UNIVERSITAT ROVIRA I VIRGILI

ANALYSIS OF CLIMATE CHANGE IMPACT ON HYDROLOGICAL ECOSYSTEM SERVICES AND WATER ALLOCATION IN WATER SCARCE MEDITERRANEAN RIVER BASINS

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DOCTORAL THESIS

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Certificate

The present thesis entitled "Analysis of climate change impact on hydrological ecosystem services and water allocation in water scarce Mediterranean river basins" is carried out by Rubab Fatima Bangash at Envronmental Analysis and Management Group in the Department of Chemical Engineering at the Universitat Rovira i Virgili (URV) under a supervision of Prof. Dr. Marta Schuhmacher and Dr. Ana Passuello.

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Tarragona, January 28, 2014

Supervisor of doctoral thesis	Co-supervisor of doctoral thesis

In memory of my wonderful father "Inayat Hussain Bangash",
who will truly be missed but never forgotten…
to my great mother, for her endless prayers,
to my beloved brothers and sisters,
for their love and support,
to my understanding husband
for his spiritual and moral support and love.

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AAR: Artificial Aquifer Recharge

ACA: Catalan Water Agency

AET: Actual evapotranspiration

AHP: Analytic Hierarchy Process

C_{area}: Ratio of groundwater catchment to topographical (surface water) catchment area

CQOF: Overland flow runoff coefficient

CKIF: Time constant for interflow

CK1-2: Time constant for routing overland flow

DEM: Digital Elevation Model

DHI: Danish Hydraulic Institute

DS: Desalination

DSS: Decision Support System

EEA: European Environment Agency

ES: Ecosystem services

ETo: Annual evapotranspiration

ETox: Reference evapotranspiration

EU: European Union

FRW: Francolí River watershed

GCM: Global Climate Model

GIS: Geographical Information System

GWLBF1: Maximum groundwater depth causing baseflow

ICC: Institut Cartogràfic de Catalunya

InVEST: Integrated Valuation of Ecosystem Services and Tradeoffs

IPCC: Intergovernmental Panel on Climate Change

K: Soil erodibiltiy

L_{max}: Max water content in root zone storage

LULC: Land use/land cover

MCDA: Multi-criteria decision analysis

MEA: Millenium Ecosystem Assessment

P: Precipitation

PAWC: Plant available water content

PI: Performance Indicators

PJA: Procés Jeràrquic Analític

PM: Performance measures

R: Erosivity index

RBMP: River Basin Management Plan

RW: Reclaimed Water

SR: Storage Reservoir

SSPD: Sistema de Suport a la Presa de Decisions

Sy: Specific yield for the groundwater storage

TG: Root zone threshold value for groundwater recharge

TIF: Root zone threshold value for inter flow

TOF: Root zone threshold value for overland flow

WD: Water Demand

WFD: Water Framework Directives

WMO: World Meteorological Organization

WRI: Water Resources Institute

WS: Water Supply

WWTP: Wastewater Treatment Plant

U_{max}: Maximum water content in surface storage

USLE: Universal Soil Loss Equation

UNEP: United Nations Environment Program

Summary

The Mediterranean region appears to be particularly responsive to global and climate change. Global mean temperature has increased by 0.8 °C compared with pre-industrial levels while Europe has warmed more than the global average, especially in the Mediterranean, the north-east region and mountain areas. Increasingly drier conditions are observed in the Mediterranean region both in the wet and in the dry season (~20%) with an increasingly irregular precipitation in both seasons (~ 40% in the dry season). The annual river flows have also decreased in the Mediterranean region, a difference projected to exacerbate due to climate and global change, which made Mediterranean region most prone to an increase in drought hazard and water stress. Iberian Peninsula has been already affected by several major droughts, e.g. the recent one in 2005. (EEA, 2008). These driving forces of global change impacts on water availability, water quality and ecosystem services in Mediterranean river basins of the Iberian Peninsula, as well as their impacts on the human society and economy makes it an important issue on the EU agenda.

This thesis is an approach to quantify and analyse the water quantity, hydrological ecosystem services and water supply in temperate regions under environmental changes. Hydrological model is developed for a low flow Mediterranean river (Francolí river) to assess the water allocation situation in the river basin using MIKE BASIN. Francolí river is analysed by applying spatially-explicit modeling tool to develop future scenarios for hydrological ecosystem services (Water provisioning) considering drivers of climate change (temperature and precipitation). InVEST model is applied to assess the change

in the delivery of two hydrological ecosystem services, one provisioning (water) and regulating (erosion control), in the heavily humanized Llobregat River basin (Catalonia, NE Spain) under climatic extreme conditions. These services are essential in semi-arid areas such as the Llobregat basin, where water scarcity can limit water-reliant activities.

Climate change scenarios developed for water provisioning in low flow river are used to develop decision support system (DSS) for water allocation in the basin. Economic, environmental and technical aspects are kept in mind while prioritization of performance indicators is selected. Alternate water resources are prioritised by conducting a stakeholder workshop in order to develop integration between academic scientists, policy makers and operational staff to enable more holistic approaches to understanding and managing water resources. To analyse the different combination of alternate water resource along with primary source, a decision support tool was developed. The Analytic Hierarchy Process (AHP) was used to solve the multi-criteria decision-making problem alternate water supply for different sectors in Francolí river basin. AHP is a procedure for describing elements of a problem hierarchically. The problem is divided into smaller parts and the procedure guides decision makers through a series of pair-wise comparison that gives the relative importance of the elements in the hierarchy.

This thesis is divided into five broad parts. The introductory part, *Part I* is elucidated in chapter 1 and chapter 2 as general description of the problem and its components. *Part II* describes the hydrological modelling under chapter 3. *Part III* consist of two chapters, chapter 4 and chapter 5 that focuses the development of scenarios of climate change impact on hydrological ecosystem services. Results obtained from part II and part III are summarised for decision makers in *Part IV* under chapter 6. The conclusions are described in the final *Part V* of the thesis.

Chapter 1 provides the introductory section that gives a brief description of the climate change impact on water resources and ecosystem services. Working hypotheses, the general and specific goal of the thesis are also described under this chapter.

Chapter 2 includes a description of different methodologies used in the different chapters of the thesis. It also explains briefly about the tools selected and used for the study analysis.

Chapter 3 illustrates the application of a basin-scale simulation model MIKE BASIN integrated with ArcGIS that provides insight into the allocation of water to different water user sectors. The model has shown its capability to simulate even at low flows, calculate runoff of the subwatersheds, and efficacy in analyzing the basin performance under data scarce conditions. The significant aspect of the model is that simulation process considered the conjunctive use of surface water and groundwater simultaneously. The model is applied in the low-flow Francolí River basin (NE Spain). The analysis shows that the wet season has increased water availability as compared to very little or no water availability in the dry season. This disparity of water availability compels the municipality to remain dependent on inter-basin water resources. Based on the results, possibilities for new storage schemes or artificial aquifer recharge should be considered to store the excess wet season water and increase dry season reliability.

Chapter 4 evaluates the climate change impacts on ecosystem services provision in medium flow river using InVEST. The analysis shows that water provisioning and erosion control are highly sensitive to climate change in the Llobregat river basin. Services supply and delivery are likely to reduce by significant amounts, indicating that urgent measures must be taken to avoid future water stress in the basin. The sub-watersheds from the Pyrenees region are responsible for most of the services provision, and also the most impacted areas regarding climate change. The results show clear trends over time, with decreases in water yield and the amounts of sediment retained being two orders of magnitude higher than that exported.

Chapter 5 illustrates the application of the ecosystem services model InVEST in Francolí River basin (NE Spain) to assess how changes in temperature and precipitation patterns related to climate change impact on water provisioning ecosystem services in low flow Mediterranean river. After model validation, InVEST seems to be a valuable tool to map ecosystem services in a river with a low flow hydrological regime. In terms of water provisioning, the analysis shows that areas responsible for least and most of the provision of water service will be the most impacted, causing desertification in the low flow areas and at the same time reductions in the source areas are expected which cause flow decreases at the whole watershed. In terms of water supply for drinking purposes, in addition to these mentioned impacted areas, the central region will be also highly impacted because of the water consumption demand by urban areas and irrigated crops land. Because of all these expected impacts mentioned above, urgent measures should be taken to mitigate the already existing water stress in the basin otherwise the situation is expected to worsen as a consequence of climate change.

Chapter 6 described the Decision Support System DSS developed on the basis of outputs from climate change scenarios of water provisioning for low flow river and water allocation. The Analytic Hierarchy Process (AHP) was used to solve the multi-criteria decision-making problem with the help of stakeholders' involvement for prioritization of alternate water supply in Francolí river basin. Different combinations of alternate water resources for domestic, agriculture and industrial sectors are analysed to meet the water demand during water stress periods.

Finally, *Chapter 7* highlights an overview of the most interesting aspects treated in this dissertation, exposing the specific and general conclusions.

Resum

Sembla ser que la regió mediterrània és particularment vulnerable al canvi global i climàtic. La temperatura mitjana anual global ha augmentat 0.8ºC en comparació amb els nivells preindustrials. Europa s'ha escalfat més que la mitjana global, especialment l'àrea mediterrània, el nord-est i les zones muntanyoses. En aquesta zona, s'hi ha observat un increment de les condicions de sequera, tant en l'estació seca com humida (~20%), i un increment de les precipitacions irregulars en ambdues estacions (~40% a l'estació seca). El cabal anual dels rius també ha disminuït a la conca mediterrània. Aquesta diferència de cabals, projectats a empitjorar com a conseqüència del canvi global i climàtic, fa que la regió mediterrània sigui més propensa a un increment de les sequeres i estrès hídric. La Península Ibèrica ja ha estat afectada per diverses sequeres, com per exemple la de l'any 2005 (EEA, 2008). Aquests factors, impulsors dels impactes del canvi global en la disponibilitat i qualitat de l'aigua, serveis ecosistèmics a les conques dels rius mediterranis de la Península Ibèrica, a la vegada que afecten a la societat i economia, fan que esdevingui una problemàtica a l'agenda EU.

La present tesi es una aproximació a la quantificació i anàlisi de la quantitat d'aigua, els serveis ecosistèmics hidrològics i la disponibilitat d'aigua en regions temperades sota canvis dels factors ambientals. Es desenvolupa un model hidrològic per un riu mediterrani amb cabal baix (riu Francolí) per avaluar la situació de la distribució de l'aigua a la conca del riu utilitzant MIKE BASIN. S'analitza el riu Francolí aplicant l'eina de modelatge explícita espacialment per desenvolupar escenaris futurs dels serveis ecosistèmics hidrològics (aprovisionament d'aigua) considerant els impactes del canvi climàtic (temperatura i precipitació). El model InVEST s'aplica per avaluar el

canvi de dos serveis ecosistèmics hidrològics. Un d'ells és l'aprovisionament (aigua) i l'altre la regulació (control de l'erosió), a la conca del riu Llobregat (Catalunya, NE d'Espanya). L'elecció d'aquesta conca es deu a està altament humanitzada i l'escassetat d'aigua pot limitar les activitats que hi depenen.

