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ADAPTIVE FLOOD RISK MANAGEMENT†

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ABSTRACT

Based on the worldwide experiences, the most important challenges of flood engineers are:

- managing substantial increase of flood risks with limited resources;
- avoiding adverse environmental consequences of flood control projects;
- coping with uncertainty in all relevant aspects.

Now in second decade of the 21st century, it has become obvious, that the approach to flood management is increasingly adaptive and non-structural. In the last decades, adaptive management has been extensively utilized in environmental and restoration projects. In this context, adopting the strategies of adaptive management in water engineering and flood management appears to offer great advantages. Adaptive management is a structured, iterative process of optimal decision making in the face of uncertainty, with an aim to reducing uncertainty over time via system monitoring. The strategies of adaptive flood management are as follows:

- adaptability (changing threat to opportunity);
- flexible decision making (to cope with uncertainties);
- monitoring and vigilance;
- learning while doing;
- application of new knowledge and technologies;
- avoiding costly irreversible mistakes;
- updating the objectives;
- extensive risk recognition;
- focus on long-term management rather than construction;
- resilience;
- harmony with environment;
- passive and active adaptive management;
- stakeholders participation;
- enhanced real time reactions. © 2020 John Wiley & Sons, Ltd.

KEY WORDS: gestion adaptative; gestion des inondations; des incertitudes; risque; approches non structurelles

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RÉSUMÉ

Sur la base des expériences mondiales, les principaux défis des ingénieurs en inondation sont les suivants:

- gérer une augmentation substantielle des risques d'inondation avec des ressources limitées;
- éviter les conséquences environnementales néfastes des projets de lutte contre les inondations;
- gérer l'incertitude sous tous ses aspects.

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Au début du 21e siècle, il est devenu évident que la gestion des inondations est de plus en plus adaptative et non structurelle. Au cours des deux dernières décennies, la gestion adaptative a été largement utilisée dans des projets environnementaux et de restauration. Dans ce contexte, l'adoption des stratégies de gestion adaptative dans les domaines de l'ingénierie de l'eau et de la gestion des crues semble offrir de grands avantages. La gestion adaptative est un processus structuré et itératif de prise de décision optimale face à l'incertitude, dans le but de réduire l'incertitude au fil du temps via la surveillance du système. Les stratégies de gestion adaptative des inondations sont les suivantes:

- adaptabilité (évolution de la menace en opportunité);
- prise de décision flexible (pour faire face aux incertitudes);
- surveillance et vigilance;
- apprendre en faisant;
- application de nouvelles connaissances et technologies;
- éviter les erreurs coûteuses et irréversibles;
- mettre à jour les objectifs;
- une reconnaissance étendue des risques;
- mettre l'accent sur la gestion à long terme plutôt que sur la construction;
- résilience;
- harmonie avec l'environnement;
- gestion adaptative passive et active;
- participation des parties prenantes;
- réactions améliorées en temps réel.

MOTS CLÉS: gestion adaptative; gestion des inondations; des incertitudes; risque; approches non structurelles

INTRODUCTION

Adaptive management (AM) is a structured, iterative process of optimal decision making in the face of uncertainty, with an aim to reducing uncertainty over time via system monitoring. In this way, decision making simultaneously maximizes one or more resource objectives and, either passively or actively, accrues information needed to improve future management. Adaptive management is a tool which, can be used not only to change a system, but also to learn about the system (Holling, 1978). Because adaptive management is based on a learning process, it improves long-run management outcomes. The challenge in using the adaptive management approach lies in finding the correct balance between gaining knowledge to improve management in the future and achieving the best short-term outcome based on current knowledge (Stankey and Allan, 2009).

Adaptive management can proceed as either passive adaptive management or active adaptive management, depending on how learning takes place. Passive adaptive management values learning only insofar as it improves decision outcomes (i.e. passively), as measured by the specified utility function. In contrast, active adaptive management explicitly incorporates learning as part of the objective function, and hence, decisions which improve learning are valued over those which do not (Holling, 1978), (Walters, 1986). In both cases, as new knowledge is gained, the models are updated and optimal management strategies are derived accordingly. Thus, while learning occurs in both cases, it is treated differently. Often, deriving actively adaptive policies is technically very difficult, which prevents it being more commonly applied. Key features of both passive and active adaptive management are:

- iterative decision making (evaluating results and adjusting actions on the basis of what has been learned);
- feedback between monitoring and decisions (learning);
- explicit characterization of system uncertainty through multi model inference;
- Bayesian inference;
- Embracing risk and uncertainty as a way of building understanding.

Adaptive management is particularly applicable for systems in which learning via experimentation is impractical.

HISTORICAL BACKGROUND OF ADAPTIVE MANAGEMENT

The use of adaptive management techniques can be traced back to ancient civilizations. For example, the Yap people of Micronesia have been using adaptive management techniques to sustain high population densities in the face of resource scarcity for centuries (Falanruw et al., 1989).

