Water in the American West

Balancing the competing need for water in water scarce catchments

WINSTON CHURCHILL MEMORIAL TRUST

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The Author

Steve Moncaster works for Anglian Water and is responsible for planning investment to maintain the balance between the supply and demand for water and water recycling services.

Most of the work that Steve and his team do involves assessing the risks posed by climate change, drought, flooding and growth and then developing plans and strategies to maintain levels of service for customers.

In recent years Steve has become increasingly interested in how to balance reliability, sustainability and affordability in water supply systems where there is significant uncertainty about the future availability of resources.

Glossary

AGWA	Alliance Global Water Adaptation
AJE	Alternative Joint Expenditure
AWWA	American Water Works Association
CAMS	Catchment Abstraction Management Strategy
CAP	Central Arizona Project
CAWCD	Central Arizona Water Conservation District
CCW	Consumer Council for Water
CCRA2	2017 Climate Change Risk Assessment
CVWD	Coachella Valley Water District
DAPP	Dynamic Adaptive Policy Pathways
Defra	Department for the Environment, Food and Rural Affairs
DMUU	Decision making under uncertainty
EA	Environment Agency
EBSD	Economics (of) Balancing Supply and Demand
EEDS	Eco Engineering Decision Scaling
Gl	Giga litre (1,000,000,000 litres)
ICS	Intentionally Created Surplus
IID	Imperial Irrigation District
IWRM	Integrated Water Resource Management
MAF	Million Acre Feet
Ml/d	Mega litres per day (1,000,000 litres per day)
MWD	Metropolitan Water District of Southern California
NE	Natural England
NRW	Natural Resources Wales
Ofwat	Water Services Regulation Authority
PGE	Portland General Electric
QSA	Quantification Settlement Agreement
RBMP	River Basin Management Plan
RDM	Robust Decision Making
RDS	Robust Decision Support
RZ	Resource Zone
SDCWA	San Diego County Water Authority
SCRB	Separable Costs Remaining Benefits
SNWA	Southern Nevada Water Authority
USACE	United States Army Corps of Engineers
USBR	United State Bureau of Reclamation
USGS	United States Geological Survey
WFD	Water Framework Directive
WRMP	Water Resource Management Plan
WUCA	Water Utilities Climate Alliance
UKWIR	UK Water Industry Research
YBIP	Yakima Basin Integrated Plan

Summary

In many places in England and Wales the level of abstraction from our rivers and aquifers is unsustainable and is damaging, or threatening to damage, valuable wetland, riparian and in-stream habitats. Climate change and growth are likely to make conditions worse, and it is clear that effects linked to water scarcity will be periodically exacerbated by drought.

In response the Government has proposed a series of policy initiatives which are designed to protect the environment while ensuring there is sufficient water for people and the economy. This includes promoting reform of the abstraction licensing system.

At the heart of the Government's new approach is collaboration between regulators, abstractors and others with an interest in the allocation and use of water resources. While there is already some experience of these partnership arrangements, best practice is still emerging and, as yet, none have had to deal with the difficult issue of balancing the competing need for water in water scarce catchments.

To support implementation of this new approach, water resource management and planning in the western US has been studied. In this region, water scarcity is driven by variable climate, a fast growing population and the demand for water for power, industry and irrigated agriculture. In response to the current drought, policy makers and others have been forced to work together to increase flexibility in their resource and supply systems, enabling these to adapt to reduced water availability. Collaboration and resilience are key objectives for the catchment based policies being promoted here, and best practice from the western US which is likely to help includes the following:

- Extensive water and water rights trading, both within and between sectors
- Shared vision planning, which is based on the principles of integrated water resource management (IWRM)
- Storage and conveyance infrastructure, both natural and built. This ensures that water can be supplied to the right place at the right time, irrespective of the prevailing hydro-climatic conditions, and
- Innovation. This is driven by collaboration and includes:
  - Long-term agriculture to municipal transfers (water “farming”)
  - Cross-sector trading of the water savings from agricultural demand management
  - Trading of ecosystem services
  - Recycling waste water discharges and water banking
  - The development and use of decision-making under uncertainty (DMUU) methods, including adaptive planning, and
  - The re-purposing of existing assets

Since the fieldwork for this project was completed (November 2015), these key learning points have been applied in a number of different settings, including:

- In meetings with key stakeholders such as Defra, the Environment Agency, Natural England, the National Farmers Union (NFU), the Royal Society for the Protection of Birds (RSPB), Fens for the Future and the Anglian Water Services Catchment Management Team
- In presentations at conferences and workshops including for the UK Irrigation Association (UKIA), Association of Drainage Authorities (ADA), the Chartered Institution of Water and Environmental Management (CIWEM), Defra and the NFU
- Arranging visits to the UK by contacts established during the fieldwork, so that stakeholders here can be briefed directly on the key learning points. This includes visitors from the following organisations:
  - Stockholm Environment Institute, Davis, California
  - State of Washington Department of Ecology, and
  - Colorado Springs Utility, Colorado
- Through the work of the Water Resources East (WRE) project[1]. This is a multi-company, multi-sector strategic water resource planning initiative in the east of England. Its purpose is to deliver water resource and water supply systems which are reliable, affordable and sustainable, as well as resilient to the long-term effects of climate change, growth and drought. The work of the WRE is based on the first practical application of advanced, multi-sector DMUU planning methods in the UK, and
- Through the work of the South Lincolnshire Water Partnership (SLWP). The SLWP is a group of organisations collaborating to plan the management of water resources in South Lincolnshire, so that these can support sustainable rural development and enhance natural capital. Outputs from the SLWP include a multi-sector water resource planning conference held in Spalding in November 2016. This was attended by around 70 delegates

Next steps include delivering a formal IWRM plan for the SLWP and using this to guide work in the Black Sluice, Welland and Glen catchments in south Lincolnshire. In addition, the work of the WRE is likely to progress to include more catchment based initiatives. The results of these will be available to inform future development of the framework for water resource management planning in England and Wales and, assuming that the key learning points are adopted, this will embed collaborative IWRM principles in the work of water companies, their regulators and others working in the water sector.

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[1] http://www.waterresourceseast.com/

Introduction

The challenge for water resource managers in England and Wales

Water resource management and planning in England and Wales is changing.

In many places licensed and actual volumes of abstraction are unsustainable and these are damaging, or threatening to damage, precious wetland, in-stream and riparian habitats. Climate change and the growth in demand for water are predicted to make things worse and where chronic conditions of water scarcity emerge, it is clear that the effect of any shortage will be exacerbated by severe or extreme drought[2].

In the worse case, the result will be widespread environmental degradation and severe restrictions on supplies, including the use of rota-cuts and standpipes.

These outcomes are unacceptable in a modern industrial society, such as ours. In response, the Government has promoted a series of policies which are designed to protect the environment, while ensuring there is sufficient water for people and the economy[3]. This includes promoting reform of the abstraction licensing system, which many consider unfit for use.

At the heart of the Government's new approach is a catchment based system for managing water resources[4]. In this, those with an interest in the abstraction and use of water are encouraged to work together to secure both individual and common goals. As well as the Environment Agency and Natural England, key decision-makers include:

- Water companies
- Local Authorities, including Local Enterprise Partnerships
- The agriculture, food and drink sectors
- Drainage Authorities
- Manufacturing, construction and service industries
- The leisure and tourism sectors, and
- The wildlife and conservation sectors

In a future where chronic conditions of water scarcity are expected but uncertain, the key challenge for these partnerships will be to ensure that the available water resources are fairly allocated.

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[2] "The case for change – current and future water availability", Environment Agency, Report GEHO1111BVEP-E-E, Bristol, 2011 and "Current and future water availability – addendum", Environment Agency, December 2013

[3] "Water for Life" Department for Environment, Food and Rural Affairs (Defra), The Stationary Office Limited, 2011

[4] "Reform of Freshwater Abstraction" POSTNOTE Number 546, Parliamentary Office of Science and Technology, Houses of Parliament, January 2017

The purpose of this project

Cross-sector collaboration and joint decision-making are new developments for water resource planning and management in England and Wales, and best practice for successful implementation is still emerging.

The purpose of this project is to identify decision-making processes and tools that can be used to support delivery of the new catchment based initiatives being promoted by Government.

Practice in the western US has been studied since this region is water scarce; fast-growing; vulnerable to climate change and has recently suffered an extended period of severe drought, all of which is driving innovation and change in the way that decision-makers balance the competing needs for water.

The history of water in the American west also points to the consequences of policy failure in this area – bitter conflicts that drive complex legal disputes, which may take decades to resolve.

About this report

This report is structured on the basis of the following:

- Background information on water resources in the western US
- A summary of the processes and tools that are being used to support water resource management and planning decision-makers in the western US
- Key points for the new catchment based initiatives in England and Wales, and
- Details about the work completed since visiting the western US in November 2015

This is one of two Winston Churchill Memorial Trust reports that have recently been published about water resources in England and Wales. The first was published in 2014 and was based on fieldwork in Australia[5]; its purpose was to provide learning for those drafting legislation to reform the abstraction licencing system in England and Wales.

5 Markets, water Shares and droughts: Lessons from Australia, what can the water industry in England and Wales learn from Australia's water reform story?, Piure, A., 2014

Water resource management in the western US

Current situation

In hydrological terms, the western US comprises those States to the west of the 100th meridian, where rainfall in most areas averages less than 500 mm per year (20 inches, see Figure 1a below).