Els escenaris del canvi climàtic desenvolupats per l'aprovisionament d'aigua en un riu de cabal baix són utilitzats per desenvolupar el sistema de suport a la presa de decisions (SSPD) per la distribució d'aigua a la conca. S'utilitza el criteri ambiental i econòmic per tal de seleccionar la combinació apropiada de fonts primàries i alternatives de recursos hídrics durant els períodes d'estrès hídric. Els recursos hídrics alternatius són prioritzats a través d'un taller amb totes les parts implicades amb l'objectiu de desenvolupar la integració entre els científics acadèmics, els responsables de formular polítiques i el personal d'operació, i així aconseguir un enfocament holístic per poder entendre i gestionar els recursos hídrics. S'ha desenvolupat l'eina de suport a la presa de decisions per analitzar les diferents combinacions dels recursos hídrics alternatius de font primària. El Procés Jeràrquic Analític (PJA) s'ha utilitzat per resoldre el problema de l'alternativa de disponibilitat d'aigua segons diversos criteris de decisió per a la conca del riu Francolí. El PJA és un procediment que serveix per descriure un problema jeràrquicament on el problema es divideix en parts petites. El procediment guia als que prenen les decisions a través de sèries de comparació per parelles que proporciona la importància relativa dels elements en jerarquia.

Aquesta tesis es divideix en cinc parts. La introducció, la Part I formada pel capítol 1 i 2, on hi consta una descripció general del problema i els seus components. La Part II descriu el model hidrològic del capítol 3. La Part III la formen dos capítols, el capítol 4 i 5 que es centra en el desenvolupament d'escenaris d'impacte del canvi climàtic en els serveis ecosistèmics hidrològics. Els resultats obtinguts en la Part II i Part III són resumits pels responsables de formular polítiques a la Part IV en el capítol 6. Les conclusions es descriuen a la Part V de la tesi.

El *Capítol 1* proporciona la secció introductòria, que dóna una breu descripció dels impactes del canvi climàtic en els recursos hídrics i serveis ecosistèmics. Les hipòtesis de treball, i l'objectiu global i específic de la tesis també es descriuen en aquest capítol.

El Capítol 2 inclou una descripció de diferents metodologies utilitzades en els diferents capítols de la tesi. També explica breument les eines seleccionades i utilitzades per l'anàlisi.

El *Capítol 3* il·lustra l'aplicació del model de simulació a escala de conca MIKE BASIN, el qual està integrat amb ArcGis i que proporciona la distribució dels usos de l'aigua a diferents sectors. El model ha resultat ser apte per simular cabals baixos, calculant l'escolament de les subconques, i també és eficaç en l'anàlisi en condicions d'escassetat de dades. L'aspecte significant d'aquest model és que el procés de simulació es realitza de manera conjunta i simultània per l'aigua superficial i subterrània. S'aplica el model per la conca de baix cabal del riu Francolí (NE Espanya). L'anàlisi mostra que durant l'estació humida, la disponibilitat d'aigua ha augmentat en comparació amb l'escassa o nul·la disponibilitat durant l'estació seca. Aquesta diferència de disponibilitat d'aigua obliga als municipis a que continuïn sent dependents dels recursos hídrics d'altres conques. D'acord amb el resultats obtinguts, s'hauria de considerar l'emmagatzematge d'aigua o bé la recàrrega artificial d'aqüífers, i així poder emmagatzemar l'excés d'aigua durant l'estació humida i augmentar la fiabilitat de l'estació seca.

El *Capítol 4* avalua l'impacte del canvi climàtic en l'aprovisionament dels serveis ecosistèmics en un riu de cabal mitjà utilitzant InVEST. L'anàlisi mostra que l'aprovisionament d'aigua i el control de l'erosió són molt sensibles al canvi climàtic a la conca del riu Llobregat. És probable que els serveis de disponibilitat i aprovisionament es redueixin en quantitats significants, indicant que s'haurien de prendre mesures urgents per evitar un futur estrès hídric a la conca. Les subconques de la regió dels Pirineus són responsables de la majoria dels serveis d'aprovisionament d'aigua, esdevenint la zona més impactada pel canvi climàtic. Els resultats mostren tendències temporals clares, amb disminucions en la quantitat d'aigua i en la quantitat de sediments fins retinguts dos ordres de magnitud superiors que els exportats.

El *Capítol 5* mostra l'aplicació del model de serveis ecosistèmics InVEST a la conca del riu Francolí (NE Espanya) per avaluar com els canvis en els patrons de temperatura i precipitació relacionats amb el canvi climàtic impacten en l'aprovisionament dels serveis ecosistèmics hidrològics en un riu mediterrani amb cabal baix. Havent validat el model, sembla ser que l'InVEST és una eina vàlida per avaluar els serveis ecosistèmics en un riu amb cabal de règim hidrològic baix. En termes de disponibilitat d'aigua, l'anàlisi mostra que les àrees responsables de més i menys aigua disponible seran les més impactades, causant desertificació a les zones amb cabal baix, a la vegada que la reducció de la quantitat d'aigua a l'àrea de naixement del riu s'espera que causi reduccions al cabal de tota la conca. En termes de disponibilitat d'aigua pel consum, a més a més de totes aquestes àrees esmentades, la regió central també esdevindrà altament impactada com a conseqüència de la demanada d'aigua per usos urbans i zones de regadiu. Així doncs, s'haurien de prendre mesures urgents per mitigar l'estrès hídric ja existent a la conca, ja que s'espera que la situació empitjori com a conseqüència del canvi climàtic.

El *Capítol 6* descriu el Sistema de Suport a la Presa de Decisions (SSPD) desenvolupat en base als resultats obtinguts dels escenaris de canvi climàtic en termes de disponibilitat i distribució de l'aigua per un riu de cabal baix. S'analitzen diferents combinacions de fonts d'aigua primàries i recursos d'aigua alternatius per tal de satisfer la demanda d'aigua durant períodes d'estrès hídric. Com a criteri d'anàlisi s'utilitza l'índex econòmic i ambiental. El Procés Jeràrquic Analític (PJA) va ser utilitzat per resoldre el problema de l'alternativa de disponibilitat d'aigua segons diversos criteris de decisió per a la conca del riu Francolí.

Finalment, el *Capítol 7* mostra una visió general dels aspectes tractats que han resultat ser més interessants en la present tesi, exposant les conclusions especifiques i generals.

This thesis belongs to Chemical, Environmental and Process Engineering PhD programme of the Universitat Rovira I Virgili Tarragona (Spain). The research work is carried out within the research group of Environmental Analysis and Management (AGA) at the Department of Chemical Engineering from March 2011 to March 2014.

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The thesis is based on the following papers, which have either been published, accepted or under review in international peer-reviewed journals;

Marquès M, **Bangash, R.F.**, Kumar, V., Sharp, R., Schuhmacher, M. The impact of climate change on water provision under a low flow regime: A case study of the ecosystems services in the Francoli river basin. J Hazard Mater 2013;263, Part 1:224-32.

Bangash, R.F., Passuello, A., Sanchez-Canales, M., Terrado, M., López, A., Elorza, F.J. et al. Ecosystem services in Mediterranean river basin: Climate change impact on water provisioning and erosion control. Science of the Total Environment 2013;458–460:246-55.

Bangash, R.F., Passuello, A., Schuhmacher, M. “Analysis of Water Resource Allocation and Water Quality for Low Flow River in Mediterranean Watershed: Hydrological Simulation Model Overview” International Environmental Modelling and Software Society (iEMSs) 2012 International Congress on Environmental Modelling and Software Managing Resources of a Limited Planet: Pathways and Visions under Uncertainty, Sixth Biennial Meeting, Leipzig, Germany, pp. 2769-2777, ISBN: 978-88-9035-742-8

Bangash, R.F., Passuello, A., Hammond, M., Schuhmacher, M. “Water allocation assessment in low flow river under data scarce conditions: A study of hydrological simulation in Mediterranean basin”. Science of the Total Environment 2012; 440:60-71.

In addition, the work included in this thesis has been presented in the following oral communications and posters in national and international conferences;

Bangash RF, Kumar V, Schuhmacher M. Story of three rivers: Climate change impact on Mediterranean river basins in Catalonia. Oral presentation in 16th Biennial Seminar on Water Resources and Environmental Management: Towards a Sustainable Future. Tarragona (Spain) June 25, 2013.

Bangash RF, Kumar V, Schuhmacher M. Decision support system based on DPSIR framework for a low flow Mediterranean river basin. Poster presentation in EGU General Assembly, 07-12 April 2013, Vienna, Austria.

Bangash RF, Passuello A, Schuhmacher M. Hydrology and water quality modelling under data scarcity for low flow river in Mediterranean watershed. Poster presentation in 2nd SCARCE International Conference. Madrid (Spain) November 26-27, 2012.

Bangash RF, Passuello A, Schuhmacher M. Identification of alternate solutions to mitigate river health degradation and their effect on ecosystem services in low flow river watershed. Poster presentation in SETAC Europe 22nd Annual Meeting, Berlin (Germany) 2012.

Bangash RF, Passuello A, Schuhmacher M. Analysis of water resource allocation and ecosystem services for low flow river basin in Mediterranean watershed. Oral presentation in Climate Change and its Impacts: Regional Coupled Human-Natural Systems and Evidence- Based Policy Making workshop. Rhode Island (USA) 2012.

Bangash RF, Passuello A, Schuhmacher M. Analysis of Water Resource Allocation and Water Quality for Low Flow River in Mediterranean Watershed: Hydrological Simulation Model Overview. Oral presentation in 6th International Congress on Environmental Modelling and Software (iEMSs), Leipzig (Germany) 1 - 5 July, 2012.

Bangash RF, Kumar V, Schuhmacher M. Integrated hydrological and ecosystem services models for a low flow Mediterranean river basin. Poster presentation in 3rd SCARCE International Conference. Valencia (Spain) November 23-24, 2012.

Furthermore, during the research period, another parallel research carried out as a result of successful proposal on “Socio-economic vulnerability to flood risk in informal urban settlements: A tale of two cities” submitted during Brown International Advanced Research Institutes (BIARI) workshop on “Climate Change and its Impacts: Regional Coupled Human-Natural Systems and Evidence- Based Policy Making” funded by Bank Santander held at Brown University, Providence, Rhode Island (USA), June 2012.

Moreover, a short research stay was conducted at Centre of Ecology and Hydrology (CEH) Bangor, UK from January 2014 to March 2014 under a supervision of Dr. Bernard J. Cosby.

Part I
INTRODUCTION AND FRAMEWORK

Chapter 1

Introduction and framework

1. INTRODUCTION

1.1 Water scarcity and climate change

Climate is expected to continue to change in the future in spite there are still many uncertainties, which will affect natural and human systems such as forestry, fisheries, water resources, human settlements and human health (IPCC, 2001). Global surface temperature has risen by 0.74 ^{o}C in the past 100 years, with temperatures increasing more rapidly in the past 50 years. Heat and water are closely linked, and in recent decades, warming trends have led to changes in the hydrologic cycle (Intergovernmental Panel on Climate Change (IPCC, 2007)). Disturbances in the hydrological cycle can cause water scarcity in a region. Water scarcity refers to the relative shortage of water in a water supply system that may lead to restrictions on consumption. Scarcity is the extent to which demand exceeds the available resources and can be caused either by drought or by human actions such as population growth, water misuse and inequitable access to resources. Most of the Mediterranean countries are facing water scarcity. Whereas, drought is a recurrent feature of climate that is characterized by temporary water shortages relative to normal supply, over an extended period of time – a season, a year, or several years. The term is relative, since droughts differ in extent, duration, and intensity.