The origin of the adaptive management concept can be traced back to ideas of scientific management pioneered by Frederick Taylor in the early 1900s (Haber, 1964). While the term ‘adaptive management’ evolved in natural resource management workshops through decision makers, managers and scientists focusing on building simulation models to uncover key assumptions and uncertainties (Bormann et al., 1999).

Two ecologists at the University of British Columbia, Holling (1978) and Walters (1986), further developed the adaptive management approach as they distinguished between passive and adaptive management practice. Kai Lee, notable Princeton physicist, expanded upon the approach in the late 1970s and early 1980s, while pursuing a post-doctorate degree at UC Berkeley. The approach was further developed at the International Institute for Applied Systems Analysis (IIASA) in Vienna, Austria, while Holling was director of the Institute. In 1992, Hilbourne described three learning models for federal land managers, around which adaptive management approaches could be developed, these are reactive, passive and active.

Adaptive management has probably been most frequently applied in Australia and North America, initially applied in fishery management, but received more broad application in the 1990s and 2000s. One of the most successful applications of adaptive management has been in the area of waterfowl harvest management in North America, most notably for the mallard (Johnson et al., 1993), (Nichols et al., 2007).

ADAPTIVE MANAGEMENT IN ENVIRONMENTAL PRACTICES

Applying adaptive management in a conservation project or program involves the integration of project/program design, management, and monitoring to systematically test assumptions in order to adapt and learn. The three components of adaptive management in environmental practices are:

- testing assumptions is about systematically trying different actions to achieve a desired outcome. It is not, however, a random trial-and-error process. Rather, it involves using knowledge about the specific site to pick the best known strategy, laying out the assumptions behind how that strategy will work, and then collecting monitoring data to determine if the assumptions hold true;
- adaptation involves changing assumptions and interventions to respond to new or different information obtained through monitoring and project experience;
- learning is about explicitly documenting a team’s planning and implementation process and its successes and failures for internal learning as well as learning across the conservation community. The learning enables conservation practitioners to design and manage projects better and avoid some of the perils others have encountered (Stankey et al., 2005).
- open standards for the practice of conservation lay out five main steps to an adaptive management project cycle (Figure 1). The open standards represent a compilation and adaptation of best practices and guidelines across several fields and across several organizations within the conservation community. Since the release of the initial open standards (updated in 2007), thousands of project teams from conservation organizations (e.g. World Wildlife Fund (WWF)), local conservation groups, and donors alike have begun applying these open standards to their work.

ADAPTIVE MANAGEMENT IN OTHER PRACTICES AS A TOOL FOR SUSTAINABILITY

Adaptive management as a systematic process for improving environmental management policies and practices is the traditional application; however, the adaptive management framework can also be applied to other sectors seeking sustainable solutions such as business and community development. Adaptive management as a strategy emphasizes the need to change with the environment and to learn from doing. Adaptive management applied to ecosystems makes overt sense when considering ever changing environmental conditions. The flexibility and constant learning of an adaptive management approach is also a logical application for organizations seeking sustainable methodologies. Businesses pursuing sustainable strategies would employ an adaptive management framework to ensure that the organization is prepared for the unexpected and geared for change. By applying an adaptive management approach the business begins to function as an integrated system adjusting and learning from a multi-faceted network of influences not just environmental but also, economic and social (Dunphy et al., 2007). The goal of any sustainable organization guided by adaptive management principals must be to engage in active learning to direct change towards sustainability (Verine, 2008). This ‘learning to manage by managing to learn’ will be at the core of a sustainable business strategy (Bormann et al., 1993).

Sustainable community development requires recognition of the relationship between environment, economics and social instruments within the community. An adaptive management approach to create sustainable community policy and practice also emphasizes the connection and confluence of those elements. Looking into the cultural mechanisms which contribute to a community value system often highlights the parallel to adaptive management practices, ‘with [an] emphasis on feedback learning, and its treatment of uncertainty and unpredictability’ (Berkes et al., 2000). Often this is the result of indigenous knowledge and historical decisions of societies deeply rooted in ecological practices

Figure 1. Adaptive management cycle. [Colour figure can be viewed at wileyonlinelibrary.com]

(Berkes et al., 2000). By applying an adaptive management approach to community development the resulting systems can develop built in sustainable practice as explained by the Environmental Advisory Council:”active adaptive management views policy as a set of experiments designed to reveal processes that build or sustain resilience”. It requires, and facilitates, a social context with flexible and open institutions and multi-level governance systems that allow for learning and increase adaptive capacity without foreclosing future development options’.