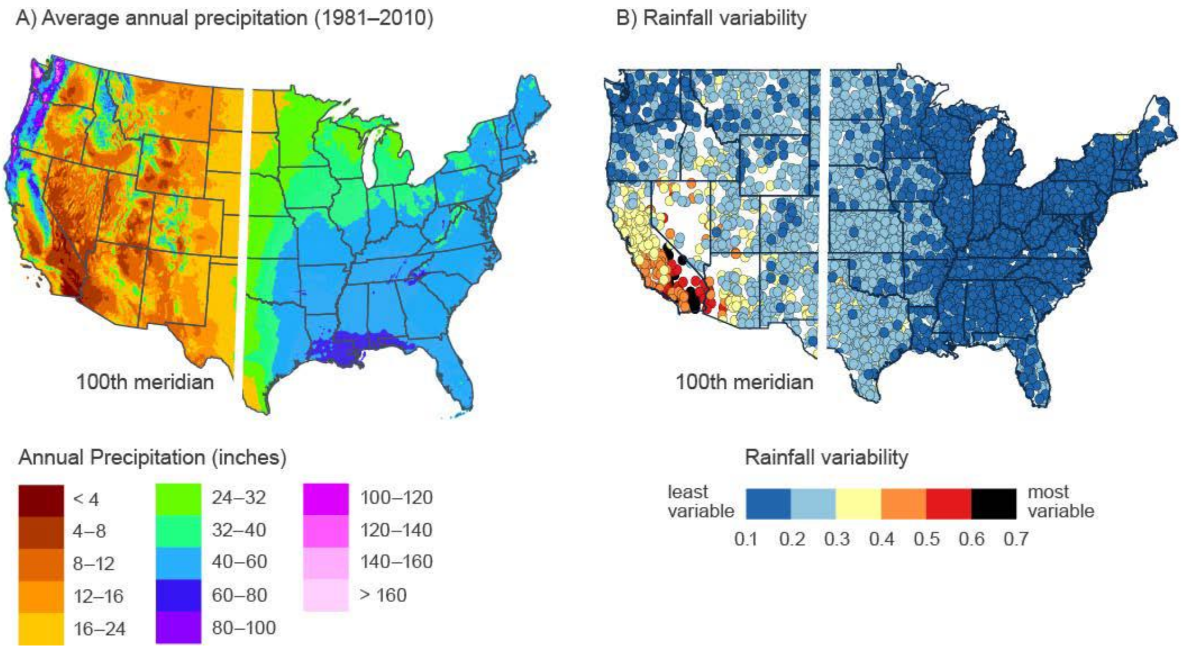


Figure 1a: Long-term average rainfall in the United States (1961 to 1990) and Figure 1b Rainfall variability in the United States in 2014[6]

With the exception of the Pacific coast and inland mountainous areas, the climate is continental or sub-continental with cold winters and hot summers. Large parts are either arid or semi-arid and rainfall may vary significantly from year to year owing to El Nino or southern oscillation events (see Figure 1b). Droughts are common and flows in rivers, which in many areas are supported by the annual melting of the snow pack, are noted for their huge variability.

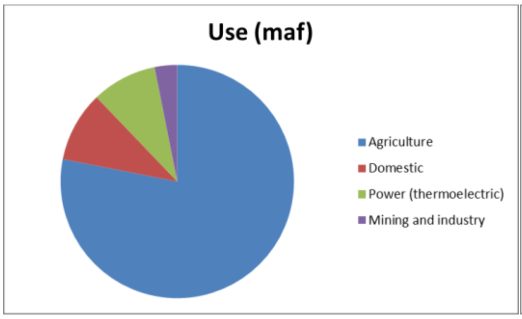
In 1990, approximately 179 million acre feet (MAF) or 221,000 giga litres (Gl) of freshwater was abstracted in this region7. This is equivalent to 605,000 Ml/d.

[6] "Improving the Federal Response to Western Drought: Five Areas for Reform" Public Policy Institute of California, February 2016

[7] "Water in the West: Challenge for the Next Century" Report of the Western Water Policy Review Advisory Commission (1998)

By comparison, the total volume abstracted in England and Wales is currently just under 34,500 Ml/d[8].

The majority of the abstracted water, 140 MAF (172,000 Gl), was used in agriculture. Domestic consumption and the generation of thermoelectric power accounted for 17.5 MAF (22,000 Gl) and 16.2 MAF (20,000 Gl) respectively, while the remaining 6 MAF (7,000 Gl) was used in mining and industry. Approximately a third of the abstracted water was groundwater (58 MAF or 71,000 Gl); the rest was surface water[9]. This pattern of abstraction and use is illustrated below:



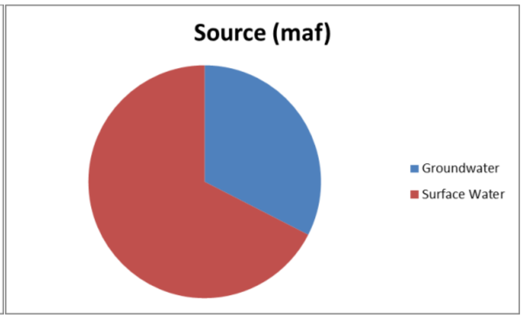


Figure 2: Patterns of water use in the western United States (1990)

Given variable precipitation and vulnerability to drought, water storage is critical in the west. The total capacity of the large reservoirs which have been built is approximately 325 MAF (400,000 Gl). This compares with 84,000 Gl in Australia and 1,600 Gl in England and Wales[10].

Most of the reservoirs are owned and operated by Federal agencies. The US Bureau of Reclamation (USBR) and the US Army Corps of Engineers (USACE) are responsible for 238 MAF (294,000 Gl) of capacity and the Department of Agriculture 26 MAF (32,000 Gl). The remaining reservoirs are operated by the Bureau of Indian Affairs; US Fish and Wildlife; the Department of Energy or by municipal and state agencies.

Since most dam building sites have been used, the era of reservoir construction is widely assumed to be over. Instead, new resource development is concentrated on the use of groundwater, with smaller volumes being derived from groundwater recharge, conjunctive use, water reuse, desalination and water conservation.

[8] "The case for change – current and future water availability", Environment Agency, Report GEHO1111BVEP-E-E, Bristol, 2011

[9] "Water in the West: Challenge for the Next Century" Report of the Western Water Policy Review Advisory Commission (1998)

[10] "Markets, water shares and drought: Lessons from Australia. What can the water industry in England and Wales learn from Australia's water reform story" a Winston Churchill Memorial Trust report by Alice Piure, 2014

Without the water infrastructure which has been built in the last 100 years, large areas of the west would have remained undeveloped. Through "reclamation" efforts which have largely involved the management of water, a large and diverse economy has been established which supports in excess of 89 million people, around a third of the population of the US. In 1990, the largest users of water, agriculture, produced crops with an estimated value of $9 billion while power sales and flood risk management benefits from the USBR and USACE dams were estimated to be worth $5.7 billion[11].

As well as providing social and economic benefits, however, water resource development in the west has profoundly altered the natural characteristics of rivers, groundwater systems and watersheds. The environmental cost of reclamation includes flooded valleys, blocked and disrupted fish passages, drastically changed flow characteristics that include both reduced frequency of flooding and exceptionally low flows, disrupted temperature regimes and reduced sediment and nutrient loads. Some river basins contain only fragments of previously existing riparian and wetland habitats and many aquatic species have suffered extinction or near extinction.

Future challenges

Issues with the potential to affect the future water resource availability in the west include the following:

- **Population growth:** The population of the western US grew by 32% in the period between 1978 and 2002 and further large increases are forecast. In 2002, eight of the ten fastest growing cities in the US were in the west[12]
- **Climate change:** Changes in the pattern of precipitation, snowmelt and runoff, combined with changes in withdrawal and consumption, have reduced surface and groundwater availability in many areas. These trends are expected to continue, increasing the likelihood of water shortages for public water supply, agriculture and ecosystems[13]
- **Drought:** drought is a permanent feature of US climate, with extended periods of extreme drought widespread during the 1930's ("dust bowl") and 1950's. Since the early 2000's large areas of the west have experienced chronic and severe drought conditions – see Figure 3 and Figure 4 below. These have resulted in depleted snowpack, a reduction in stream flow and reduced levels of reservoir storage.

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[11] "Water in the West: Challenge for the Next Century" Report of the Western Water Policy Review Advisory Commission (1998)

[12] "Water and population in the American West" Fort, D.D., in Human Population and Freshwater Resources, Yale Forestry and Environmental Studies Bulletin No. 107 (2002)

[13] "Chapter 3: Water Resources" Georgakakos, A., Fleming, P., Dettinger, M., Peters-Lidard, C., Richmond, T., Reckhow, K., White, K. and Yates, D. in "Climate Change Impacts in the United States: Third National Climate Assessment, US Global Change Research Programme, 69-112 (2014). See also Chapter 20 and Chapter 21 on the Southwest and Northwest respectively.

Climate change is expected to intensify short-term, seasonal droughts in most US regions. In the Southwest, longer term, multi-season, droughts are also expected to intensify[14].

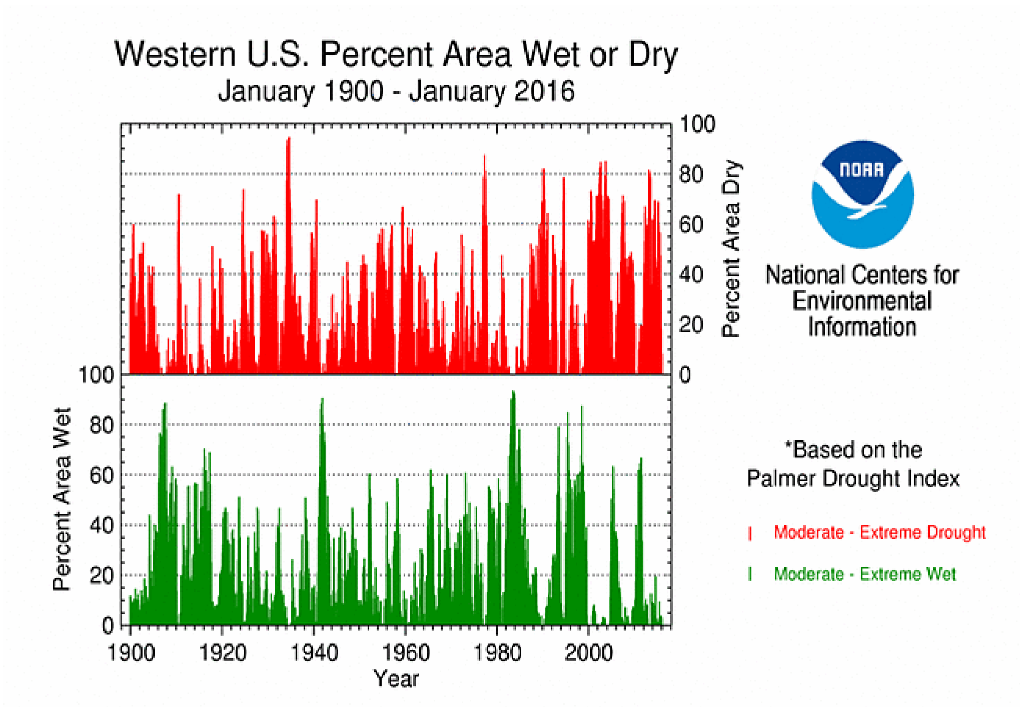

Figure 3: Incidence of extreme drought in the Western US (from National Centers for Environmental Information, NOAA, 2016)[15]