According to World Resources Institute (WRI), the world’s water systems face formidable threats. More than a billion people currently live in water-scarce regions, and as many as 3.5 billion could experience water scarcity by 2025. Increasing pollution degrades freshwater and coastal aquatic ecosystems. And climate change is poised to shift precipitation patterns and speed glacial melt, altering water supplies and intensifying floods and drought in different parts of the world (Fig 1.1).

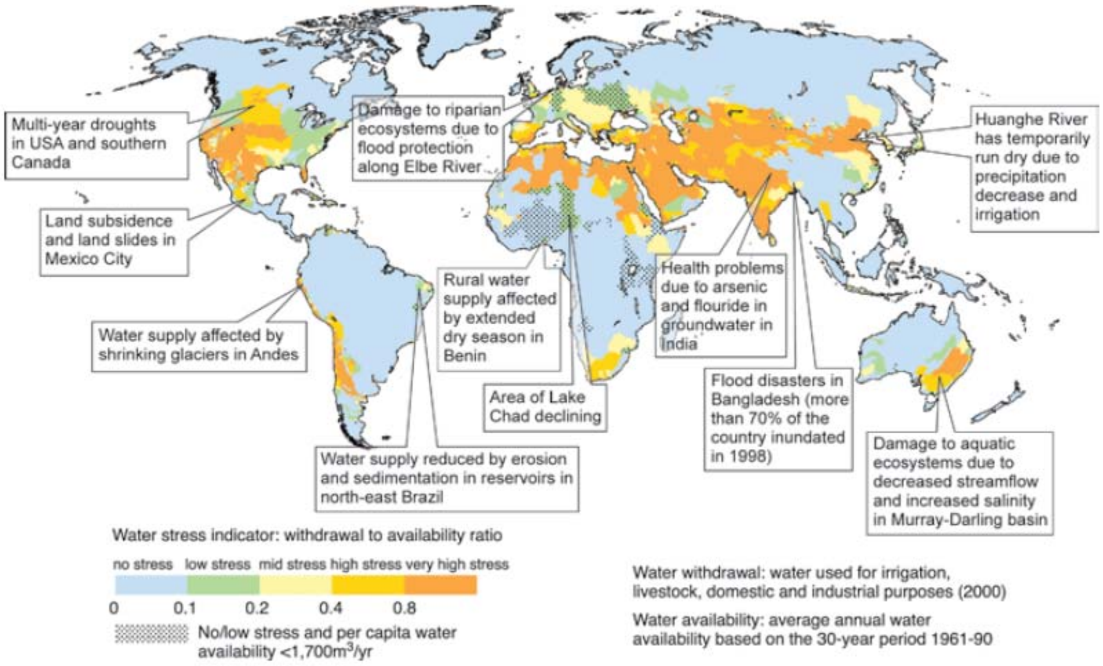


Fig 1.1. Examples of current vulnerabilities of freshwater resources and their management; in the background, a water stress map based on WaterGAP *(Source: Alcamo et al., 2003)*

Global water use is probably increasing due to economic growth. In most countries, except for a few industrialised nations, water use has increased over recent decades, due to population and economic growth, changes in lifestyle, and expanded water supply systems, with irrigation water use being by far the most important cause. Irrigation accounts for about 70% of total water withdrawals worldwide and for more than 90% of consumptive water use (i.e., the water volume that is not available for reuse downstream) (Bates et al., 2008).

The water scarcity has also affected some temperate regions with normally plentiful resources, such as Europe and North America, where periods of drought are becoming more frequent and are lasting longer. Due to successive droughts over the last decades, some watercourses have dried up and the level of groundwater supplies has reached a critical point in many parts of Italy, France, Spain and the UK. Europe's waters are affected by several pressures, including water pollution, water scarcity and floods. Major modifications to water bodies also affect morphology and water flow (EEA, 2012). The Mediterranean region is undergoing rapid local and global social and environmental changes. All indicators point to an increase in environmental and water scarcity problems with negative implications towards current and future sustainability. The water scarcity pressures are not homogeneous across the Mediterranean region and sectors of water use. The risk of water scarcity is proposed to manage by preparedness rather than a crisis approach along with the importance of local management at the basin scale (Iglesias et al., 2007).

Climate change increases water resources stresses in some parts of the world where runoff decreases, including around the Mediterranean, in parts of Europe, central and southern America, and southern Africa. In other water-stressed parts of the world—particularly in southern and eastern Asia—climate change increases runoff, but this may not be very beneficial in practice because the increases tend to come during the wet season and the extra water may not be available during the dry season (Arnell., 2004). Future population growth will increase the pressure on available water resources in many countries as well as globally. How countries around the world manage water resources is becoming more critical with each passing day. And climate change is likely to play havoc with even the best laid management plans.

Climate change will increase water temperature and the likelihood of flooding, droughts and water scarcity in the years to come. There are many indications that water bodies already under stress from pressures are highly susceptible to climate change impacts, and that climate change may hinder attempts to restore some water bodies to good status. Preparing for climate change is a major challenge for water management in Europe. The Water Framework Directives (WFD) is the first piece of European environmental legislation that addresses hydromorphological pressures and impacts on water bodies. It requires action in those cases where the hydromorphological pressures affect the ecological status, interfering with the ability to achieve the WFD objectives. Implementation of the WFD is to be achieved through the River Basin Management Plan (RBMP) process, which requires the preparation, implementation and review of a RBMP every six years. Water resource management needs an integrated part of the RBMP. In more arid river basins, such as in the Mediterranean, drought management plans are already partly integrated into RBM planning.

The main aim of EU water policy is to ensure that throughout the EU, a sufficient quantity of good-quality water is available for people's needs and for the environment. The WFD, which came into force on 22 December 2000, establishes a new framework for the management, protection and improvement of the quantity and quality of water resources across the EU. EU Member States should aim to achieve good status in all bodies of surface water and groundwater by 2015 unless there are grounds for derogation. Only in this case may achievement of good status be extended to 2021 or by 2027 at the latest. Achieving good status involves meeting certain standards for the ecology, chemistry, morphology and quantity of waters. In general terms, 'good status' means that water shows only a slight change from what would normally be expected under undisturbed conditions. There is also a general 'no deterioration' provision to prevent deterioration in status (EEA 2012).

1.2Water allocation

Water allocation describes a process whereby an available water resource is distributed to legitimate claimants and the resulting water rights are granted, transferred, reviewed, and adapted (Quesne et al., 2007). Allocation of water among competing uses (industry, agriculture and municipal) is already under pressure due to demographic change, increased environmental awareness and changing patterns of water demand. Some of the world's major rivers are now completely dry for stretches and periods of time. But the most effective means of allocating water will always be determined by local demographic, environmental, political and social circumstances: there is no single approach that can simply be replicated globally. Meeting the new challenges on water resources management, implies the quantification of climate change impact on basin-scale hydrology (Varies et al., 2004).

Hydrologic analysis of climate change scenarios indicate possible reductions in stream flows in some areas, increased flood frequencies in other areas, and changes in the seasonal pattern of flows, with reduced summer flows likely in many semi-arid and Mediterranean river basins. By the middle of the 21st century, annual average river runoff and water availability are projected to increase as a result of climate change at high latitudes and in some wet tropical areas, and decrease over some dry regions at mid-latitudes and in the dry tropics (Bates et al., 2008). This phenomenon is making water allocation in summer more difficult and challenging. Initially, sufficient water is available to meet the needs of all water sectors within a catchment without jeopardising hydrological ecosystems. As a consequence, little management is required. An increase in agricultural and industrial activity coupled with population change lead to increasing water demands. In Spain there are 9 River Basin Organizations (RBOs), since the 1920's for the development and allocation of water resources and the control of water use and pollution at basin level, with water user participation in governing bodies and advisory stakeholder participation at national and basin levels(GWP, 2002). It is obvious that allocation processes usually arise from a familiar pattern in the development of water use. However, some augmentation of supply through engineering approaches is usually possible to meet increased demand, like alternated water resources notably the construction of increased storage capacity and inter-basin transfer etc.

Water resources that comprise surface water, groundwater and water from alternate water resources are an essential input for various economic sectors, such as agricultural, industrial, domestic, hydropower, recreation and environmental. With the increased population growth rates, change in climate and improved life style, the competition over scarce water resources is increasing. Water scarcity is expected to rise in the Mediterranean, greatly increasing the need for efficient water allocation systems. However in several situations, a new and more sophisticated approach to water management is required instead of engineering approach when water stress is reached. These approaches seek to allocate water efficiently and restore river flow through a multi-disciplinary and multi-stakeholder process of managing water resources.

1.3Ecosystem services

Many aspects of our planet are changing rapidly due to climate change and human activities and these changes are expected to accelerate during the next decades (IPCC, 2001). For example, water scarcity and floods are frequent (Millenium Ecosystem

Assessment, 2003), forest area in the tropics is declining (Geist and Lambin, 2002), and rising atmospheric carbon dioxide results in global warming (IPCC, 2001). Many of these changes will have an immediate and strong effect on agriculture, forestry, biodiversity, human health and well-being, and on amenities such as traditional landscapes and hydrological ecosystem services (Watson et al., 2000; UNEP, 2002).

Ecosystem services are the benefits people obtain from ecosystems, which the Millinium Ecosystem Assessment MA describes as provisioning, regulating, supporting, and cultural services. Ecosystem services include products such as food, fuel, and fiber; regulating services such as climate regulation and disease control; and nonmaterial benefits such as spiritual or aesthetic benefits (Millenium Ecosystem Assessment, 2003). Changes in these services affect human well-being through impacts on security, the basic material for a good life, health, and social and cultural relations. These constituents of well-being are, in turn, influenced by and have an influence on the freedoms and choices available to people (Fig 1.2).

