13 conveyance modelling techniques is an important feature of the proliferation stage. Each technique may be seen as an unconnected component to one another, in the sense that there is little knowledge on the relative merits of each technique in solving practical problems. The research programme initiated by the Environment Agency is tantamount to sparking off a paradigm shift towards the norming stage.

Practitioners often experience many barriers against desirable courses of action but normally unable to remove them. Examples are inability to transfer a model across different systems, a lack of confidence on modelling results, and many hidden problems to deliver safe systems. The paper flags two possible causes for these barriers. A lack of interconnection among the various subsystems is an important barrier and this was discussed above. The other source of barriers is related to differences in the paradigmatic stages in the makeup of a system. The paper argues that a system or science is seen as a selection of intertwined paradigms, where each paradigm can be at its different stage of paradigmatic shift. For instance, the Environment Agency has successfully interconnected the delivery of the flood forecasting and warning services to end users through a wide range of information channels—a capability that is approaching customised solutions. Yet there are problems in the process of being solved on improving reliability of flood forecasting results—a capability that is currently in the proliferation stage but intensive research is underway to norm the practice.

CONCLUSION

As science is not a monolithic body of doctrine, this paper shows that so is not hydraulics. If fact, hydraulics is selecting and intertwining a whole range of paradigms, some native to hydraulics and many are laterally transferred from other disciplines. The postulate is evident in hydraulics on the formation of a paradigm and its subsequent shifts through proliferating, norming and performing stages. Some paradigms in hydraulic systems are in the proliferation stage, e.g. proprietary modelling systems; many paradigms are in their norming stages, e.g. flood forecasting and warning; and some are approaching towards their performing stages, e.g. modelling. The paper reveals a generic transparency between hydraulics and other disciplines of science through the application of systemic knowledge management in the context of paradigm shifts. This transparency confirms that science has a foresight in a generic level.

Paper II highlighted the role of categorisation as a conscious process for the norming stage of hydraulic systems to gain a better insight into inter-component synergies. The need for customised solutions is evident in many fields of flood forecasting and warning but such a solution is not often possible due to many barriers. These barriers often stem from a lack of interconnection between the components, some of which are outlined in this paper, together with their tentative solutions. This paper also highlights the lateral holism to be an important problem and suggests that systemic approaches are capable of interconnecting the various systems at their interfaces. Some of the problems together with their tentative solutions are discussed in this paper and these include the following: (i) enhancing the level of confidence on forecasting results, (ii) interconnecting technical drivers with other drivers, (iii) selecting a modelling solution, (iv) interconnecting the service with other flood management measures, (v) creating a systemic arrangement within the service, and (vi) promoting open architecture in software development towards 'user-designed software systems'.

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