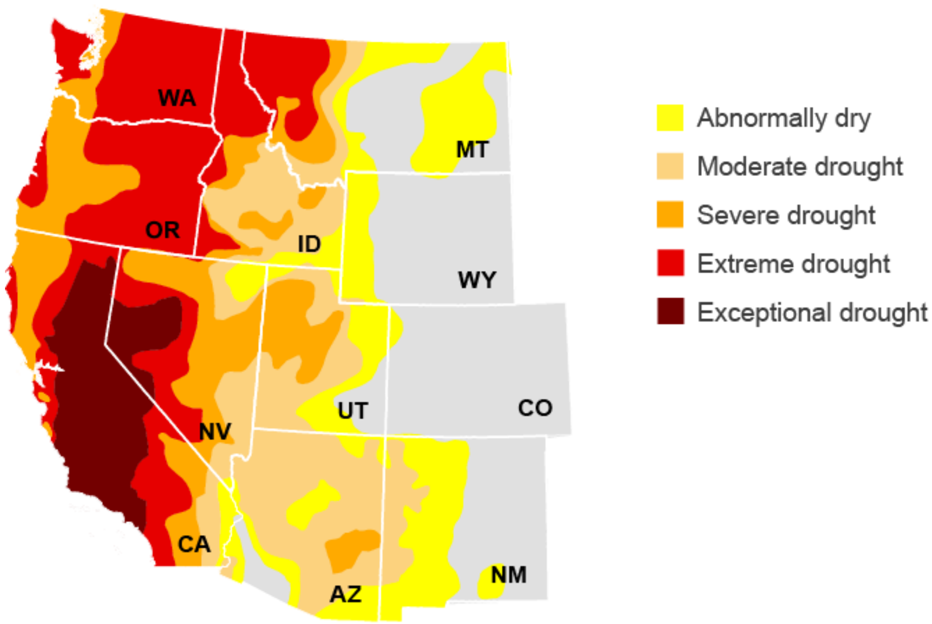

Figure 4: Distribution of drought conditions in the west[16]

[14] ibid
[15] https://www.ncdc.noaa.gov/sotc/drought/201601#det-wus

Water (abstraction) rights in the west are typically administered by State governments using the doctrine of prior appropriation. This system was developed during the early settlement period and permits the withdrawal of water for "beneficial use". It also prioritises rights on the basis of the date of the claim. As a consequence, the rights of senior claims are protected at the expense of the more junior ones and since most rivers in the west are fully allocated, it is difficult to find water for environmental or ecological use.

Under the "Winter's" doctrine, Native American rights pre-date most other rights and in recent adjudications this has resulted in reallocation of the available resources. In some areas, this process has exposed long-standing tensions between different communities.

[16] "Improving the Federal Response to Western Drought: Five Areas for Reform" Public Policy Institute of California, February 2016

Findings from interviews and discussions

The fieldwork for this study was completed between October and November 2015 and involved meetings and discussions with water managers, policy makers, conservationists, academics, consultants and regulators in Oregon, Washington, Colorado, Arizona, California and Washington DC. Where practice from other areas was identified, such as emerging adaptive planning approaches from the Netherlands, further discussions and meetings were held.

From each of these interviews, best practice in balancing the competing need for water in water scarce systems has been identified. In the sections that follow, these have been categorised in terms of:

- Water resource management initiatives, and
- Water resource planning initiatives

These may be thought of as tactical and strategic responses to the problems of chronic water scarcity and severe drought respectively.

Best practice water resource management

The best practice (tactical) responses to water scarcity that are evident in the western US include:

1. Trading of water, water rights and ecosystem services
2. Demand management and trading of water savings
3. The innovative use of water resources, such as water reuse and water banking, and
4. Alignment of policy objectives

Details are given below:

Trading of water and ecosystem services

As well as trading within sectors, examples include trading of water and water rights between sectors:

- Following the 2007 Interim Guideline for Colorado River Operations, the Southern Nevada Water Authority (SNWA) operates a Tributary Conservation "Intentionally Created Surplus" (ICS) scheme. In this, retired agricultural water rights are used to transfer water via the Virgin River and the Muddy River to Lake Mead where it can be stored until needed, and then abstracted for use in Las Vegas and the surrounding areas, and
- The City of Phoenix operates a series of long-term contracts to secure supplies of Central Arizona Project (CAP) water from other CAP users, including from irrigation districts and Native American communities. This water accounts for approximately 30% of the CAP supplies which are available to the City

The CAP is designed to allow diversion of 1.6 MAF of Colorado River water for use in central and southern Arizona. It was completed in 1992 at a cost of approximately $5bn and comprises a 335 mile aqueduct, 15 pumping stations and a series of recharge basins that are used to store unused allocations of water for future use. Details are given below:

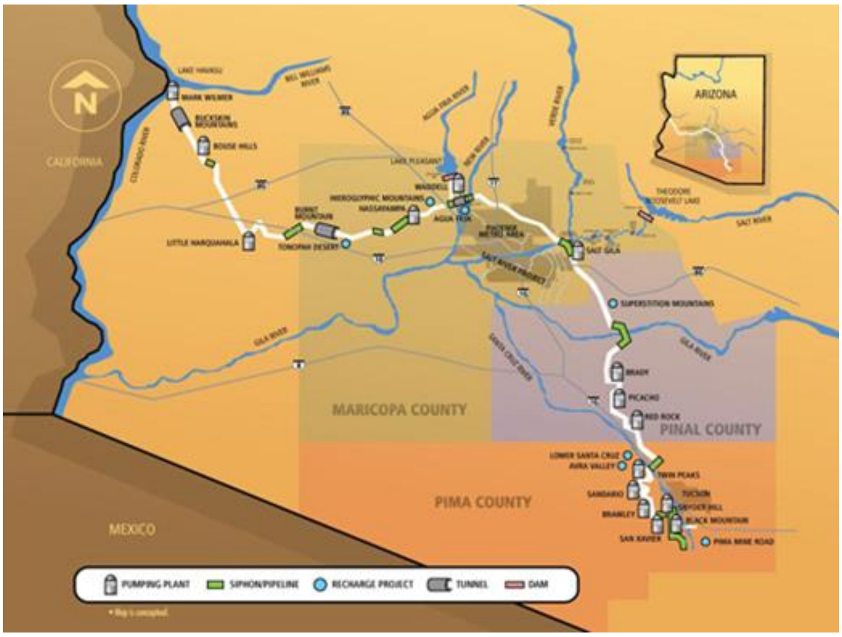

Figure 5: Central Arizona Project[17]

The CAP was originally promoted to access the water Arizona was entitled to from the Colorado River; reduce shortage related risks to Arizona agriculture, which was heavily reliant on diminishing reserves of groundwater and to meet growing municipal demands. It has also provided the state with a valuable tool to mitigate the impact of the current, severe drought as well as the likely longer-term effects of climate change.

Features which are common to each of these schemes include:

- The large volume of senior water rights which are held in the agricultural sector and the ability of the water right holders, through the beneficial use elements of prior appropriation, to trade without losing their water rights, and
- The use of existing natural or engineered infrastructure to convey the traded water. For the Phoenix contracts, this includes the reservoirs and canals that were built by the USBR in the lower Colorado system

In Oregon, the Portland General Electric (PGE) company is using payment for ecosystem services to offset the impact of its hydroelectric operations on fish populations in the Clackamas River[18].

[17] Arizona Department of Water Resources

Figure 6: PGE assets on the Clackamas River, Oregon

The $8m scheme facilitates payment for services that include the management of riparian, wetland or upland habitat; water rights acquisition or leasing; in-stream habitat improvements and fish passage improvements. Any person, private company or government agency can participate in the project, which was developed as part of the process for re-licensing existing power infrastructure on the river.

Demand management and trading of water savings

Where the effects of the current drought are particularly acute, changes in land-use management are being funded as part of efforts to make more effective use of the available resources.

In these areas, municipalities are contracting with irrigation districts to implement conservation measures and then take the water which is saved. The measures include fallowing, improvements in irrigation efficiency (trickle irrigation) and reductions in leakage from canals and ditches.

This type of scheme is being used in Southern California to increase supplies to San Diego and Los Angeles. Here, the Imperial Irrigation District (IID) has water rights for 3.1 MAF/yr of Colorado River water which is used to irrigate 500,000 acres of farmland in the Imperial Valley. Through the Quantification Settlement Agreement (QSA)[19] up to 500,000 AF/yr of this will be conserved and then transferred to the San Diego County Water Authority (SDCWA), Coachella Valley Water District (CVWD) and the Metropolitan Water District of Southern California (MWD). Based on 2013 contracts with the SDCWA, the water is sold at a cost of $540/AF, equivalent to approximately 30p/m^3. The QSA agreements are for between 35 and 75 years.

[18] "The Clackamas River Hydroelectric Project Mitigation and Enhancement Fund Implementation Plan" Clackamas River Hydroelectric Project 2195, Relicensing Settlement Agreement, Exhibit H, 2006

[19] "Quantification Settlement Agreement, Implementation Report 2010-2013, Imperial Irrigation District, 2014

Innovative use of water resources - water reuse

In recent years, there has been significant interest in the recycling of water from waste water treatment plants. In the severely water stressed parts of the Southwest, including Arizona and California, options to further develop reuse are being examined:

- In Arizona, reclaimed water is currently 3.3% of the available supply and options to increase this are being examined (see below), and
- In California, DWR has recommended the development of a "California Municipal Water Recycling Strategic Plan" to guide expanded use of recycled water. When complete, this should:
    - Quantify the available capacity and likely demand for recycled water
    - Evaluate treatment options to better align waste water treatment with water recycling for both agricultural and environmental use
    - Consider the salt and nutrient related groundwater degradation issues, and
    - Evaluate barriers to water reuse

In Arizona, around 30% of the projected supply-demand imbalance could be met using recycled water. Since this is derived from water which has already been supplied, it would be available even when there are severe shortages in the Colorado and Salt River systems:

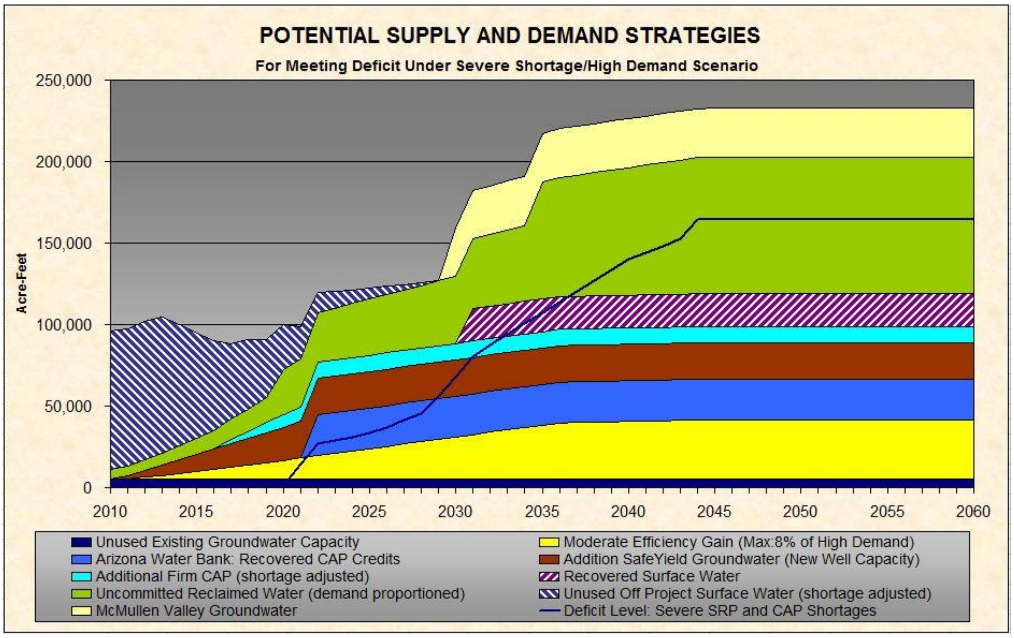

Figure 7: Potential use of water reuse for meeting the projected increase in demand for water in Arizona[20]

[20] "Water Resource Plan" City of Phoenix, 2011

Innovative use of water resources - water banking

Water banking in Arizona involves recharging unused Colorado River entitlements into the deep, basin-fill alluvial aquifers of the central and southern parts of the State. As well as the Arizona entitlements, entitlements from Nevada and California are also banked. During periods of water stress, this water can be recovered, reducing the economic and environmental impacts of any shortages in the lower Colorado system.