ADAPTIVE MANAGEMENT IN FLOOD MANAGEMENT AND WATER ENGINEERING

Till 1927, the main flood policy of U.S. Army Corps of Engineers was ‘levees only’. After the great flood of 1927, flood management by reservoirs was also included. The concept of non-structural measures (NSM) was first used in the context of flood control some 50 years ago, as a means to reduce the ever increasing damages, without unduly expanding the costly infrastructure. In that sense, NSMs were perceived rather as complementary additions to the essentially structural solutions to flood control, in order to reduce costs and enhance efficiency (WG-AFM). This concept has been changed in the last few decades by introduction of new approaches as shown in Figure 2:

- development of the new Swiss safety concept for dams in 1985 (Biedermann, 1997), (Biedermann, 1985);
- publication of the *Manual on non-structural approaches to flood management* by the International Commission on Irrigation and Drainage (ICID) in 1999 (ICID, 1999);
- publication of the International Commission on Large Dams (ICOLD), *Non-structural risk reduction measures; benefits and costs for Dams* in 2001 (ICOlD, 2001);
- UNESCO (IHP-V) Workshop on *Non-structural measures for water management problems* in 2001 (Simonovic, 2002);
- publication of U.S. Army Corps of Engineers manual on *Adaptive management for water resources project planning* in 2004 (U.S. Army Corps of Engineers, 2004);
- Publication of the proceedings of Question 53 of ICID congress on *Harmonic coexistence with floods* in Beijing in 2005.
- The latest manual of ICID’s Working Group on Comprehensive approaches to flood management (WG-CAFM) on *Adaptive flood management* (in preparation).

Now in the second decade of the 21st century, it has become obvious, that the approach to flood management

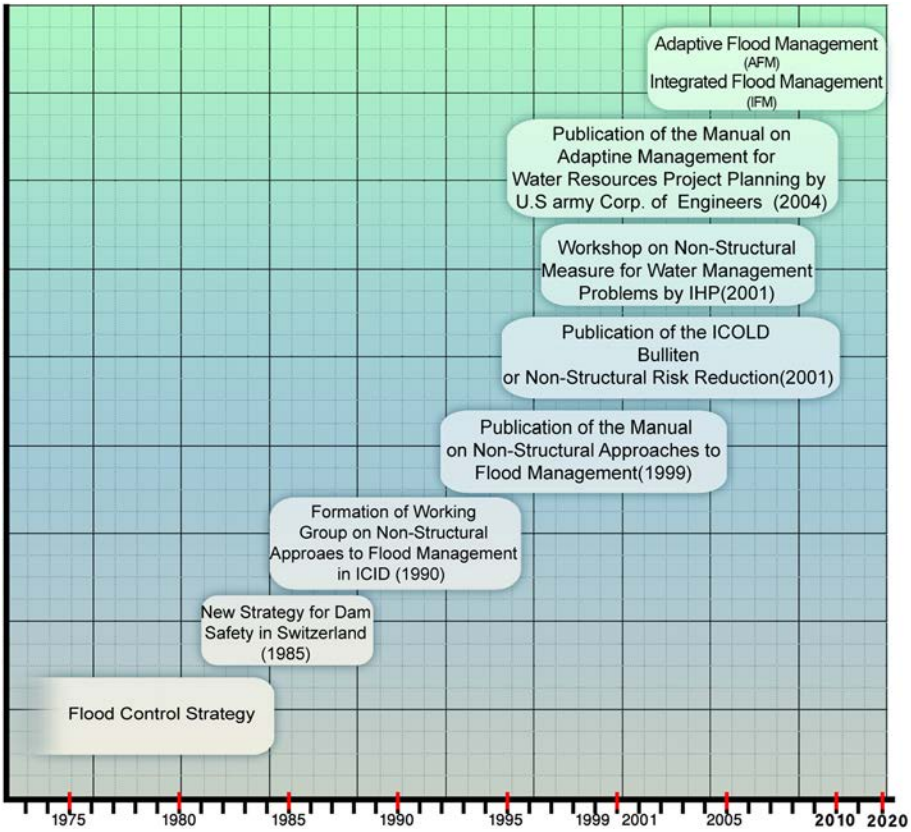

Figure 2. Evolution of non-structural approaches and adaptive management in flood management. [Colour figure can be viewed at wileyonlinelibrary.com]

is increasingly shifting toward adaptive and non-structural measures: structural, engineering solutions appear as indispensable complements to the essentially non-structural, integrated water resources management, of which flood damage reduction is but an integral part.

ADAPTIVE MANAGEMENT CONCEPTS AND RATIONALE

During the 20th century, scientists like Bohr and Heisenberg challenged traditional paradigms with discoveries and theorems that emphasized uncertainties, complexities, and the limits of scientific knowledge (Peat, 2002),(PM World Today, 2008). These contrasting paradigms are today reflected in distinctly different scientific schools of thought. On one hand, a Newtonian vision of the world is based on stability and predictability of natural systems. On the other, the vision promoted by Bohr and Heisenberg recognizes that change and surprises are the essence of natural systems. Newtonian principles are appropriate when working in stable systems and for designing civil engineering structures, for example, but are not fully adequate when applied to complex, dynamic ecosystems.

Adaptive management applications

As the world changes, or as unanticipated consequences are being revealed, organizations should adjust plans and operations to deal with the new conditions and to incorporate improved understanding.