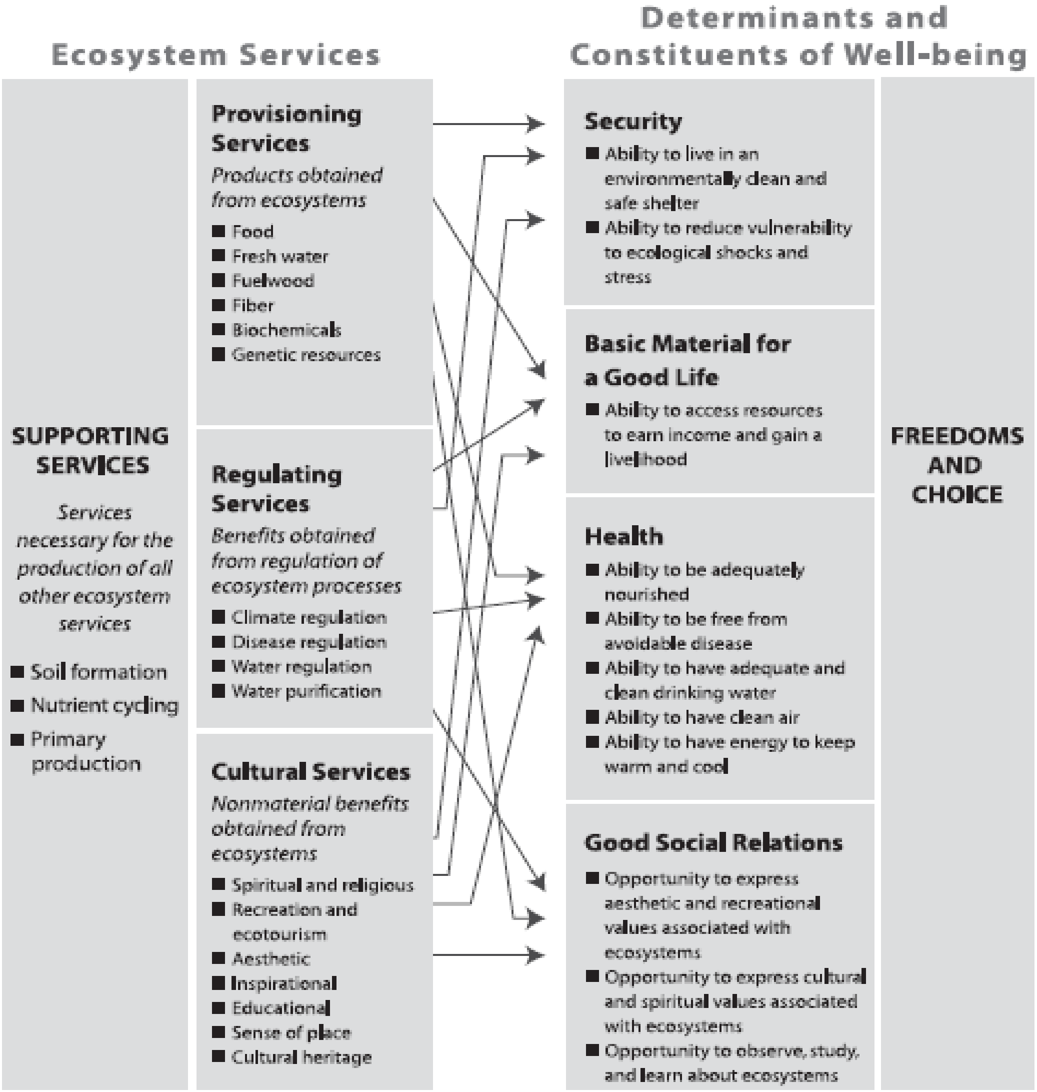


Fig 1.2 Ecosystem Services and their links to Human Well-being. *(Source: Millenium Ecosystem Assessment, 2003).*

Mediterranean region’s aquatic ecosystems are threatened because of the deterioration of water quality and quantity. The Mediterranean Sea faces heavy pollution problems, resulting from human activities (agricultural, industrial and residential) on land. The coastal ecosystems are at their most vulnerable in the face of the process to built-up the Mediterranean coasts. Globally, many freshwater ecosystems are suffering from massive over abstraction. Urbanisation, pollution, over-exploitation of natural resources and fragmentation management approaches of natural resources pressure Mediterranean aquatic ecosystems and biodiversity. The region has lost more than the 50% of its wetlands and in some places this rate reaches the 90% or more (Scoullos et al., 2002).

Over the last decades many people have become increasingly aware of these environmental changes, such that they are now commonly recognised as ‘global change’ (Steffen et al., 2001).

Global climate change will cause significant alterations in temperature regimes and precipitation patterns over the next 100 years. The global surface climate is expected to warm by 1.4 to 5.8°C by 2100 owing to the emissions of greenhouse gases (Harrison et al. 2003). But temperature increases will be higher in Mediterranean climate regions. According to Tin et al. (2005), a global temperature rise of 2°C is likely to lead to a corresponding warming of 1-3 °C in the Mediterranean region. Such changes in global climate will seriously affect inland freshwater ecosystems (lakes, running waters, wetlands) and coastal lakes in these regions. Hydrological ecosystem services such as water provisioning for agriculture, drinking, erosion protection, hydropower generation and water purification are threatened by increasing rainfall variability in Mediterranean river basins (Terrado et al., 2013). Proportion of severe water stress in EU river basins is likely to increase from 19% today to 35% by 2070. If temperature rises by 2 to 3°C, water scarcity would affect 1.1 to 3.2 billion people. In more prudent cases, such allocation systems may be introduced before catchments experience major water stress, but often a crisis is required to inspire reform. The 'flow regime' and water level fluctuations are one of the major determinants of ecosystem function and services in aquatic ecosystems. In many locations, water demand often exceeds availability, and in many cases exploitation of water resources has led to significant degradation of freshwater biodiversity. In many cases, location of infrastructures such as reservoirs within the basin influences hydrological ecosystem services such as erosion protection and hydropower generation.

1.4Decision support system

It is important to promote efficient use of water through better management of water resources, for social and economical sustainability in arid and semi-arid areas, under the conditions of severe water shortage. However, the selection of appropriate intervention for any situation in water stressed area is a multi-stage process. The design, development, and implementation of effective decision support systems bring together disciplines, people, and institutions necessary to address complex water resources challenges. Decision Support Systems (DSS) are technical tools intended to provide valid and sufficient information to decision makers.

Decision support systems are integral parts of Integrated Water Resource Management IWRM processes facilitating the use of science and technology advances in public policy. A key effort during the DSS development phase is to determine the necessary and sufficient information that decision makers need to make good decisions. This information set is expected to vary by decision type (planning, management, or near real time), management agency, and stakeholder group, and significant interaction should take place with the decision makers defining the most suitable information. Many research projects and several environmental assessments are currently addressing these concerns at all relevant scales, frequently in multidisciplinary collaborations. However, integrating this wealth of information across disciplines remains a considerable challenge (Millenium Ecosystem Assessment, 2003).

1.5 Climate change standards

Hydrological ecosystem services are under considerable pressure due to climate and global change all over the world. During last two decades several climate change standards and classifications have been developed to assess and quantify these issues.

The Intergovernmental Panel on Climate Change (IPCC) was created in 1988. It was set up by the World Meteorological Organization (WMO) and the United Nations Environment Program (UNEP) to prepare, based on available scientific information, assessments on all aspects of climate change and its impacts, with a view of formulating realistic response strategies. Today the IPCC's role is as defined in Principles Governing IPCC Work, "...to assess on a comprehensive, objective, open and transparent basis the scientific, technical and socio-economic information relevant to understanding the scientific basis of risk of human-induced climate change, its potential impacts and options for adaptation and mitigation". IPCC reports should be neutral with respect to policy, although they may need to deal objectively with scientific, technical and socio-economic factors relevant to the application of particular policies." Through the IPCC, climate experts from around the world synthesize the most recent climate science findings every five to seven years and present their report to the world's political leaders. The IPCC has issued comprehensive assessments in 1990, 1996, 2002 and most recently the Fourth Assessment Report (AR4) released in 2007 (IPCC, 2007).

1.6Motivation of the dissertation

Several gaps in knowledge exist in terms of observations and research needs related to climate change and water. In many cases and in many locations, there is compelling scientific evidence that climate changes will pose serious challenges to the water systems (Gleick and Adams, 2000). Observational data and data access are prerequisites for adaptive water management. There is a need to improve understanding and modelling of climate changes related to the hydrological cycle at scales relevant to decision making. Information about the water related impacts of climate change is inadequate – especially with respect to hydrological ecosystems – including the aspect of water and data scarcity constraints in Mediterranean river basins. As a conclusion to this chapter, following issues are proposed for research in the dissertation:

1. Assessing water allocation is crucial to meet stakeholders' needs in case of water scarcity, notably in the Mediterranean region. Technological issues need to be addressed of quantifying water and analysis of its allocation to different sectors, in addition where to find more water and how to make more use of the water we have already in the river basin (*Part II*).
2. Climate change has the potential to cause abrupt negative changes in hydrological ecosystem services in already water scarce Mediterranean river basins of Spain that needs to be quantified and assessed by developing different scenarios (*Part III*).
3. There are several alternatives to ensure water supply in the water scarce region, e.g. wastewater reuse, artificial aquifer recharge etc. However selection of a specific intervention considering cost, technical and environmental aspect has to be carried out by decision making tool (*Part IV*).

1.7Objectives

The general aim of the thesis is to provide a better overall understanding of the effects of climate change on freshwater ecosystem services in Iberian rivers as a result of loss of quality associated with water scarcity and prevent further deterioration of rivers and enhance the status of water resources. In order to achieve this goal, the following tasks are carried out:

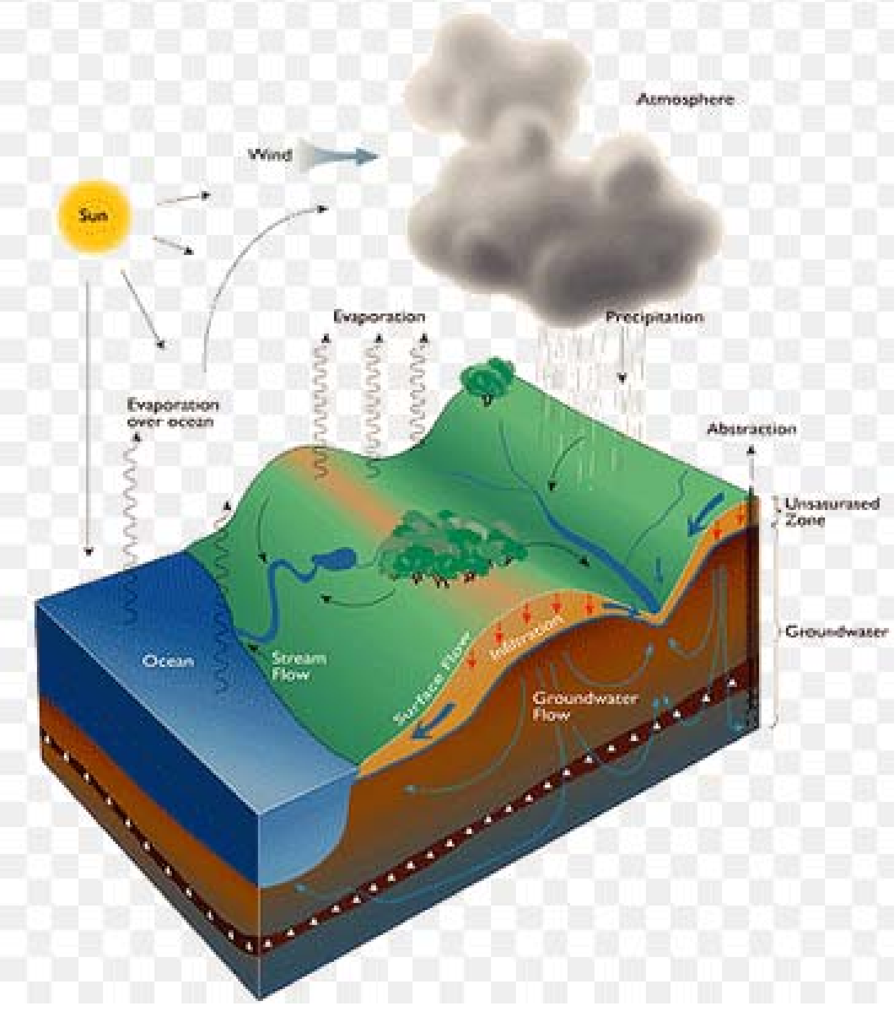
1. To develop a model capable of simulating water allocation in a low flow Mediterranean river watershed:
    a. To develop rainfall-runoff model of low flow water and data scarce river watershed.
    b. To develop catchment-scale hydrological model.
    c. To quantify unallocated water in the watershed.