Alignment of policy objectives

Land and water management in the Western US is administered by a variety of State and Federal agencies. Details of the Federal agencies are given below:

<table>
<tr><th>Function</th><th>Principal Agencies</th></tr>
<tr><td>Interstate and international river management</td><td>Department of the Interior</td></tr>
<tr><td>Water infrastructure</td><td>USBR, USACE, FERC, EPA, RUS, HHS, HUD, BIA</td></tr>
<tr><td>Agricultural stewardship</td><td>USDA</td></tr>
<tr><td>Environmental protection</td><td>USFWS, NMFS, EPA, USACE, FERC</td></tr>
<tr><td>Forest and rangeland management</td><td>USDA, NPS, BLM</td></tr>
<tr><td>Water information</td><td>NOAA, USGS, NASA, DOE, NRCS, USBR, USACE</td></tr>
<tr><td>Emergency drought relief</td><td>USDA, FEMA</td></tr>
<tr><td colspan="2">USBR – US Bureau of Reclamation; USACE – US Army Corps of Engineers; FERC – Federal Energy Regulatory Commission; EPA – Environmental Protection Agency; RUS – Rural Utilities Service; HHS - Department of Health and Human Services; HUD – Department of Housing and Urban Development; BIA – Bureau of Indian Affairs; USDA – US Department of Agriculture; USFWS – US Fish and Wildlife Service; NMFS – National Marine Fisheries Service; NPS – National Parks Service; NOAA – National Oceanic and Atmosphere Administration; USGS – US Geologic Survey; DOE – Department of Energy; NRCS – National Resources Conservation Service; FEMA – Federal Emergency Management Agency</td></tr>
</table>

Table 1: Federal roles in ecosystem and water management[21]

The operations conducted by these agencies are not always aligned and in particular circumstances, conflicting objectives may emerge. The effect of this is to reduce the resilience of watersheds and ecosystems to drought and water stress. This, in turn, has implications for the availability and reliability of water supplies and for the dependent ecosystems.

A recent review of the Federal response to the western drought recommends the following improvements[22]:

[21] "Improving the Federal Response to Western Drought: Five Areas for Reform" Public Policy Institute of California, February 2016

[22] ibid

- Using Federal powers to intervene and resolve long-standing water conflicts in areas such as the Klamath Basin, the Colorado Basin and the Sacramento-San Joaquin delta
- Coordinate Federal actions more effectively, including reducing institutional complexity and providing more clarity about how to align economic and environmental goals with statutory obligations. A key initiative in this respect is developing drought biodiversity plans that are capable of withstanding the effects of a warming climate
- Change agricultural support programmes to encourage drought resilience at a basin scale, as well as improve in-stream flows and wetlands, and
- Improving systems for the collection and management of water data, including water use monitoring

In practice, there is evidence that the activities of some State and Federal agencies are starting to become more coordinated. For example, in Washington, the Department of Ecology was able to promote changes to operating rules for the Grand Coulee Dam complex. These ensured that water could be released into the river at critical times to support ecological and abstraction related needs. This agreement resolved a 20-year dispute over water rights on downstream parts of the river.

Best practice water resource planning

The best practice (strategic) responses to water scarcity that are evident in the western US include:

1. IWRM and the transition from single-sector requirement based planning
2. Application of decision-making under uncertainty (DMUU) methods, and
3. The emergence of adaptive planning approaches

Details are given below:

Integrated Water Resource Management

The 1992 UN conference on the environment and development identified a need for Integrated Water Resource Management (IWRM). This comprises "the holistic management of freshwater as a finite and vulnerable resource, and the integration of sector based water plans and programmes within a framework of economic and social policy"[23]. Based on the 1992 UN definition, the objectives of IWRM are:

1. To promote dynamic, interactive, iterative and multi-sector approaches to water management
2. To plan for the sustainable and rational utilisation of water resources
3. To design and implement projects that are both economically efficient and socially appropriate, and

[23] "Sustainability and the future of western water law" Guruswamy, L. and Tarlock, D.A. in "In search of Sustainable Water Management, International Lessons for the American West and Beyond" Kenney, D.S. (Ed) Edward Elgar, Cheltenham, 2005

4. Develop the appropriate institutional, legal and financial mechanisms to ensure that water policy is a catalyst for sustainable social progress and economic growth

IWRM planning is an alternative to simpler, single-sector, requirement based planning and is now established as the basis for most of the significant water resource planning and management efforts in the west, including the Department of the Interior "water SMART" programme. The IWRM plans and strategies being developed are designed to meet different combinations of water supply, water quality, flood risk management and environmental need for sectors which include agriculture, power, public water supply, leisure and recreation. Examples include:

- Washington: Yakima Basin Integrated Plan, Columbia River Water Management Program
- Oregon: Oregon Integrated Water Resource Strategy and the subsequent "place-based" Integrated Water Resource Planning pilots
- Colorado: Colorado Basin Study, Colorado Water Plan
- Nevada and Arizona: Colorado Basin Study, and
- California: Colorado Basin Study, Southeast California Regional Basin Study, California Water Plan Update 2013.

In California, 48 IWRM planning groups have been established for the purpose of developing local IWRM plans and strategies. The distribution of these is illustrated below:

Figure 8: California IWRM Groups

Summarising from the California Water Plan Update 2013: integrated water management leads to stakeholder and decision-maker support for investment in various aspects of resource management, such as innovation and infrastructure as well as a greater number of "implementers and financiers".

The Yakima Basin Integrated Plan (YBIP) is another example of IWRM planning.

The Yakima Basin is located in Eastern Washington, a semi-arid region in which flow in the rivers is derived from snow-melt from the Cascade Mountains. Historically these rivers supported large populations of migratory salmon and sea-trout. In more recent times, they have been used to develop and support a large agricultural sector.

Prior to the YBIP, there was widespread dissatisfaction with the allocation and use of water in the Yakima Basin, with much of the drought related risk borne by junior water rights holders and the environment. The YBIP was developed in response to this and its primary purpose is to address water resource and ecosystem problems which include drought impacts on irrigated agriculture, the extinction of some salmon species and a drastic decline in the population of others. The project combines conflict resolution with planning for multiple objectives and some degree of change through crisis. It has resulted from close collaboration between State and Federal agencies, farmers, Native American communities and the environmental sector. Historically, the relationships within this group have been difficult.

The YBIP is based on a $3.5bn portfolio of schemes which include:

1. Structural and operational changes to existing storage and transfer infrastructure
2. New surface water storage, including a new off-channel reservoir
3. New groundwater storage, including shallow aquifer recharge and aquifer storage and recovery
4. Fish passage
5. Habitat protection and enhancement
6. Enhanced water conservation for municipalities and agriculture, and
7. Market reallocation to reduce barriers to trading

The details are illustrated in Figure 9.

Other notable features of the YBIP include an innovative funding model, in which farmers will meet 10% of the total cost, while delivery of the schemes has been phased with "easy wins" in the early stages. This is deliberate and is intended to build trust and the capacity within the Basin for future multi-sector planning and investment efforts.

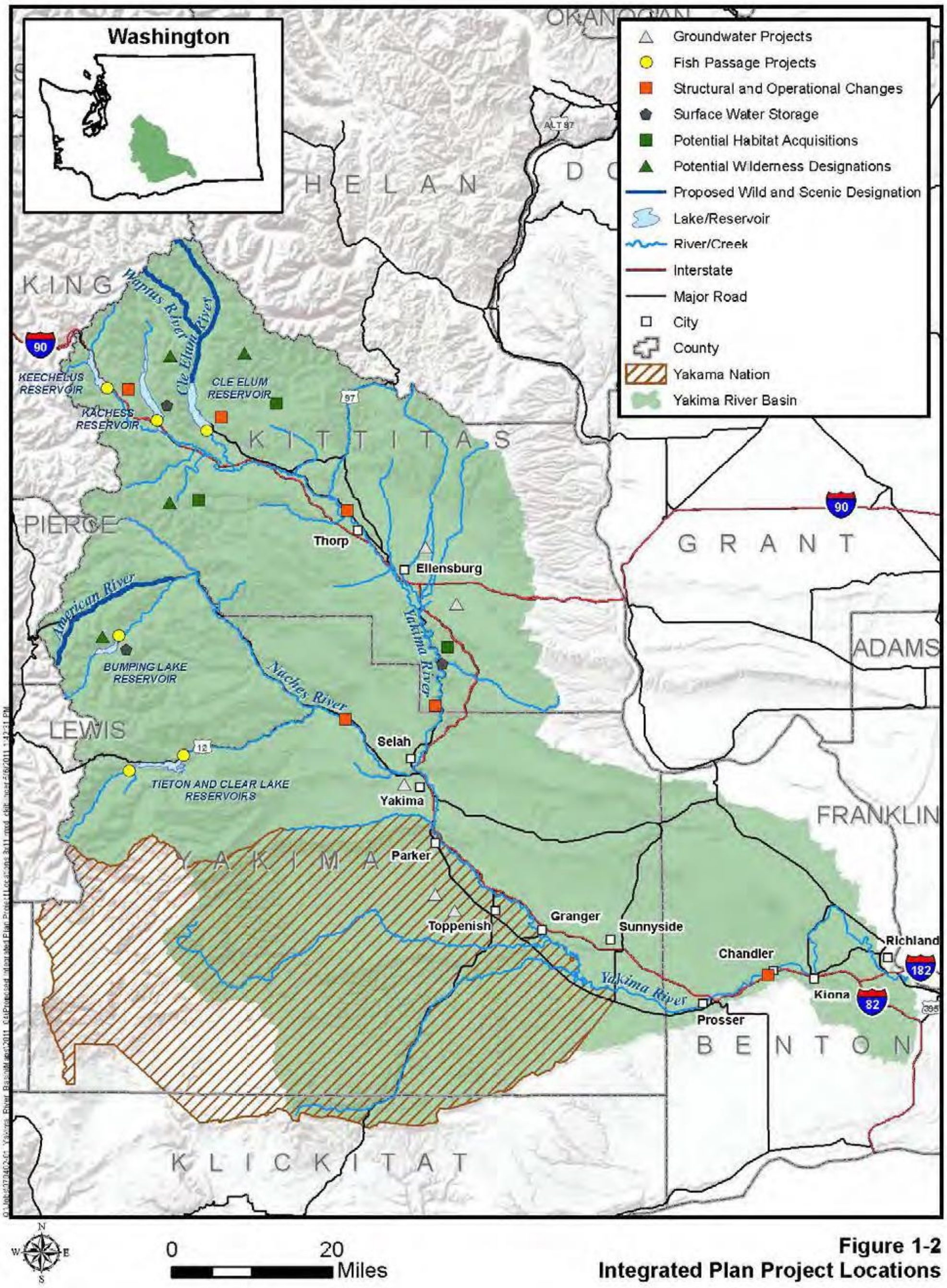

Figure 9: Yakima Basin Integrated Plan[24]