Adaptive management is a common sense strategy for addressing the reality of a changing and uncertain environment. Recognition of the need to adjust management strategies can derive from at least three broad sources. First, *scientific advances* can provide better understanding of the complex linkages between human activities and environmental impacts. The U.S. Army Corps has experienced such paradigm shifts, one of the most famous being the abandonment of its ‘levees only’ strategy in the early 20th century (Barry, 1997). Through much of the 19th century and the early 20th century, the Corps of Engineers based its flood control program on the notion that levees were, by themselves, adequate for controlling all floods and that other measures (e.g., upstream reservoirs) were not necessary. Devastating floods along the lower Mississippi River in 1927 proved the inadequacy of this policy and ultimately resulted in the Corps moving toward a broader approach to manage flood risks. Second, *environmental changes and variability* affect the operations and impacts of Corps projects. For example, climatic variability may affect precipitation patterns, which in turn may affect the parameters of dam and reservoir operations. Thirdly, *shifts in social objectives and preferences* may challenge conventional operations schemes. In the United States, for example, the 1960s and 1970s marked a period of increasing concern over environmental issues.

Adaptive management theories, frameworks, and practices

Adaptive management seeks insights into the behaviour of ecosystems that are utilized by humans, and it draws upon theories from ecosystem sciences, economics and social sciences, engineering, and other disciplines. Adaptive management incorporates and integrates concepts such as social learning, operations research, economic values, and political differences with ecosystem monitoring, models, and science.

Adaptive management aims to create policies that can help organizations, managers, and other stakeholders respond to, and even take advantage of, unanticipated events (Holling, 1978), (Walters, 1986). Instead of seeking precise predictions of future conditions, adaptive management recognizes the uncertainties associated with forecasting future outcomes, and calls for consideration of a range of possible future outcomes (Walters, 1986). Management policies are designed to be flexible and are subject to adjustment in an iterative, social learning process (Lee, 1999).

Adaptive management is intended to increase the ability to fashion timely responses in the face of new information and in a setting of varied stakeholder objectives and preferences. It encourages stakeholders to bound disputes and discusses them in an orderly fashion, while environmental uncertainties are being investigated and better understood.

Adaptive management can help reduce decision making gridlock by making it clear that decisions are provisional, that there is often no ‘right’ or ‘wrong’ management decision, and that modifications are expected. Adaptive management should help stakeholders, managers, and elected officials and other decision makers recognize the limits of knowledge and the need to act on imperfect information.

Adaptive management is not simply a ‘trial and error’ process, but rather represents a more systematic ‘learning while doing’ process (Lee, 1999).

Some degree of learning is inevitable in almost any management approach; adaptive management is structured to make that learning more systematic and efficient.

A distinction is often made between adaptive management approaches that are ‘passive’ and those that are ‘active.’ Within ‘passive’ adaptive management, a single, preferred course of action, based on existing information and understanding, is selected. Outcomes of management actions are monitored, and subsequent decisions are adjusted based on the outcomes. This approach contributes to learning and to more effective management, but it is limited in its ability to enhance scientific and management capabilities for conditions that go beyond the course of action selected. By contrast, an ‘active’ adaptive management approach reviews information before management actions are taken. A range of competing, alternative system models of ecosystems and related responses (e.g. demographic changes; recreational uses), rather than a single model, is then developed. Management options are then chosen based upon evaluations of these alternative models. All modes of adaptive management require outcomes of management actions to be monitored.

Elements of adaptive management that have been identified in theories and practice are:

- management objectives that are regularly revisited and accordingly revised;
- a model(s) of the system being managed;
- a range of management choices;
- monitoring and evaluation of outcomes;
- a mechanism(s) for incorporating learning into future decisions;
- a collaborative structure for stakeholder participation and learning.

Table I summarizes practices that were fairly standard as of a generation ago, as well as ways in which those practices are evolving.

An important aspect of evolving concepts of engineering practice is the way uncertainty is recognized and addressed. It is today widely appreciated that many consequences of civil engineering investments cannot be precisely forecasted. Whether the objective is to take advantage of new opportunities or to insure against bad outcomes, the goal is to create the capacity to respond appropriately as new situations which may include unforeseen surprises develop. Flexibility over the life of the project is essential to effective development and functioning of civil engineering systems.

Table I. Trends in the evolution of civil engineering design practice

	Nature of change	
Design element	From traditional	Broadening to
Scope	Project	System of projects
Purpose	Single purpose	Multiple and sometimes conflicting objectives
Means	Structural	Non-structural
Focus	Construction	Long-term management
Risk Recognition	Little	Extensive

Adaptive management concepts and practices represent innovative, current thinking on resolving conflicting demands and adjusting to changing social preferences and priorities.

Many of adaptive management's benefits come in the form of better knowledge of ecosystem response to management actions. This improved knowledge reduces uncertainties and should therefore improve management decisions. Benefits of better future management decisions will be realized in the future. These benefits, however, are difficult to measure and translated into dollars, the standard metric of economic analysis. The intangible nature of these benefits stands in contrast to the direct, up-front costs of adaptive management programs, such as ecosystem monitoring programs, scientific staff, and institutional support.

The strategies of adaptive flood management (AFM) are shown in Figure 3 (ICID, in preparation).