2. To assess the effects of climatic extremes on the delivery of hydrological ecosystem services in a Mediterranean low and medium flow river basins:
    a. To develop climate change scenarios for water provisioning.
    b. To develop climate change scenarios for sediment retention.

3. To develop decision support system to allocate water to different levels of water use units to provide water for all essential uses even under aggravated climatic conditions:
    a. To analyse the cost effective alternate water resource in water scarce region.
    b. To analyse alternate water resources for different sectors by considering sustainability ranking.

Chapter 2

Material and methods



2. MATERIAL AND METHODS

2.1 Methodological approach

Future water resource management is of primary importance to society, economy and the environment. Understanding of the complex consequences of climate change for the hydrology and human and environmental uses of water and planning for climate change and adapting to those changes, is important for a water scarce region and sustainable future. This research study holistically explored possible implications of global climate change on water resources and hydrological ecosystem services in Mediterranean river basins (NE Spain).

Figure 2.1 represents the methodological integration and framework of different analysis performed during present dissertation. Combining with rainfall-runoff model, MIKE BASIN is used to assess water allocation situation in low flow river basin, as described under chapter 3. Impact of climate change on hydrological ecosystem services is presented in chapter 4 and 5. The results obtained from both analyses, water allocation and hydrological ecosystem services, are incorporated in developing decision support system as presented in chapter 6.

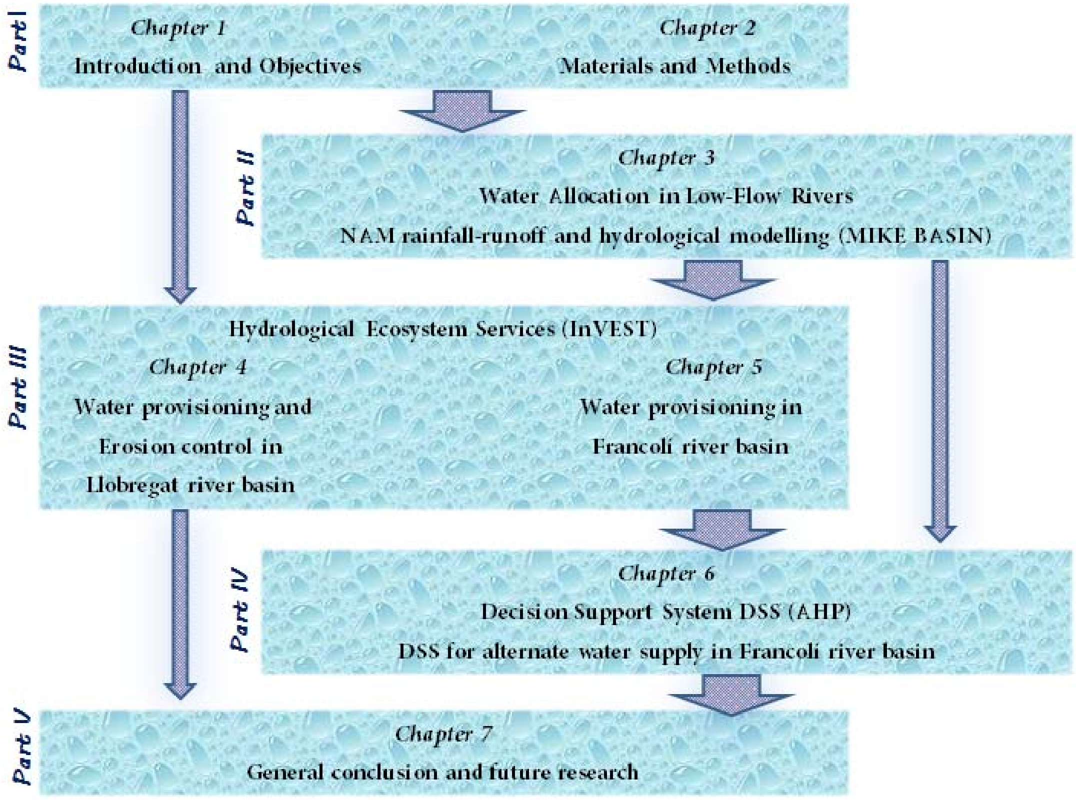


Fig. 2.1 Methodological framework of present dissertation

2.2 Hydrological modeling

Hydrologic models are necessary to translate climatic forcing (rainfall and temperature) to lake rainfall, evaporation, and watershed inflow. It is defined by Maidment (2000) as "a mathematical representation of the flow of water and its components on some part of the land surface or subsurface environment". There are different tools for Water Resource Management characterised as: a) Hydrologic Models (physical processes) that simulate river basin hydrologic processes (water balance, rainfall-runoff, lake simulation, stream water quality models, etc.) and b) Water Resource Models (physical and management) that simulate current and future supply/demand of system, operating rules and policies, environmental impacts, hydroelectric production and Decision Support Systems (DSS) for policy interaction. Hydrological models are normally designed for stationary conditions, but they are used under conditions of change in climate change studies (Xu et al., 2005).

To assess the variability of surface water and groundwater resources over selected Iberian river basins several different programs can be used. Modelling is now a common tool in the field of hydrological research, and a rapid development of computational power, the ability to model the natural water cycle has progressed enormously over the recent decades. Considerable effort has been expended on developing improved catchment hydrological models for estimating the effects of climate change (Arnell and Liu, 2001). Many new techniques and methodologies have been raised to facilitate the river basin research. For example, the use of GIS, remote sensing techniques, rainfall-runoff modelling, various modelling assessments, water quality assessments, river basin hydrology and so on. A quantitative analysis of river discharge is the base for all other fluxes researches like nutrients or water erosion modelling. However, the methodology of quantitative analysis or discharge modelling is very different from region to region.

Although the concept of the hydrologic cycle is simple, the phenomena are enormously complex and intricate. The hydrological models are developed to study the future impacts of climate and socio-economic changes on catchment hydrology and therefore, the calibration and validation of the preexisting regionalised approaches needs to be carried over a sufficiently wide range of catchment conditions such that the approach stays within or close to the calibration range. Water level fluctuations during peak flow season and water shortage or dry periods creates more data uncertainty. Of major concern is the reduction in low flows and lowered groundwater levels, which might lead to water shortages, especially during summer periods (Arnell and Liu, 2001). Usually low flow rivers are ignored by the institutions to record river flow and install enough gauging stations in the watershed. However in the absence of perfect knowledge, they may be represented in a simplified way by means of the systems concept.

Water allocation modelling has received considerable attention in the recent past by the scientific community for the analysis of water uses by all competing sectors. For example, an economic model is developed by Bielsa and Duarte (2001) for allocating water between two competing sectors, irrigation and hydropower in NE Spain. Babel et al., (2005) developed a simple interactive integrated water allocation model (IWAM), which can assist the planners and decision makers in optimal allocation of limited water from a storage reservoir to different user sectors, considering socio-economic, environmental and technical aspects. Water allocation modeling is kind of a river basin management decision support system (DSS) designed as a computer-aided tool for developing improved basin wide planning. Analysis is carried out for water balance of the river basins under different levels of water users and determines the water allocation in the basin.

2.3 Ecosystem services modelling

Hydrological processes have been identified as delivering ecosystem services that are fundamental to both human well-being and the maintenance of biodiversity. However, modeling the connections between landscape changes and hydrologic processes is not simple. Sophisticated models of these connections and associated processes (such as the WEAP model) are resource and data intensive and require substantial expertise.

Freshwater ecosystems provide society with the essential services of water supply for its sustenance, economic activity, and recreation, as well as habitat for its freshwater fishery. The WaterGAP model, used by Alcamo et al. (2003a, 2003b) to quantify freshwater-related ecosystem services, computes water availability on a grid and river basin scale by taking into account precipitation/snowmelt, evaporation, groundwater storage and runoff. The model estimates future water withdrawals according to changes in income, population, and electricity demand. Other similar tools include Advanced Terrestrial Ecosystem Analysis and Modelling (ATEAM), (Schroter et al., 2005), Artificial Intelligence for Ecosystem Services (ARIES) (Bagstad et al., 2011; Villa et al., 2011), EcoAIM, Eco Metrix, Ecosystem Services Review (ESR), LUCI (Jackson et al., 2013), ES Value, and Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST).

Ecosystem services model, Integrated Valuation of Environmental Services and Tradeoffs (InVEST) developed by Natural Capital Project, models for quantifying, mapping, and valuing the benefits provided by terrestrial, freshwater and marine systems. InVEST is designed to inform decisions about natural resource management. Decision-makers, from governments to non-profits to corporations, often manage lands and waters for multiple uses and inevitably must evaluate trade-offs among these uses; InVEST’s multi-service, modular design provides an effective tool for evaluating these trade-offs (InVEST user guide, 2.4.4, 2012).

Models are needed to anticipate ecosystem collapses so that policies can be developed to avoid or adapt to these collapses. The MA’s Conditions and Trends Report (2005) also points out the need for “both conceptual and quantitative models that can begin to give both scientific and policy communities advance warning of when the capacity of systems is beginning to be eroded, or thresholds likely to be reached."

Soil erosion is one of the biggest problems in connection with agricultural practices in many parts of the world. It is required to develop a streamlined process in which soil loss estimation and the quantity of transported sediment are calculated to identify potential high-risk areas of soil erosion. Erosion and sedimentation are natural processes that contribute to healthy ecosystems, but too much may have severe consequences. The magnitude of sediment transport in a watershed is determined by several factors. Natural variation in soil properties, precipitation patterns, and slope create patterns of erosion and sediment runoff. Vegetation holds soil in place and captures sediment moving overland. The Sediment Retention model provides the user with a tool for calculating the average annual soil loss from each parcel of land, determining how much of that soil may arrive at a particular point of interest, estimating the ability of each parcel to retain sediment, and assessing the cost of removing the accumulated sediment.

2.4 Decision making tools

Decision Support Systems (DSS) are considered the best tool for approaching an integrated analysis of water management. Such systems apply reason similar to that of a human being, who is the expert in the subject (Stevens, 1984). These systems are provided with data from many diverse sources of information, including experimental results, field survey data, and even those obtained from traditional models.

Current tools range from simple spread sheet model to complex software packages. If they are flexible enough for use in diverse decision contexts and can be affordably applied, they could reasonably be incorporated into public and private-sector environmental decision making on a routine basis (Bagstad et al., 2013). However, the development of decision-support tools that integrate ecology, economics, and geography to support decision making is a more recent phenomenon (Ruhl et al., 2007; Daily et al., 2009).

Moreover, there are also several commercial software packages, specifically designed for each type of DSS. DSSs can be either stochastic or deterministic, depending on whether or not they deal with processes containing a degree of uncertainty.

Stakeholders' preferences could generate useful information in prioritizing and developing better water resource management plans and also avoid maximum conflicts. The Analytic Hierarchy Process (AHP) is a procedure for describing elements of a problem hierarchically. AHP was used to solve the multi-criteria decision-making problem of alternate water supply for Francolí river basin. The problem is divided into smaller parts and the procedure guides decision makers through a series of pair-wise comparison that gives the relative importance of the elements in the hierarchy. Decision support systems are not only important but also quite complex and is in need of systems that facilitate more consistent and effective strategic decisions.