Other examples where water resource planning is progressing through IWRM type initiatives include:

- **Klamath Basin (Southern Oregon/Northern California):** recent events in the Klamath are an example of multi-objective planning in a water-agriculture-power system where crisis is driving efforts at conflict resolution. The basin contains remnants of an extensive wetland system that was drained for agriculture at the end of the 19th century, as well as

[24] "Yakima River Basin Study" Volume 1, Proposed Integrated Water Resource Management Plan, US Bureau of Reclamation and State of Washington Department of Ecology, April 2011

several dams on the Klamath River that were installed for hydropower generation. The introduction of the Endangered Species Act (ESA) combined with the State Scenic Waterways Act, drought, relicensing of the dams and recent adjudication of water rights in favour of Native American interests, is driving a process to reallocate resources in this system. Through efforts such as the Klamath Basin Settlement Agreement (KBSA) planners and stakeholders are attempting to resolve all of the related disputes, developing management strategies that are capable of meeting multiple environmental and socio-economic objectives, and

- **Colorado Basin, including southern California:** the resources of the Colorado Basin are allocated in accordance with a group of laws and agreements collectively known as the "Law of the River". The basis for this is a 1922 compact between the seven States in the basin which allocates 7.5 MAF/yr for the upper basin and 7.5 MAF/yr for the lower basin. Subsequently it was agreed to provide Mexico with an additional 1.5 MAF/yr. However, these agreements were made following an unusually wet period and over-estimated the amount of resource that is available. As a consequence, there is a "structural deficit" in the Colorado system which has been exacerbated in recent years by the effects of drought. Storage levels in the main reservoirs are approaching critical levels and planners are engaged in an effort to mitigate the impact of any shortage. Necessarily, this is driving a multi-objective planning and investment effort aimed at minimising the potential for conflict between stakeholders with Federal, State, environmental, agricultural, municipal, Native American and power interests.

Key features of the Yakima, Klamath and Colorado IWRM initiatives include:

1. They have arisen through conflict or the potential for conflict over the allocation of resources during increasingly frequent periods of water scarcity
2. They are multi-sector with input from Federal and State agencies, agriculture, power, Native American communities, the environmental sector and municipal water suppliers, and
3. The processes which are resulting are bottom-up and stakeholder led. Strong, local leadership is a key component of the agreements which are being reached.

Decision-making under uncertainty

The transition from single-sector requirement based plans to plans which aim to meet multiple objectives has been accompanied by the development and use of increasingly sophisticated analytical methodologies. These are typically based on water resource simulators that use a wide range of climatic, hydrological, demographic and economic data. They include:

- Robust Decision Making (RDM): involves the use of many plausible future scenarios to stress test investment plans, identifying which scenarios cause the plan to fail and so allowing an iterative process of improvement
- Multi-objective optimisation: involves specifying different performance criteria and using a search algorithm connected to a simulator to identify trade-offs between different portfolios of schemes. The trade-offs are then used to select the preferred portfolio
- Decision scaling, including eco-engineering decision scaling: involves the use of a water resource simulator or model to map system performance to variation in climate or other uncertain parameters. The results are initially used to delineate conditions which are likely to result in failure and then subsequently to evaluate the performance of planned investments, and
- Info-gap analysis: the performance of plans is evaluated through incremental change in critical uncertainties, with the results mapped to identify how much change is possible before a plan fails.

The use of these methods has been reviewed in a number of publications:

- **"Developing Robust Strategies for Climate Change and Other Risks: A Water Utility Framework"** Water Research Foundation, Report No. 4262, 2014

- **"Embracing Uncertainty, A Case Study Examination of How Climate Change is Shifting Water Utility Planning"** Report prepared for Water Utility Climate Alliance (WUCA), American Water Works Association (AWWA), Water Research Foundation (WRF) and the Association of Metropolitan Water Agencies (AMWA), May 2015

- **"Beyond Downscaling, A Bottom-up Approach to Climate Adaptation for Water Resource Management"** Garcia, L.E., Mathews, J.H., Rodriguez, M., Wijnen, K.N., DiFrancesco, P. and Ray, P. AGWA Report 01, World Bank Group (2014)

- **"Investment Decision Making Under Deep Uncertainty, Application to Climate Change"** Hallegatte, S., Shah, A., Lempert, R., Brown, C. and Gill, S. Policy Research Working Paper 6193, World Bank, September 2012

In terms of application by practitioners, most of the work to date appears to have been completed using RDM:

Robust Decision Making (RDM)
The key elements of RDM are described in the RAND publication "Shaping the next one-hundred years"[25]. In systems characterised by deep uncertainty, this proposes an approach for choosing actions in the short-term which are

[25] "Shaping the next one hundred years: new methods of quantitative, long-term policy analysis" Lempert, R.J., Popper, S.W. and Bankes, S.C., RAND, 2003

consistent with medium to longer-term interests. Deep uncertainty is described as being where there is little agreement or consensus about the issues being examined; the things that might influence them or the value of alternative outcomes.

To deal with "deep uncertainty" RAND propose an approach based on the following:

- Consider a large ensemble of scenarios: these should be as diverse as possible so that alternative near-term actions can be rigorously tested
- Seek robust rather than optimal strategies: robust strategies perform "well enough" by meeting or exceeding selected criteria across a broad range of plausible futures
- Achieve robustness through "adaptivity": adaptive strategies evolve over time in response to new information. Near-term adaptive strategies seek to influence the long-term by shaping the options available to future decision-makers, and
- Design the analysis for interactive exploration of the multiplicity of plausible futures: using computer aided analysis, bring stakeholders together in the decision-making process and allow them to directly evaluate the trade-offs between alternative actions

In practice, the RAND model requires decision-makers and those driving the related analytical processes to work closely together within an "analysis with deliberation" framework. This contrasts with the expert-led "predict-then-act" approach which is traditionally used.

For water resource planning, the starting point for a RDM study is a conversation between the decision-makers and the analysts on the basis of the following:

Exogenous Factors /Uncertainties (X)	**Management Levers/Strategies (L)**
Uncertain factors that are outside of the control of water managers but which have the potential to impact the decisions being made. *e.g. population change; climate change; new regulation …*	The options under consideration by water managers to improve the performance of a water system under consideration. *e.g. new canals; recycled water, re-operating reservoirs …*
Relationships/Models (R)	**Performance Metrics (M)**
Models that are constructed to capture the relationship between uncertain factors, management strategies, and system performance. *e.g. IRAS Modeling; expert opinion …*	The measures that will be used to evaluate the potential performance of the selected strategies in the face of identified uncertainties. *e.g. flows at specific points; compliance with regulations*

Figure 10: XLRM framework

This exercise is referred to as "participatory scoping" and it defines the planning problem, the desired outcomes and all of the related factors.

The subsequent steps typically involve:

- Building a water resource simulator, within which all of the key components of the planning problem are represented and the relationships between each can be explored ("case generation and exploration")
- Including the options which are being considered in the simulator and then testing these in many plausible future scenarios to determine the related vulnerabilities ("scenario discovery"), and
- Evaluating performance trade-offs between different combinations of options. This leads to selection of the preferred options or plan and work to develop a robust strategy for implementing it ("trade-off analysis")

The process is iterative and several points of feedback are possible. A summary is given below:

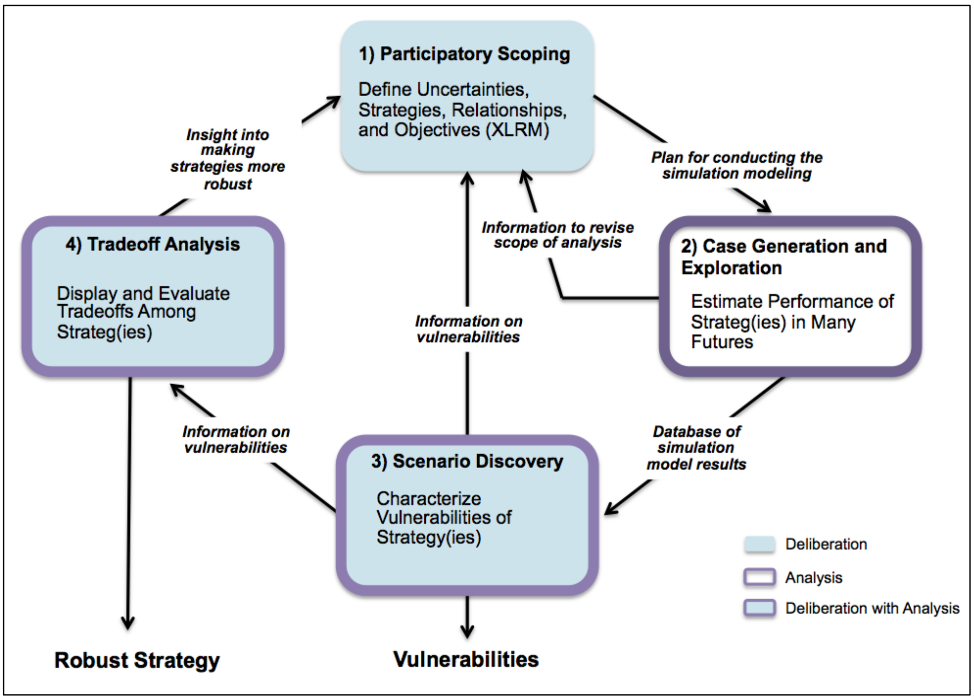

Figure 11: "Classic" RDM process

The available case studies are given in Table 2. In addition to these, other RDM work completed by the RAND Corporation or the Stockholm Environmental Institute includes the following:

- Stockholm Environmental Institute
    - Lesotho: World Bank supported RDS process to evaluate water resource management strategies in a multi-national system in South Africa that is vulnerable to growth and climate change effects