HOLISTIC DESIGN OF ADAPTIVE HYDRAULIC STRUCTURES

A doctoral dissertation entitled *Holistic design of adaptive hydraulic structures* was presented in 1998 (Emami, 1998b), (Emami, 2005a), (Emami, 2005b), (Emami, 2005e). The main strategies of the holistic design are as follows:

- Ensure a flexible and adaptive design in view of hydrosystems' changes and the inherent uncertainties of water engineering;
- Establish the interdependence of hardware (structures), software (monitoring system, management) and brain ware (experts, management and knowledge) in design;
- Adapt to the stochastic nature of river flow by integration of seasonal characteristics and river forecasting;
- Learn while doing;
- Recognize the uncertainties of risks of project and design hydraulic structures to adapt to extreme events far larger than the design parameters and remain inherently safe (structural ductility and resilience (American Society of Civil Engineers (ASCE) Task Committee, 1995), (Hansen, 1992), (Emami, 1998a), (Emami, 1998b), (Emami, 2005c), (Emami et al., 2002), (Emami, et al., 2005);
- Base the design on comprehensive management and flexibility;
- Enhance safety by 'designing' crisis management preceding the events and in real time for the structure and downstream population centres;
- Comprehensive monitoring of hydro systems and structures.

Using the function analysis system technique (FAST), which is one of the main features of the value engineering methodology, the holistic design strategies are shown in Figure 4. FAST diagram interconnects the functions by How-Why logic.

Obviously the holistic design of adaptive hydraulic structures closely corresponded with AFM. In the last two

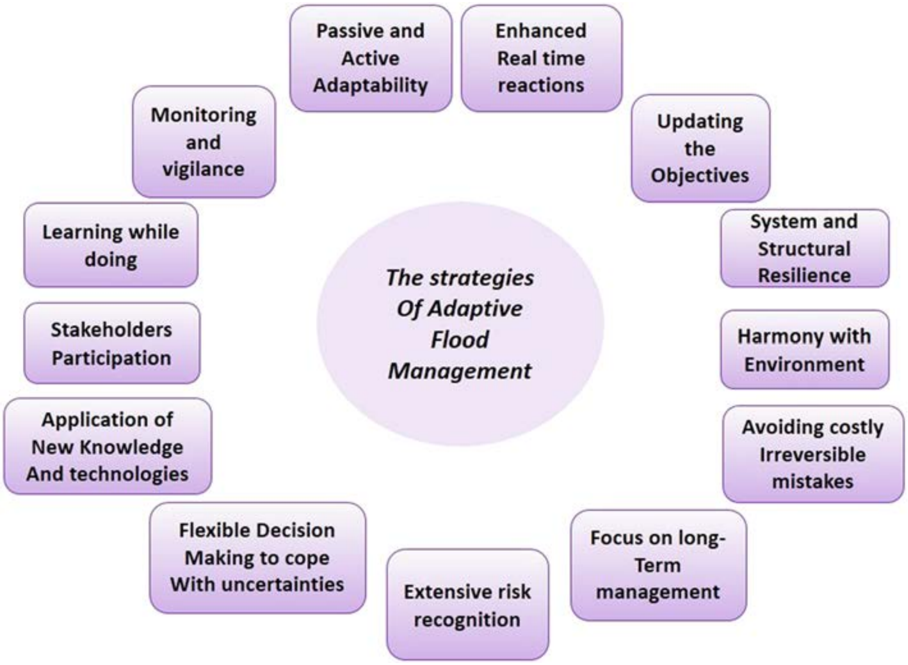

Figure 3. The strategies of adaptive flood management (AFM). [Colour figure can be viewed at wileyonlinelibrary.com]

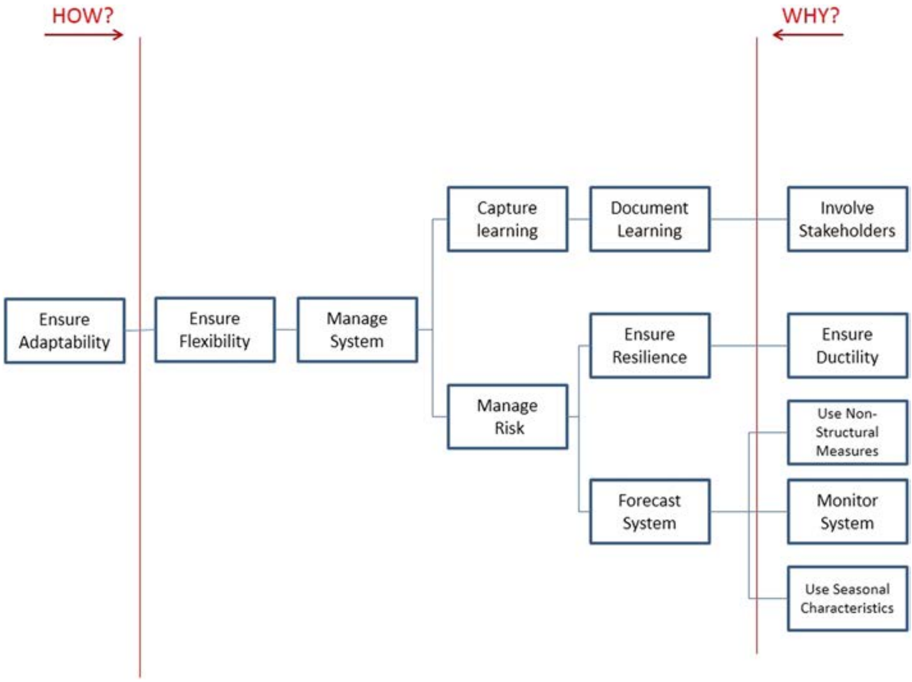

Figure 4. FAST diagram of holistic design of adaptive hydraulic structures. [Colour figure can be viewed at wileyonlinelibrary.com]