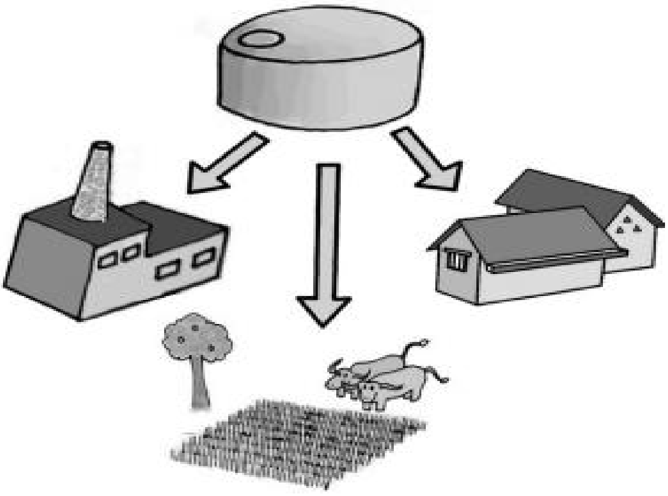
Part II

WATER ALLOCATION IN LOW-FLOW RIVERS

Chapter 3

Water allocation assessment in low flow river under data scarce conditions: A study of hydrological simulation in Mediterranean basin

Rubab F. Bangash, Ana Passuello, Marta Schuhmacher, Michael Hammond



ABSTRACT

River Francolí is a small river in Catalonia (northeastern Spain) with an average annual low flow (~2 m^3/s). The purpose of the River Francolí watershed assessments are to support and inform region-wide planning efforts from the perspective of water protection, climate change and water allocation. In this study, a hydrological model of the Francolí River watershed was developed for use as a tool for watershed planning, water resource assessment, and ultimately, water allocation purposes using hydrological data from 2002 to 2006 inclusive. The modeling package selected for this application is DHI's MIKE BASIN. This model is a strategic scale water resources management simulation model, which includes modeling of both land surface and subsurface hydrological processes. Topographic, land use, hydrological, rainfall, and meteorological data were used to develop the model segmentation and input. Due to the unavailability of required catchment runoff data, the NAM rainfall-runoff model was used to calculate runoff of all the sub-watersheds. The results reveal a potential pressure on the availability of groundwater and surface water in the lower part of River Francolí as was expected by IPCC for Mediterranean river basins. The study also revealed that due to the complex hydrological regime existing in the study area and data scarcity, a comprehensive physically based method was required to better represent the interaction between groundwater and surface water. The combined ArcGIS/MIKE BASIN model appear as a useful tool to assess the hydrological cycle and to better understand water allocation to different sectors in the Francolí River watershed.

Keywords: Low flow, Data scarcity, MIKE BASIN, NAM rainfall-runoff, Hydrological simulation.

3.1. Introduction

Global change impacts on water availability, water quality and ecosystem services in the Mediterranean river basins of the Iberian Peninsula, as well as their impacts on socio-economic system make it a key issue on the EU agenda. The challenge of managing the watershed system of low flow rivers in temperate regions which are prone to environmental change is made increasingly complex where data is scarce. It is likely that the first impacts of climate change anywhere in the world will be water resource issues like in the Mediterranean water resource system through increased frequency of water shortages and decline in water quality (IPCC, 2007). Many Mediterranean watersheds are currently water-stressed, considered in terms of the per capita water availability or the ratio of withdrawals to annual runoff. Under climate change, rainfall is expected to decrease in Mediterranean area (Milly et al., 2005), as well as river flow (López-Moreno et al., 2011), however, an increase of extremely rainy months is also predicted in Catalonia (NE Spain) (Barrera and Cunillera, 2011). Anticipated changes in the near future further threaten this precarious situation, as water demands are expected to increase, whereas water resources are expected to decrease because of climate warming and the same or decreasing precipitation (Bates et al., 2008).

River flow is the result of complex natural processes, which operate on a catchment scale. Conceptually, a river catchment can be perceived as a series of interlinked reservoirs, each of which has components of recharge, storage and discharge (Smakhtin, 2000). The low-flow regime of the river results from other natural factors besides anthropogenic effects, including the hydraulic characteristics and extent of the aquifers, infiltration characteristics of soils, frequency and amount of recharge, evapotranspiration rates, vegetation types, topography, and last but not least, the climate. The total area of lower infiltration capacity land increases as built-up areas expands, affecting the spatial distribution of saturated hydraulic conductivity (Wijesekara et al., 2011). Even countries in southern Europe with relatively more water resources could suffer ever-more frequent regional water shortages due to the twin problems of climate change and rising demand. Some water supplies could become unusable due to the penetration of salt water into rivers and coastal aquifers as sea level rises. Water pollution - already a major health hazard in the region - would become still worse as pollutants become more concentrated with reductions in river flow (IPCC, 2007).

Water is typically allocated according to historical, institutional, political, legal, and social traditions and conditions. This division of water resources can be slow to adapt to environmental or water demand changes (Harou et al., 2009). Conflicts often arise when different water users (including the environment) compete for a limited water supply. In order to achieve sustainable development, institutions and methodologies for water allocation should be reformed, especially for regions having water resources shortages (Wang et al., 2008). The allocation of water resources in river basins is one of the critical issues. An integrated analysis at the watershed-scale would be valuable, where individual water related sectors, such as agriculture, municipal, and industrial water supply are brought together in a framework.

Understanding low-flow hydrological features is crucial for efficient development and integrated water resources management and a lot of effort has been made by the scientific community to deal with low flow parameters estimation in ungauged sites (Longobardi and Villani, 2008). A major challenge in low-flow river watershed planning is the general lack of long-term data records. The variability of flows effectively constitutes the ‘temporal’ component of low-flow hydrology and requires continuous streamflow time series for the analysis (Smakhtin, 2001). An analysis is required to select an appropriate model for low flow rivers that provides the best fit to the available data. The majority of simulation based water allocation models are based on mass balance principles and use a network linear program with user-defined priorities to allocate resources in a river system. Among the models that fall in this category are MODSIM-DSS (Fredericks et al., 1998), Mike BASIN (DHI, 2001), WEAP (Yates et al., 2005; McCartney and Arranz, 2007) and REALM (Perera et al., 2005). In Europe, the Water Framework Directive (WFD) (European Union, 2000) establishes a framework for the management of surface water and groundwater resources. Moreover, the Directive stipulates that long term river basin plans, that are obtained using low–flow analysis, are defined for integrated water resource management. The aim of this study was to investigate the use of hydrological modeling software for a data scarce low-flow river watershed, in order to propose tools that could be used to support decision-making required for conformity with the EU WFD. All member states and candidate countries have to adapt their water management system to the requirements of the WFD and introduce participatory river basin management (Mostert, 2003). In this work we apply MIKE BASIN to evaluate the low-flow Francolí River (NE Spain) with respect to the water bodies’ characteristics and impact assessments of human activities aiming to achieve good water status for all waters to comply with the WFD for its River Basin Management Plan. Based on ArcGIS, MIKE BASIN is a versatile decision support tool that provides a simple and powerful framework for managers and stakeholders to address multisectoral allocation and environmental issues in river basins. This study reviews different components of hydrological modeling and gives the highlights of the process adopted to achieve the project objectives as shown in Fig. 3.1. The idea is to look into the subject of water allocation in a low-flow hydrological situation in a balanced and systematic way, to provide an up to date documentation on the subject and to examine water allocation under data scarce conditions. It is important to note that the assessments facilitate the main decision-making procedure. They are linked to decision-making, but are not themselves decision-making procedures. Another aim is to gain insight into the effectiveness of MIKE BASIN as an integrated water resource model for low-flow rivers. Integrated strategic scale resource management models should be capable of reproducing the physical behavior of the system, with a realistic representation of the different surface and groundwater resources, including their interaction, and the spatial and temporal variability of resource availability.

3.2. Study area and dataset

In the framework in Fig. 3.1, the focus is on crucial features of low-flow simulation which exhibit the most relevant dynamic behavior. The modeling scale is also a critical subject encompassing spatial and temporal domain and discretization (Jakeman and Letcher, 2003). Discretization illustrates the subdivision of the spatial and temporal modeled domains. The spatial domain is to be separated into sub-domains (e.g. grid size, sub-basins) while the temporal domain is divided into time-steps. Scale determines what issues the model will be able to address. Accordingly, data collection and processing is to be carried out according to the spatial and temporal domain for the entire simulation process of a river flow.

A NAM rainfall-runoff model was used to obtain historical catchment flow data due to the unavailability of required catchment flow data. NAM is a built in model in MIKE BASIN and calculates the total runoff in the watersheds. The analysis of the simulated results obtained from the MIKE BASIN model focuses on decisions at the project rather than strategic levels. The study developed an approach to quantify water allocation to different sectors for sustainable water resources management in a low-flow river watershed. This work represents an attempt to quantify hydrological vulnerability in a manner that takes into account the concept of sustainability.

3.2.1. Hydrological regime

The Francolí River in NE Spain is about 109 km including tributaries and the river basin area is approximately 855 km^2. The Francolí River Basin has been under considerable pressure for water availability and water quality over the past few decades due to the population growth, climate change and increased demand in cities like Montblanc, La Riba and Tarragona, located in the Francolí River watershed (FRW). The river is the main collector of industrial and municipal treated wastewater and provides irrigation water to the seasonal farms.

The main river starts from Espluga del Francolí (Conca de Barbera), flowing through coastal mountains range and passing by Montblanc, La Riba, Vallmoll, Puig, Glorieta, Tarragona and finally leads to the west of the port of Tarragona. A freshwater stream from the mountains of Prades is a major tributary to the main River Francolí and enters into the river at La Riba. According to The River Planning Areas, the confluence of tributary, Anguera and main Francolí River is a large accumulation of solid material in the river that can modify the morphology of the area and therefore aggravate the consequences of their own flow path (ACA, 2008).

In this study, five major sub-watersheds of 19 sub-watersheds of Francolí river basin were analysed: The Montblanc, La Riba, Vallmoll, Selva and Tarragona sub-watersheds (Fig. 3.2). Montblanc and La Riba represent the upper part of the river, Vallmoll represents middle and sub-watersheds, and Selva and Tarragona represent the lower part of the Francolí River. Before 1988, Tarragona, located at the mouth of the Francolí River, was solely dependent on its own water resources available in the river basin. Sea water intrusion in the groundwater aquifers compelled the municipalities to get water from neighboring river basins. Moreover, most of the industries in Francolí River basin are located close to Tarragona including a large petrochemical industry, while many small industries are located in neighboring municipalities as well. The agricultural demand varies all along the river basin depending on the crop type and cultivated area.