    - South America: USAID supported RDS projects in watersheds in Columbia (4 no.), Bolivia (1 no.) and Peru (2 no.). Common approach used in each whereby initial efforts targeted at stakeholder mapping. Subsequently, the stakeholders were aided in a process to define objectives, uncertainties, options and metrics of performance which ultimately led to characterisation of system vulnerabilities and the evaluation of different management strategies, and
- RAND Corporation
    - City of Lima: World Bank supported development of a RDM based investment strategy for the municipal water authorities in the capital city of Peru. The strategy that was developed was more robust than that in the pre-RDM Master Plan, ensuring reliability across a wide range of possible future conditions while being economically efficient. The work was based on a combination of vulnerability assessment and multi-criteria assessment of the performance of investment alternatives. It also utilised decision scaling and adaptive pathways approaches.[1]

Case Study	Summary
California State Water Plan[26]	RDM used to evaluate the vulnerability of the current water management systems in the Central Valley to a combination of climate change, urban growth and changes in irrigated agriculture. Analysis also used to compare the impact of different response packages on the resilience of the system. For the 2018 Update, and extension of the RDM work is planned.
Colorado Basin Study[27]	Basin-wide RDM study of the vulnerability of the Colorado River system to drought, climate change and growth including a multi-criteria evaluation of the performance of future management strategies. These were based on increasing supplies, managing demand and modifying the operation of existing assets. The multi-criteria evaluation was completed using metrics for water supply, hydropower, flood control, water quality, recreation and the environment. The study identified the conditions which would lead to future water shortages; explored the trade-offs between different investment strategies for maintaining the supply-demand balance and identified "sign-posts' that could be used to trigger adaptive management responses to changing conditions in the Basin.
Colorado Springs Utilities[28]	Evaluation of supply system vulnerability using a RDM based approach with the results being incorporated into on-going Integrated Water Resource Planning (IWRP) effort. There were three phases of work: define risks, issues and vulnerabilities; identify and evaluate management strategies and, finally, use the results to develop an IWRP. Subsequent work has progressed to the development and evaluation of multi-objective optimisation techniques, for evaluating trade-offs between different, high-performing investment portfolios.
El Dorado Irrigation District[29]	Use of RDM to examine the vulnerability of the current water management plan to climate change, population growth and the availability of new supplies. Issues that were investigated include how reliable is the supply system likely to be in the future; under what conditions will the supply system be vulnerable; whether or not the supply system vulnerabilities can be reduced through management activity; what are the key management activity trade-offs and how can they inform decisions.
Denver Water[30]	Initially used a scenario based planning approach to examine issues related to "compounding risks" such as the simultaneous occurrence of dry weather and wildfires. Currently in the process of incorporating RDM methods into a planning framework which will examine issues related to climate change.

Table 2: RDM projects

[26] "California Water Plan Update 2013" State of California Department of Water Resources, October 2014 (Volume 1, Chapter 5 Managing an Uncertain Future)
[27] "Colorado River Basin Water Supply and Demand Study" Bureau of Reclamation, December 2012
[28] "Developing Robust Strategies for Climate Change and Other Risks: A Water Utility Framework" Water Research Foundation, 2014
[29] "Addressing Climate Change in Local Water Agency Plans" Groves, D.G., Bloom, E., Johnson, D.R., Yates, D. and Mehta, V., RAND, 2013
[30] "Embracing Uncertainty: A Case Study Examination of How Climate Change is Shifting Water Utility Planning" Water Utility Climate Alliance, May 2015

Case Study	Summary
Inland Empire Utilities Agency[31]	Comparison of RDM, scenario based and probability weighted scenario based planning approaches. RDM used to identify vulnerabilities in an existing Regional Urban Water Management Plan in both the scenarios that were developed and a wider range of scenarios. RDM was also used to develop options for reducing the vulnerabilities, assessing which ones should be taken in the short term and which could be deferred to later.
Metropolitan Water District[32]	RDM used to examine vulnerabilities in the Metropolitan Water District 2010 Integrated Water Plan; to guide development of a flexible and robust strategy for managing water resources and to facilitate related discussions with stakeholders. Using RDM, conditions in which the IRP strategy failed were identified. From this, a series of indicators were developed which were then used to drive an adaptive management strategy.
New York Department of Environmental Protection[33]	Using a RDM approach, the performance of a number of adaptation strategies for the City of New York water supply system was tested. The work revealed vulnerabilities to population growth; that the range of adaptation measures may not be enough to meet desired levels of reliability and that further work to determine the relationship between climate change and turbidity in raw water supplies was needed.
USEPA[34]	Pilot for the USEPA to determine if RDM can be used to aid the development of flexible and adaptive plans for managing total maximum daily load (TMDL) effects on river water quality. Work based on two case studies and showed that climate change is likely to affect water quality planning and that existing, available water quality simulators can be adapted for use in RDM studies.
Yuba County, California[35]	RDM supported development of an Integrated Water Resource Management Plan (IWRMP) in which water resource management strategies in the Yuba Basin were tested for vulnerability to climate change and new environmental regulations.
Yolo County	RDS used to investigate options for mitigating the risk of shortages in a flood control and water conservation district. The options tested were based on the conjunctive use of groundwater and surface water.

Table 2: RDM projects (continued)

[31] "Preparing for an Uncertain Future Climate in the Inland Empire: Identifying Robust Water-management Strategies" Groves, D.G., Lempert, R.J., Knopman, D. and Berry, S.H., RAND, 2008

[32] "Developing Key Indicators for Adaptive Water Planning" Groves, D., Bloom, E., Lempert, R., Fischbach, J., Nevills, J., and Goshi, B., Journal of Water Resource Planning and Management, Volume 141 Issue No. 7, July 2015, American Society of Civil Engineers

[33] "Developing Robust Strategies for Climate Change and Other Risks: A Water Utility Framework" Water Research Foundation, 2014

[34] "Managing Water Quality in the Face and Uncertainty A Robust Decision Making Demonstration of EPA's National Water Programme" Fischbach, J.R., Lempert, R.J., Molina-Perez, E., Tariq, A.A., Finucane, M.L. and Hos, F., RAND, 2015

[35] "Yuba County Integrated Water Resources Management Plan 2015 Update" Yuba County Regional Water Management Group, May 2015

Decision Scaling

Decision scaling, including eco-engineering decision scaling (EEDS) is another important technique for assessing the robustness of investment plans.

The example which is usually referred to in the literature is derived from analysis of decisions about the management of water levels in the Great Lakes[36]. In this, lake levels are equated with the reliability of water supplies and a two-step process is used to determine the vulnerability of the system to climate change.

In more generic terms, decision-scaling involves:

1. Creating a decision framework, within which information can be collected. This step involved specifying objectives, the processes likely to affect whether or not the objectives can be achieved and, if required, options for future action to achieve the objectives. For complex systems a numerical model of the system is usually constructed, and
2. Using the information collected in Step 1, complete a series of stress tests. This step involves incrementally changing the value of key parameters and then assessing whether or not the performance of the system is acceptable or unacceptable. The results are then mapped and from this the system vulnerabilities are identified.

An example is given below. In this, the red region corresponds to the combination of temperature and precipitation which result in unacceptable performance while performance in the blue region is acceptable.

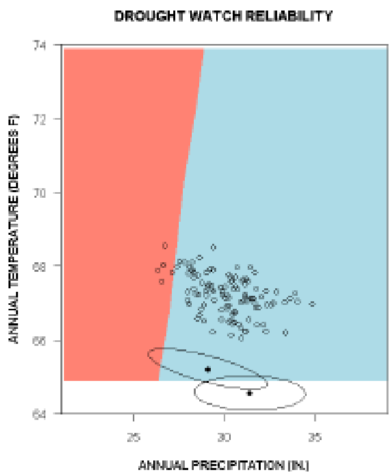

Figure 12: Supply system reliability under a range of possible future climate conditions[37]

[36] "A Decision-Analytic Approach to Managing Climate Risks: Application to the Upper Great Lakes" Brown, C., Werick, W., Leger, W. and Fay, D., Journal of the American Water Resources Association, Volume 43 Number 3 (2011)

[37] "Embracing Uncertainty: A Case Study Examination of How Climate Change is Shifting Water Utility Planning" Water Utility Climate Alliance, May 2015

Once the system vulnerabilities have been mapped, these can be compared to historical conditions or climate projections. In the example above, this shows that the system being considered has only limited vulnerability to climate change effects (i.e. relatively few points in the red region).

More recently, the climate vulnerability of engineered systems has been mapped to equivalent metrics for ecological performance in a process referred to as eco-engineering decision scaling[38]. In this, a process of layering the vulnerability domains for different performance metrics is used to identify the extent to which different actions satisfy stakeholders. This includes identifying the opportunities for making trade-offs.

Adaptive planning

Having identified plans that are likely to perform robustly in most plausible future scenarios, the challenge is to devise a cost-effective implementation strategy. Given the large uncertainties associated with drought, climate change and population growth and the potential for stranded assets or aborted expenditure, this is not a trivial problem. Two complementary approaches have been identified:

- **Analytical approach:** the use of "sign-posts" and "triggers", identified from system simulation and decision making under uncertainty methods, and
- **Policy approach:** the use of dynamic adaptive policy pathways

Sign-posts and triggers

In the USBR Colorado Basin study, "sign-posts" were used to help develop dynamic investment portfolios. In these, supply-system vulnerabilities were used to trigger the implementation of (more) cost-effective options to maintain the supply-demand balance. Typically these options require more time to accrue benefits than larger, more reactive options and so need to be implemented in anticipation of future need. An example is given below. In this, the trigger combines the following:

- 5-year running mean natural streamflow in the Colorado River at Lees Ferry (not shown), and
- Current year level of Lake Mead

When the trigger is reached (in 2042), a decision on investment to avoid the level of the lake falling below a critical level in 2052 is required.