decades, the strategies of AFM were successfully applied to a few large water projects in Iran. A summary of these cases studies are presented below.

Case study #1: Sistan flood management project

The history of floods and droughts in the Sistan Plain extends to hundreds of years ago. During the past fifty years, major floods have occurred in 1957, 1982 and 1991 with tens of million dollars in total damage and unimaginable human suffering. The droughts for their part have prevented the development of this impoverished province of Iran. For example, the notable drought of 1971 was so severe that 70% of the population was forced to migrate to other provinces. Chahnime off-channel reservoirs, constructed in 1980 and shown in Figure 5, effectively prevented a similar disaster during 1984–1986 droughts.

After the floods of 1991, two alternatives were proposed for flood mitigation of the Sistan Plain. The first one was an option of flood control through huge dike construction. The alternative scheme was based on a holistic approach and called for addressing drought and flood problems by construction of more reservoirs and diverting the flood peak into the reservoirs by using non-structural approaches. The scheme would have resulted in enormous saving and reduced construction time. In practice, financed by the World Bank, the flood control dikes were constructed after 7 years in 1999. When the unprecedented drought in the history of the region began in 2000 and extended for 3 years, it became apparent what the region needed most were more reservoirs and holistic thinking. The Sistan River with an average volume of 2300 MCM (million cubic metres) dried up for 3 years. The drought was so severe that the irrigation area decreased from 100,000 to less than 10,000 ha.

Case study #2: Early impoundment of Marun dam

In view of water crisis in the world and economic considerations, impoundment of reservoirs during construction can be very important especially for large dams in developing countries. Using seasonal characteristics and forecasting models, the first filling can be achieved after the flood season. But the spillway should be in service before the next flood season. In the course of a research on early impoundment of 165 m high Marun Dam in Iran, application of holistic design strategies resulted in an innovation that would enhance the safety and flexibility of the first impoundment, which is the most dangerous period in the life cycle of a dam (Emami, 1998a), (Emami, 2001). A thin concrete shell was proposed for plugging of the diversion tunnel, which could readily be exploded if required to reverse the impoundment. The concrete shell was appropriately called fuse shell. The fuse shell would enhance the flexibility of the design especially in view of common uncertainties of water engineering. Unfortunately the fuse shell idea was not implemented for the first filling of Marun Dam in March 1996. So when unexpected leakage of more than 7 m^3/s occurred during the filling (Figure 6), the 10 m long concrete

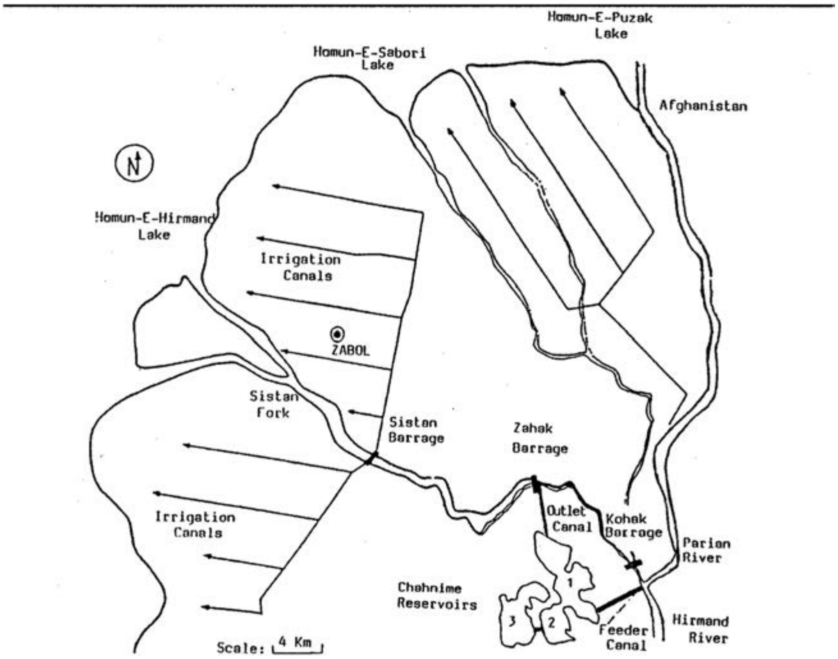

Figure 5. General Map of the Sistan Region in South-East Iran.