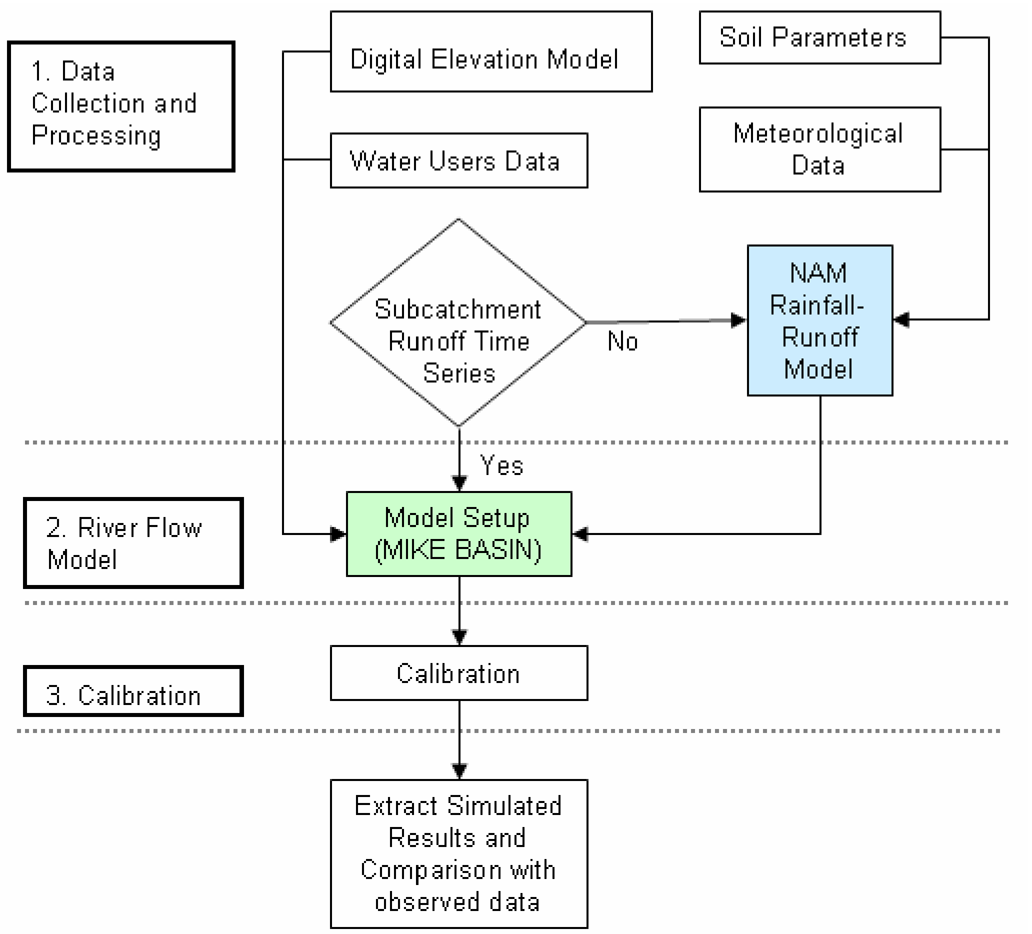


Fig. 3.1. An integrated framework for watershed hydrological modelling under data-scarce conditions

Mediterranean mountains, providing most of the main rivers' discharge, are 'source areas' for water resources of Mediterranean watersheds where precipitation is scarce, evapotranspiration is intense and there is marked seasonality of the rainfall, often causing drought periods during summer (Delgado et al., 2010). The same climate change effect causing water stress is observed in the River Francolí watershed. Less precipitation will cause less watershed runoff and lower availability of water in the river basin.

Water management along the Francolí River and its tributaries is complex because it is a Mediterranean environment and there is a limited supply of water to satisfy the demand of all the sectors and environmental needs (Table 3.1). The groundwater – surface water interplay and the temporal nature of water demands also lend complexity to the system. Irrigation water causes groundwater levels to rise seasonally. It is believed that this shallow groundwater storage is slowly released back to the Francolí River which sustains stream flows for couple of months later.

In the Mediterranean region, a typical runoff process is the infiltration excess process which is a threshold phenomenon limited by the soil properties (Longobardi and Villani, 2008). In addition to low-flow regime, the basin is also prone to flash floods, another natural phenomenon for low-flow regime catchments. For these reasons, it is anticipated to evaluate the current baseline hydrological conditions and water allocation to different sectors in the sub-watersheds of main Francolí River.

3.2.2. NAM Rainfall-runoff model

The NAM Rainfall-Runoff model is a deterministic, lumped and conceptual rainfall-runoff model accounting for the water content in mutually interrelated but different storages representing the surface zone, root zone and the groundwater storages. The NAM model was originally developed by the Technical University of Denmark (Nielsen and Hansen, 1973) and has been both modified and applied extensively by the DHI. NAM represents various components of the rainfall-runoff process by continuously accounting for the water content in different storages, each one representing different physical elements of the catchment (DHI, 2009). Rainfall-runoff modeling is a pre-processing step in MIKE BASIN that generates the runoff time series for the individual catchments. The simulations by MIKE BASIN are done subsequently.

The NAM Rainfall-Runoff simulation must not necessarily cover the same period as the MIKE BASIN simulation.

Along with precipitation and evapotranspiration input data (2001 – 2006), several parameters are specified for each representative sub-watershed to develop the NAM model for the River Francolí. The type of model selected was NAM RR, 2-Layer GW for simulation. Most of the values of parameters used in the model were selected from Table 3, according to sub-watershed characteristics.

Rainfall was applied to 6 sub-watersheds (Tarragona, Alio, Mont-ral, Montblanc, Vimbodi and Rocafort de Queralt) using weighted average rainfall data acquired from the Catalan Water Agency (ACA). As the available data tends to vary less between sub-watersheds, rainfall time series data were applied to other sub-watersheds using data from the gauging station nearest to the sub-catchment.

3.2.3. Dataset collection and processing

Scarcity of field data is an underlying problem in many hydrological modeling projects. Choosing the appropriate modeling tool that represents and is able to generalize the catchment hydrological situation establishes an imperative approach in a data scarce condition. Most of the meteorological input data is provided by the Catalan Water Agency (ACA). In Table 3.2, the sources of the different input data are listed. Topographical, hydrological, rainfall, water use, and meteorological data were used to develop the model segmentation and input, and detailed stream flow data were selected to conduct simulations. It is referred to as 'recycling' and concerns all time series. For desired periods later than the record, the last equivalent period in the record is recycled; for periods earlier than the record, the first equivalent period in the record is recycled (DHI, 2006).

On the basis of a literature review, input evapotranspiration data were generated for the NAM rainfall-runoff model, using a soil water balance method of indirect calculation (Rana and Katerji, 2000; Galleguillos et al., 2011). Along with the different soil and climate parameters, evapotranspiration has an important contribution to runoff generation. The data series of evapotranspiration were interpolated for the remaining sub-watersheds by considering the peak values of wet and dry seasons. In Catalonia, the seasonal behavior of precipitation is less regular and the range of variation much larger than in the case of temperature (Barrera and Cunillera, 2011).

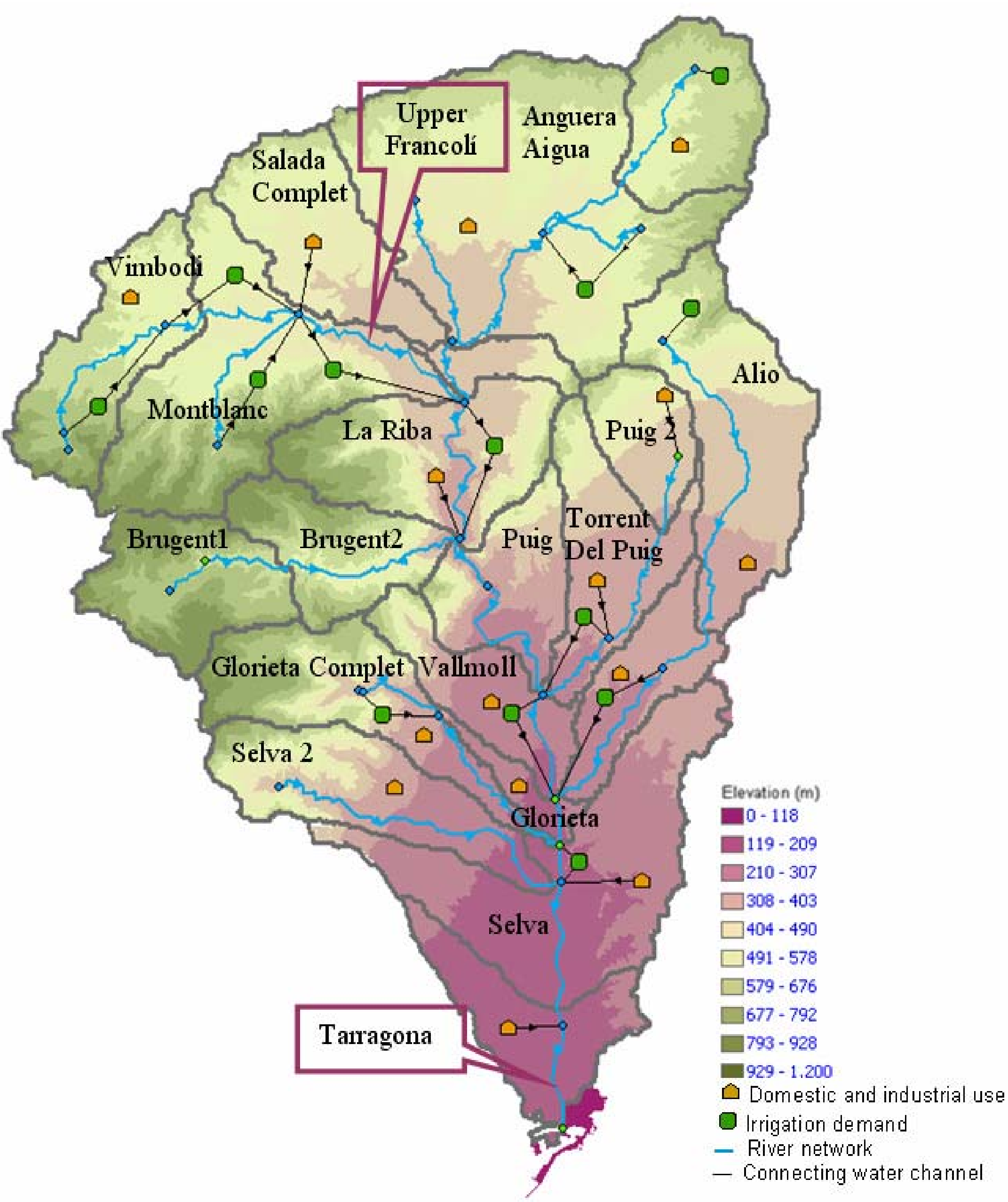


Fig. 3.2. River Francolí Network

Table 3.1
The sub-catchment water demand status for the year 2003 (ACA, 2008)

Location		**Water Demand (m^3/year)***	**Catchment Area (km^2)**	**Population**
Upper Francolí	Montblanc	435,204	79	6,388
	La Riba	751,000	51	1,230
Lower Francolí	Selva	784,475	75	15,941
	Tarragona	9,610,935	35	121,076

*Domestic, Industrial and Agricultural

The NAM model simulates the rainfall-runoff process in a lumped fashion so provision is given for combining meteorological data from different stations within a single catchment or sub-catchment into a single time series of weighted averages. The resulting time series will represent the mean area values of rainfall and potential evapotranspiration for a catchment.