[38] "Sustainable water management under future uncertainty with eco-engineering decision scaling" Poff, L.N., Brown, C.M., Grantham, T.E., Mathews, J.H., Palmer, M.A., Spence, C.M., Wilby, R.L., Haasnoot, M., Mendoza, G.F., Dominque, K.C. and Baeza, A., Nature Climate Change, September 2015

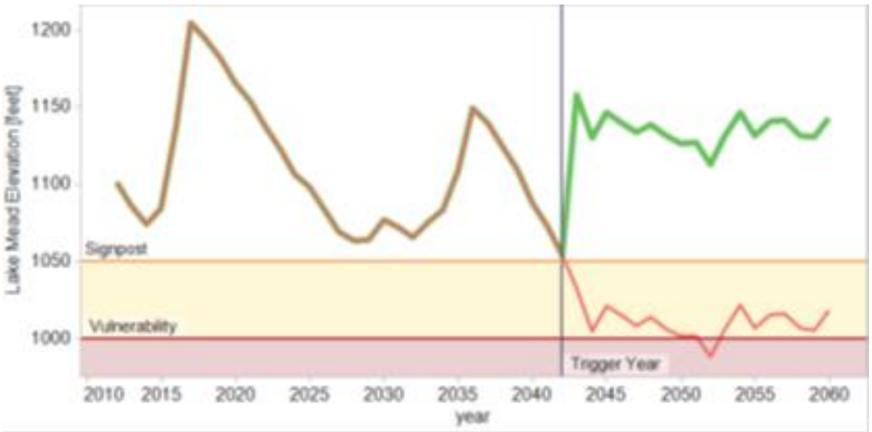

Figure 13: Illustration of a sign-post that triggers investment to prevent levels in Lake Mead reaching 1000 ft msl[39]

For the City of Lima supply system, an approach based on decision scaling was used to identify climate and population vulnerabilities for different investment portfolios. These were distinguished on the basis of budget and the feasibility of developing the options. The results are illustrated below, together with details of key investment portfolios:

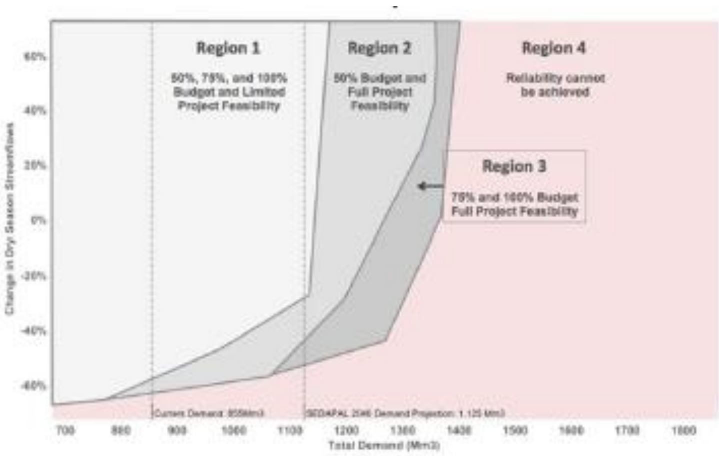

Figure 14(a): Future conditions in which different investment portfolios can achieve supply system reliability[40]

[39] "Colorado River Basin Water Supply and Demand Study" Bureau of Reclamation, December 2012

[40] "Robust Decision-Making in the Water Sector: A Strategy for Implementing Lima's Long-term Water Resources Master Plan" Kalra, N., Groves, D.G., Bonzanigo, L., Molina-Perez, E., Ramos, C., Brandon, C. and Rodriguez, I., policy Research Working paper No. 7439, World Bank

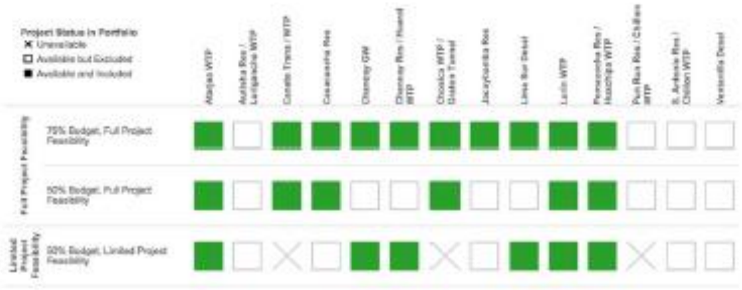

Figure 14(b): Investment portfolios used in Figure 20(a)[41]

Using this information, the City planners were able to develop an adaptive management strategy in which changes related to population growth and climate change (the "sign-posts") can be used to trigger longer-term investment:

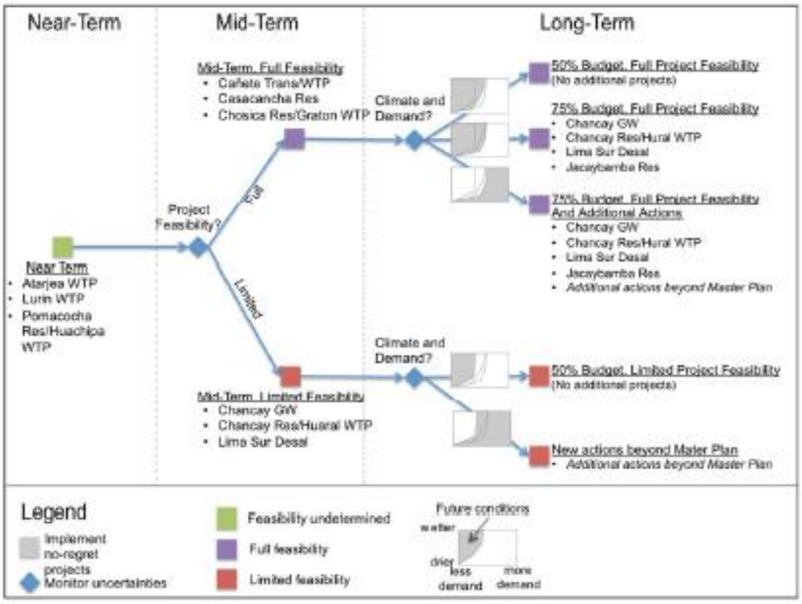

Figure 15: A decision-tree for robust, adaptive implementation of the City of Lima Master Plan

Dynamic adaptive policy pathways (DAPP)[42]

DAPP is an approach to decision-making which attempts to deal with the challenge of balancing affordability and risk in conditions of deep uncertainty. The component elements are:

- Adaptive pathways: this provides insight into the sequencing of actions over time, and
- Adaptive policy-making: this specifies a step-wise approach to developing a plan.

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[41] "ibid

[42] "Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world" Haasnoot, M., Kwakkel, J.H., Walker, W.E. and ter Maat, J., Global Environmental Change, Volume 23 Number 2 (2013)

Common to both is the concept of an "adaptation tipping point" or a "trigger"; this is the point at which a particular action is no longer adequate for meeting the objective of a plan and so the point at which an action to change the plan is taken. Figure 16 illustrates the components of a plan based on adaptive pathways:

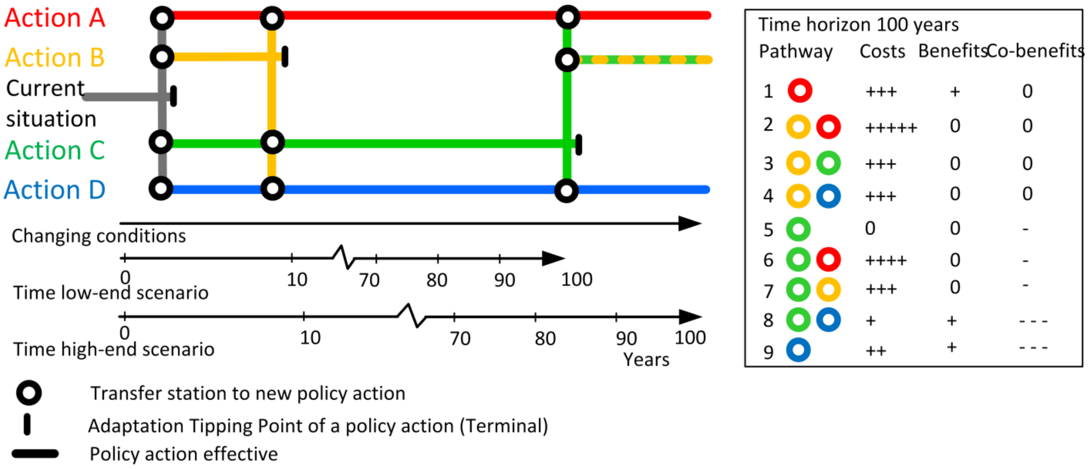

Figure 16: The Adaptive Pathways approach

A summary of the overall DAPP approach is illustrated below. In this, the triggers are specified in Step (7) following a rigorous appraisal of the problem and the development of different management strategies. Monitoring in Step (10) is then used to determine if the trigger has been reached and if some related action is needed.

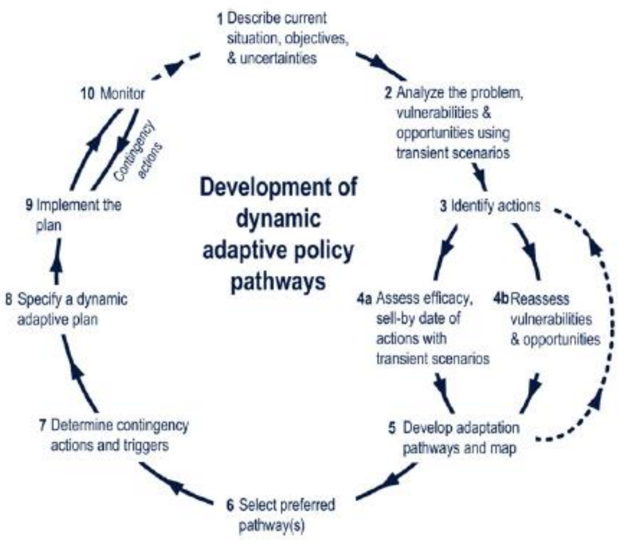

Figure 17: The Dynamic Adaptive Policy Pathways (DAPP) approach

An example in which DAPP has been applied to a flood risk management problem is given below. In this, an attempt has been made to identify the strategies preferred by different stakeholders. Subsequent discussions on the basis of these is used to identify the trade-offs which are possible at different points and so the development of agreed adaptive management strategy or plan.