Figure 6. Marun Dam after first filling. [Colour figure can be viewed at wileyonlinelibrary.com]

plug lacked the desired flexibility. The fuse shell could have saved the day. It could have ended the crisis in 2 or 3 days instead of 6 months. The probability of piping in the core, the delay in construction activities and the environmental damages to the fishes after the explosion of the gates could have been avoided. In practice, the first application of the fuse shell was in another Iranian dam, Godalandar on Karun River for the first impoundment in December 2000 (Emami, 2001). Unlike the Marun Project, there was no need for explosion of the plug in the first impoundment of the Godalandar Dam in December 2000. However, the existence of the fuse shell gave the owner and the consultants the assurance required for a safe and flexible impounding scheme(Emami, 2005d).

Case study #3: Value engineering of Vanyar spillway

In a value engineering study undertaken in 2003 on the spillway of Vanyar Dam in North-West of Iran, the Kurit expert system guidelines on selection initial reservoir elevation in routing of the design flood and season characteristics resulted in considerable reduction of spillway length. The length of the side channel spillway, which was 110 m in the base case (Figure 7), was reduced to 40 m when a lower initial reservoir elevation for routing of the design floods in spring for wet years was proposed in the creative phase of the value engineering studies. The water resources modelling of the system demonstrated that if the decision for reservoir drawdown were based on the forecasting model, the drawdown would not reduce the regulated flow of the reservoir. The intelligent operation proposed not only decreased the spillway cost by 40% and solved the geological problems at some part of the spillway, but also considerably would reduce the outflows of different floods in Tabriz, which is located just 5 km downstream of the dam. Finally the damages of flood inundation on the reservoir rim would be reduced substantially. It is interesting to note that a comprehensive flood forecasting and warning system (FFWS), emergency action plan (EAP) and decision supporting system (DSS) have been designed for this project (Figure 8). Based on the results of forecasting models for spring volume of Ajichay River in three consecutive years, a drastic improvement of the models and learning has been observed.

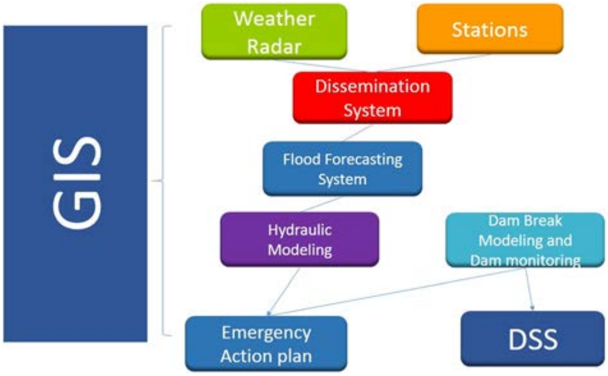

Figure 8. General view of the comprehensive Ajichay non-structural system (monitoring, forecasting, EAP and DSS). [Colour figure can be viewed at wileyonlinelibrary.com]

Furthermore, in the context of the restoration of Urmia Lake, which is the largest salt lake in the Middle East, it was decided to change the main objective of Ajichay Dam from agriculture to lake restoration in 2015. In this context the non-structural approaches adopted for hydrological safety of the dam is much more adaptive than the structural alternative and consequently billions of rials would be saved.

Case study # 4: Early impoundment of Karkheh dam

The Karkheh Dam is a large multi-purpose earthen embankment dam built in Iran on the Karkheh River in 2001. The

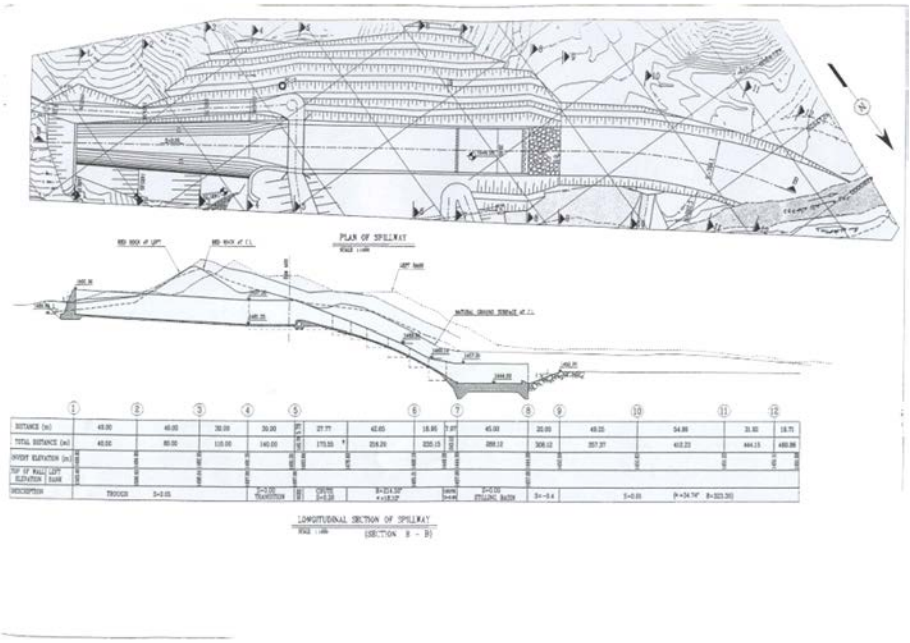

Figure 7. Plan and cross section of Vanyar Spillway (base case, 110 m long side channel spillway). [Colour figure can be viewed at wileyonlinelibrary.com]

dam is on the Karkheh River in the Northwestern Province of Khūzestān, the closest city being Andimeshk to the East. It is 127 m high and has a reservoir capacity of 5.9 BCM (billion cubic metres) (Figure 9). The Karkheh Dam is designed to irrigate 320,000 ha of land, produce 520 MW of hydroelectricity and to prevent downstream floods. In 1956, studies began on the Karkheh Dam by the American company Development and Resources Corporation, which was headed by David E. Lilienthal, the former Chairman of the Tennessee Valley Authority. In 1990, the final studies were completed by MahabGhods Consulting Engineers. The construction of the Karkheh Dam started in 1992 and the dam was completed in 2001. During construction, 120 contractual and over eight consultative companies worked on the dam.

Based on the worldwide experiences of dam failures, the first filling of a dam is the most dangerous period in the life cycle of dams. In this context, a comprehensive study for first filling was undertaken in the last 20 months of construction. In the context of this study, the strategies of AFM were applied in an integrated approach (Emami, 2005e). A day to day monitoring of the Karkheh Basin was undertaken and climate forecasting models based on El Niño southern oscillations (ENSO) were utilized along with hydrological forecasting models. When the models predicted below average inflow in next spring in February 2000, the impoundment of the reservoir started while the dam was still under construction and the embankment crest was below the spillway crest (Emami, 2005a). The following spring was one of the driest seasons in the history of the river but a volume of 400 MCM of water stored in the reservoir in the previous winter saved the day!

Case study # 5: ENSO based seasonal flood warning in Iran (2015)

In August of 2015, a very strong El Niño was forecasted and a study undertaken for six selected basin in Iran (Figure 10), indicated a good teleconnection of Strong ENSO events and precipitations in autumn. The historical finding supported the teleconnection observed. These forecasts were used for enhanced real time management of extreme floods observed in the south-west basins (Such as Marzi Gharb and Karkheh). In fact, the Iranian power ministry issued a warning on large floods forecasted for November and December 2015 one months in advance. The mentioned ENSO based forecasts and warning matched closely with the observed

Figure 10. Basins used for climate forecasting and flood warning in 2015–2016 in Iran. [Colour figure can be viewed at wileyonlinelibrary.com]

Figure 9. A general View of Karkheh Dam. [Colour figure can be viewed at wileyonlinelibrary.com]

floods and consequently the devastating effects of the floods were reduced (Emami, 2015a),(Emami, 2015b).

SUMMARIES AND CONCLUSIONS

The most important challenge of the flood engineers in the 21st century is to design and construct safe and low cost environment-friendly hydraulic structures with uncertain design parameters. Solution of this problem will above all require adopting a holistic and adaptive approach. The main strategies of the holistic design are to:

- ensure a flexible and adaptive design in view of hydrosystems' changes and the inherent uncertainties of water engineering;
- establish the interdependence of structural and non-structural approaches in design. In this context 'management of hydraulic structures' would have to be designed too;
- adapt to the stochastic nature of river flow by integration of seasonal characteristics and river forecasting;
- learn while doing;
- recognize the uncertainties of risks of project and design hydraulic structures to adapt to extreme events far larger than design parameters and remain inherently safe (structural ductility and resilience);
- base the design on comprehensive management and flexibility;
- Enhance safety by 'designing' emergency and crisis management preceding the events and in real time for the structure and downstream population centres.

In the past decade the holistic design has been used for several water projects including dam construction, flood management and value engineering studies. In all the cases the holistic design has resulted in enhanced safety and reduced cost and construction time. The experiences of application AFM in the above mentioned projects are as follows:

- the large projects are inherently unique; consequently the adaptation of holistic design for each case varies greatly from one to another project. In some cases one or two strategies have more effect on the proposed alternative;
- value engineering is an effective tool for achieving a unique solution for a unique project. The creativity phase and job plan of Value Engineering (VE) provide a good base for non-structural proposal. The participation of operation personnel in VE workshops would help the holistic approach of the team;
- for most cases, the clients and consultants readily accept the holistic approach for early impoundment of reservoirs. In this case, the non-structural approach can be very effective;
- in view of inherent uncertainties associated with determination of design floods, structural ductility has crucial importance in hydrological safety of cofferdams. In this context, it should be pointed out that in the last 15 years, 4 large cofferdams were overtopped and failed in Iran;
- implementation of AFM can result in innovations in hydraulic structures such as 'fuse shell' for early impoundment of reservoir;
- information technology can greatly help implementing AFM measures;
- the tragic experiences of great tsunamis of December 2004 and March 2011 vividly indicated the crucial role of non-structural measures especially emergency and crisis management and the need for robustness and resilience of hydraulic structures.

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