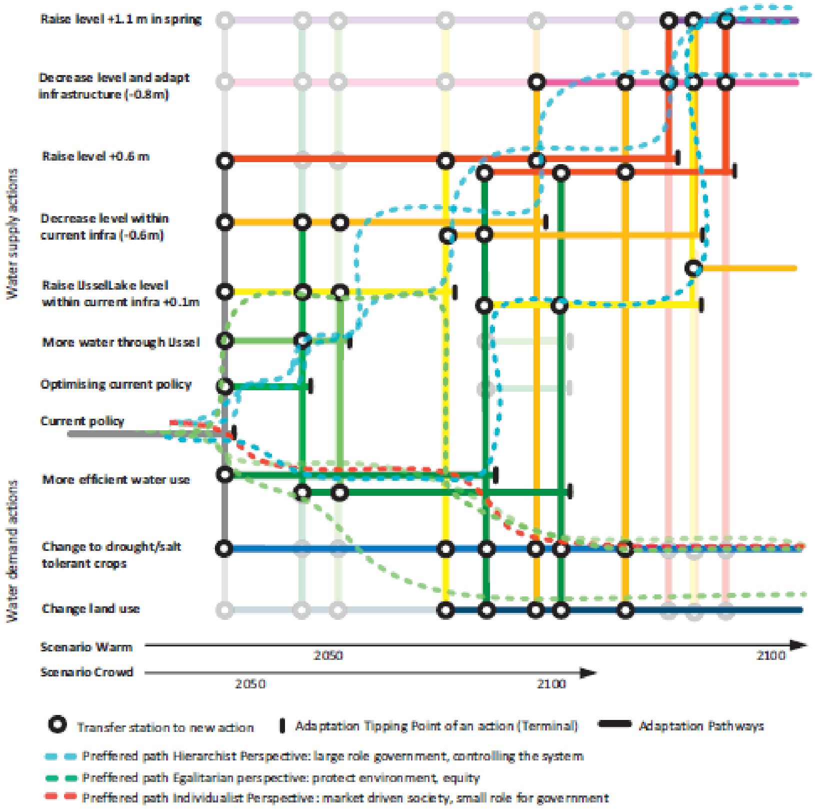

Figure 18: Example application of the DAPP approach

Key points for catchment based initiatives in England and Wales

Water resource management

Initiative	Key learning point (*case study*)
Trading of water, water rights and ecosystem services	The use of catchments as management and planning units, within which (a) overall conservation targets can be set, and (b) the trading of water and water rights can be balanced. Within such catchments, flows in natural watercourses are used to transfer water between the trading parties (*Southern Nevada Water Authority*)
	The requirement for conveyance and storage infrastructure to support transfers and trading between catchments. This includes between different sectors (*Southern Nevada Water Authority, Imperial Irrigation District and Central Arizona Project*)
	The trading of eco-system services to create net environmental gain. By allowing abstractors and others the flexibility to buy ecosystem services at a catchment scale, the expense involved with removing or modifying existing (damaging) assets is avoided (*Portland General Electric*)
Demand management and the trading of water and water rights	Demand management and an innovative approach to land management allows the agricultural sector to "farm" water, trading surplus water rights in long-term arrangements with municipal authorities to meet the growth in demand for public water supply (*Imperial Irrigation District*)
Innovative use of water resources	The importance of recycling water within catchments, to make the most of the resources that are available and to increase the resilience of natural and engineered systems (*State of Arizona and the State of California*)
	Where suitable hydrogeological conditions exist, the use of aquifer storage and recovery systems to support water banking. Such systems may be built for the benefit of multiple users, offsetting the risk of water shortages during periods of drought or water stress (*Central Arizona Project*)
Alignment of policy objectives	A lack of alignment between the policy objectives of Government and regulators can undermine efforts to manage the effects of drought an water scarcity, reducing the resilience of the natural systems upon which water supply systems depend (*Pacific Institute*)
	Traditional, single sector, operations can "lock in" resources in such a way that water scarcity effects are exacerbated. More collaborative approaches can prevent the escalation of disputes about the allocation and use of resources (*State of Washington, Department of Ecology*)

Table 3: Key water resource management learning points

Water resource planning

Initiative	Key learning point (*case study*)
IWRM and the transition from single sector requirement based planning	In many places in the western US, conflict and disputes about the allocation and use of water are endemic. Where these issues are being resolved, strong local leadership and the support of Government is necessary. Balancing the needs of all abstractors and water users in these water scarce catchments requires new planning processes that build trust and collaboration (*Yakima Basin Integrated Plan, Klamath Basin and the Colorado Basin*)
	The principles of Integrated Water Resource Management (IWRM) planning are being used in most States and by Federal Authorities to plan the future development and use of water resources. These multi-sector planning initiatives are designed to resolve legacy disputes and meet different combinations of water supply, water quality, flood risk management and environmental need (*States of California, Oregon, Washington, Colorado, Nevada and Arizona and the US Department of the Interior, water SMART programme*)
Use of decision making under uncertainty (DMUU) methods	The transition from single-sector requirement based planning to plans which aim to meet multiple needs in an uncertain future has been accompanied by the development of DMUU methodologies. At the simplest level, these are based on collaborative planning which is supported by scenario testing using trusted water resource planning models and tools. The more sophisticated methods rely on simulators that are capable of being used to quantitatively assess multi-sector vulnerabilities, as well as the performance of different investment options in many plausible future scenarios. Methods include Robust Decision Making (RDM), optimisation using Multi-Objective Evolutionary Algorithms (MOEA), Decision Scaling and Info-gap analysis. The best known application of this type of planning is the Colorado Basin Study (*Colorado Basin Study, US Bureau of Reclamation*)
Emergence of adaptive planning	Where large portfolios of schemes are needed to deal with the possible future effects of climate change, drought and growth in demand, approaches based on adaptive planning are being used to develop cost-effective delivery strategies. Adaptive planning relies on monitoring of key performance indicators and the triggering of investment in time to meet critical needs, without building under-utilised or stranded assets. The flexibility to adapt to changing conditions is a key element of adaptive planning (*Dynamic Adaptive Policy Pathways,, Colorado Basin Study, City of Lima Long-term Water Resource Master-plan*)

Table 4: Key water resource planning learning points

Common themes from the key learning points include the following:

- **Increased levels of collaboration** between abstractors and users of water, either through trading the available resources or joint planning. This willingness to cooperate and share enables the most effective use of available resources in water scarce systems
- **Use of storage and conveyance infrastructure** (either built or natural) to ensure that water can be delivered to the right place at the right time. Without this, water mangers are not able to share resources, or have the necessary flexibility to be able to manage the effects of drought and water shortage. Examples of natural storage "infrastructure" include the deep, basin fill, alluvial sediments in central Arizona which have been developed for aquifer storage and recovery
- **Innovation** in both the management and planning of water resources:
    - Long-term agriculture to municipal transfers (water "farming")
    - Trading the water savings from agricultural demand management
    - Trading of ecosystem services
    - Recycling waste water discharges and water banking, and
    - Policy change, including re-purposing existing assets and support for IWRM planning efforts
- **Decision making under uncertainty and adaptive planning** is being used to better understand the risks associated with planning for expected but uncertain futures, ensuring that investment programmes remain affordable.

In the western US, this combination of top-down and bottom-up initiatives has helped water managers and planners avoid catastrophic failure, despite chronic conditions of water scarcity in many catchments and, for the last 15-years, an extended period of severe drought.

Work completed since November 2015

Since the fieldwork for this project was completed in November 2015, the key learning points have been applied in a number of different settings. These include:

Conferences and outreach

Includes the following IWRM-themed presentations and discussions:

- Meeting with Defra officials, November 2015 and May 2016
- Cam and Ely Ouse Winter Conference, Bury St Edmunds, February 2016
- UK Irrigation Association conference, March 2016
- Meeting with Anglian Water Services catchment management team, August 2016
- Defra workshop "Water resilience for growers, farmers and others – AHDB survey and case studies", October 2016
- South Lincolnshire Water Partnership water resource planning conference, Spalding, November 2016
- East Suffolk Water Abstractors Group (ESWAG), Annual General Meeting, February 2017
- Meeting with RSPB, February 2017
- Chartered Institute of Water and Environmental Management (CIWEM), East Anglian branch meeting, March 2017
- Fens for the Future meeting, Boston, March 2017
- UK Irrigation Association conference, March 2017
- Association of Drainage Authorities (ADA), Floodex 2017 conference, May 2017
- Meeting with the EA water resource planners, July 2017
- Meetings with the NFU Water for Food Group (various, 2016/17)
- NFU Irrigation Policy workshop, December 2017

To support this work, visits from contacts established during fieldwork in the western US have been organised. These include:

- David Purkey and Vishal Mehta (Stockholm Environment Institute, Davis, California) to the Water Resources East project, the South Lincolnshire Water Partnership and the NFU Water for Food Group
- Tom Tebbs (State of Washington, Department of Ecology) to the Fens for the Future, South Lincolnshire Water Partnership and the UK Irrigation Association meetings, and
- Leon Basdekas (Colorado Springs Utility, Colorado) to the Water Resources East project

In addition, the author was invited back to the US in spring 2017 to support an Water Research Foundation (WRF) project on resilience planning for municipal water supply systems. This involved the application of DMUU techniques and has helped maintain links with contacts established during the fieldwork.

Water Resources East

The Water Resources East (WRE) project is a multi-company, multi-sector strategic water resource planning initiative being completed by abstractors and others in East Anglia and the adjacent regions. Partners in the collaboration include:

- Affinity Water, Anglian Water, Cambridge Water, Essex and Suffolk Water, Severn Trent Water and Thames Water
- Defra, Environment Agency, Drinking Water Inspectorate and Natural England
- NFU and ADA
- RSPB and the Rivers Trust
- Energy UK
- Greater Lincolnshire LEP and Cambridgeshire County Council
- British Sugar and Sainsburys

The purpose of the WRE is to develop a reliable, affordable and sustainable system of supply which is resilient to the long-term effects of climate change, population growth and drought[43].

The author chairs the Technical Steering Group (TSG) for the WRE project and is responsible for planning and delivering the work needed to help senior decision-makers agree a long-term water resource strategy for the region. This has involved the first practical application of advanced, multi-sector DMUU techniques in the UK, as well as the development of the related stakeholder management processes. The WRE work is supported by Defra, the Environment Agency and Natural England, as well as by the abstractors and water users in the group, and is being considered as a model for multi-sector water resource planning in the future.

Experience from the fieldwork to the western US has been used to guide the development of the WRE project.

South Lincolnshire Water Partnership

The South Lincolnshire Water Partnership (SLWP) is a group of organisations who are collaborating to plan the management and use of water resources in the South Lincolnshire Fens and adjacent areas. They include:

- Anglian Water
- Lincolnshire County Council and the Greater Lincolnshire LEP
- Black Sluice Internal Drainage Board (IDB) and the Welland and Deepings IDB
- Lincolnshire Wildlife Trust and the South Lincolnshire Fenland Partnership
- Fenland Agricultural Water Group and the NFU
- Environment Agency and Natural England

[43] http://www.waterresourceseast.com/

The SLWP is using an integrated approach to promote sustainable rural development in a relatively deprived area where water supply, drought and flood risk are constraints on economic development. Stakeholders have come together to develop innovative strategies for increasing resilience, while simultaneously enhancing the natural capital that underpins much of the local food, farming and visitor economies. SWLP is leading the way in terms of collaboration between stakeholders, addressing issues related to rural deprivation and the use of leading edge decision-support tools for exploring the relationship between water resources, ecosystem services and economic growth.

Details of the work of the SLWP have been submitted to Defra for use as a case study in the 25-year Environment Plan.

The SLWP is chaired by the author, and is benefitting from the IWRM experience gained in the western US.

Next Steps

In the short term, it is planned to develop a formal IWRM plan for the SLWP, which can be used to guide the work of partners in the project over the next 10-15 years. It is expected that this will be published early in 2018.

At the same time, plans are being developed for the next phase of work for the WRE project. Building on the regional strategy and the work of the SLWP, this will seek to develop additional catchment based IWRM initiatives in the WRE region. Candidate areas include:

- Wensum and north-west Norfolk
- East Suffolk and Essex
- Cam and Ely Ouse, and
- The Vale of St Albans and the Chilterns

Using the WRE regional water resource simulator, adaptive planning strategies will also be developed and assessed.

In addition, the work of the WRE and the SLWP is being considered by Defra and the Environment Agency in the context of planning for the 2024 round of statutory water resource management plans. Assuming that the key learning points from these initiatives are adopted, this will embed IWRM planning principles in the work of water companies, their regulators and others working in the water sector.