Table 3.2
Maps and time series used as input to MIKE BASIN with reference to the source and the spatial discretization

Data Type	Data Source	Spatial Discretization
Distributed maps		
Topography/DEM	ICC (Institut Cartogràfic de Catalunya, 2006)	As DEM, 30 X 30 m^2
Watershed boundary	Extracted from DEM using GIS algorithms	As DEM, 30 X 30 m^2
Subwatershed boundaries	Shape file provided by Catalan Water Agency	As DEM, 30 X 30 m^2
Time series		
Precipitation	Catalan Water Agency	6 stations
Discharge	Catalan Water Agency	2 stations
Pot. Evapotranpiration	Calculated and Interpolated (Soil water balance method)	19 subwatersheds
Irrigation water demand	Catalan Water Agency	5 subwatersheds
Industrial/domestic water demand	Catalan Water Agency	16 subwatersheds
Discharge from WWTP	Catalan Water Agency	8 stations
Subwatershed runoff	Simulated by NAM rainfall-runoff model	19

Daily time series data of water use, like domestic, industrial and agricultural water consumption and treated water from wastewater treatment plants (WWTP) contributing to the main river channel are generated from accumulated yearly data provided by Catalan Water Agency (ACA, 2008). The yearly data is converted to daily time series considering the peak demand values in summer and winter. It has been observed that 70% of the water demand is allowed to be abstracted from groundwater aquifers.

The important factors considered for interpolation of meteorological data were land use and elevation of the sub-watersheds. Meteorological data were available with the daily time step as well as monthly time step, but the historical records with daily time steps were selected for the model development.

3.3. Model application

3.3.1. The Francolí river flow model

Integrating GIS and catchment models provides a tool to support integrated catchment management, defined as the co-ordinated planning and management of land, water and other environmental resources for their equitable, efficient and sustainable use at the catchment scale (Bathchelor, 1999). MIKE BASIN is an integrated water resource management and planning computer model that integrates GIS with water resource modeling (DHI, 2006). Technically, it is a quasi-steady-state mass balance model, however allowing for routed river flows. This gives a framework to address multisectoral allocation and environmental issues in a river basin. In general terms, MIKE BASIN is a mathematical representation of the river basin, including the configuration of the main rivers and their tributaries, the hydrology of the basin in space and time, and existing as well as potential major water use schemes and their various demands for water. The basin scale simulation model that accommodates a basin-wide representation of water availability and water demand is structured as a network model in which the rivers and their main tributaries are represented by a network consisting of branches and nodes. The branches represent individual tributary sections while the nodes represent confluences, locations where certain water activities may occur, such as abstraction for agriculture, and important locations where model results are required. Figure 3.1 shows a schematic of the river modeling concept.

The special features of the model take account of watershed delineation, priority-based allocation principles, water supply and irrigation allocation, low flow controls and river routing. However, there are certain limitations such as the inability to simulate erosion and sediment transport. Moreover, the model comes as a commercial package and better information could be provided regarding the equations and methods used in flow and water quality modeling.

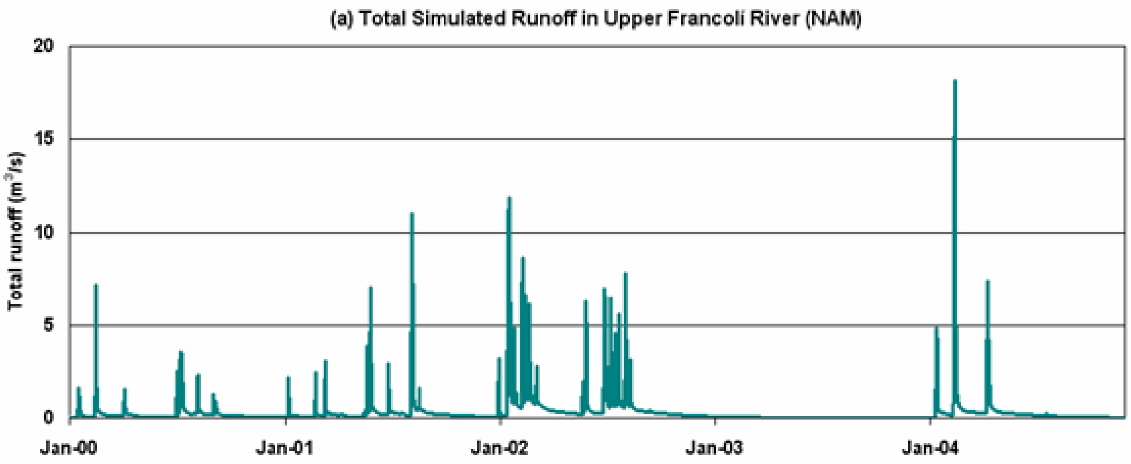
A Digital Elevation Model (DEM) with 30 m grid cells provided an appropriate resolution of elevation data over the entire catchment. The DEM is presented in Fig. 3.2, with the main river network and its tributaries. Simulated sub-catchment runoff time series data were associated with the representative sub-catchments.

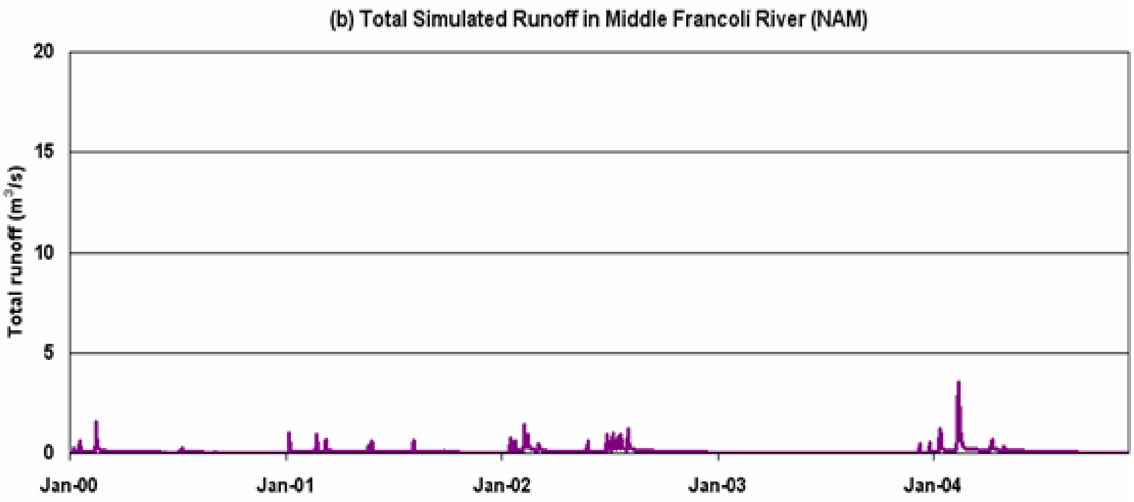
Table 3.3
Main NAM parameters

Zone	Symbol	Definition	Range of Values
Surface-Rootzone	U_{max}	Maximum water content in surface storage	10 – 20 mm
	L_{max}	Max water content in root zone storage	50 – 300 mm
	CQOF	Overland flow runoff coefficient	0.0 – 1.0
	CKIF	Time constant for interflow	500 – 1000 hrs
	CK1_2	Time constant for routing overland flow	3 – 48 hrs
	TOF	Root zone threshold value for overland flow	0 - 0.99
	TIF	Root zone threshold value for inter flow	L/L_{max}
Ground-Water	TG	Root zone threshold value for groundwater recharge	0 – 0.99
	C_{area}	Ratio of groundwater catchment to topographical (surface water) catchment area	1
	Sy	Specific yield for the groundwater storage	Clay (0.01 - 0.10) Sand (0.10 – 0.30)
	GWLBF1	Maximum groundwater depth causing baseflow	0*

* Default value

Similar to many other hydrologic models, MIKE BASIN requires the entire watershed to be segmented into a series of sub-watersheds. The individual watersheds are assumed to demonstrate relatively homogenous hydrological/hydraulic behavior. This segmentation provides the basis for assigning identical inputs and/or parameter values to the whole of the catchment or channel length contained within a model sub-catchment. Hydrological and water demand data are the major model inputs while outputs includes the magnitude and frequency of any water shortages as well as simulated time-series of flows at all nodes, providing information on the performance of each sub-catchment.





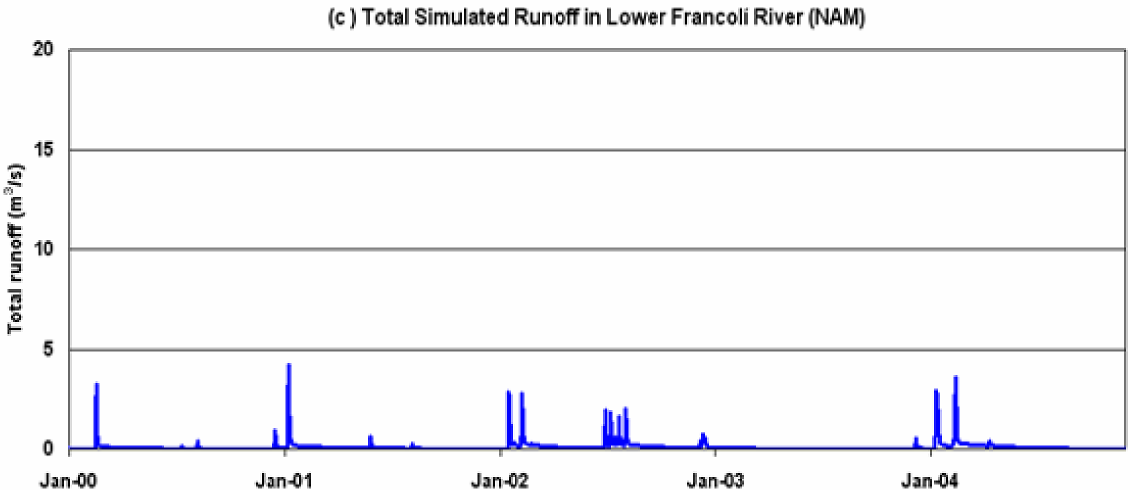


Fig. 3.3. Total runoff in (a) Upper, (b) Middle and (c) Lower Francolí River simulated by NAM

Water use data (2002 – 2007) were converted to daily time series and allocated to the respective nodes. Once the water usage has also been defined, the model simulates the performance of the overall system by applying a water mass balance method at every node. The simulation takes into account the water allocation to multiple usages from individual extraction points throughout the system.

Irrigation return flows from agricultural fields are widely recognized as contributing to additional sub-surface drainage directly to the river channel or through 'return' canals, which may constitute a large proportion of a stream's water balance (Blodgett et al., 1992). Another important component of stream flow is base flow, which comes from groundwater storage or other delayed sources (shallow subsurface storage, lakes, melting glaciers, etc.). During the dry season, the stream flow discharge is composed entirely of base flow. In the wet season, discharge is made up of base flow and quick flow, which corresponds to the direct catchment response to rainfall events. Moreover, at the catchment scale, to evaluate and quantify these impacts, technical procedures need to be performed which include hydrological modeling, downscaling climate data, modeling water resources, and evaluating water availability in the water system under study. Unavailability of the entire water use or demand data (domestic, agricultural and industrial) may not ascertain or underestimate the exact outcomes of the study but it can provide an overview of the Francolí River basin hydrological status. However, available water use data as input time series has been considered in the hydrological simulation (Fig. 3.2).

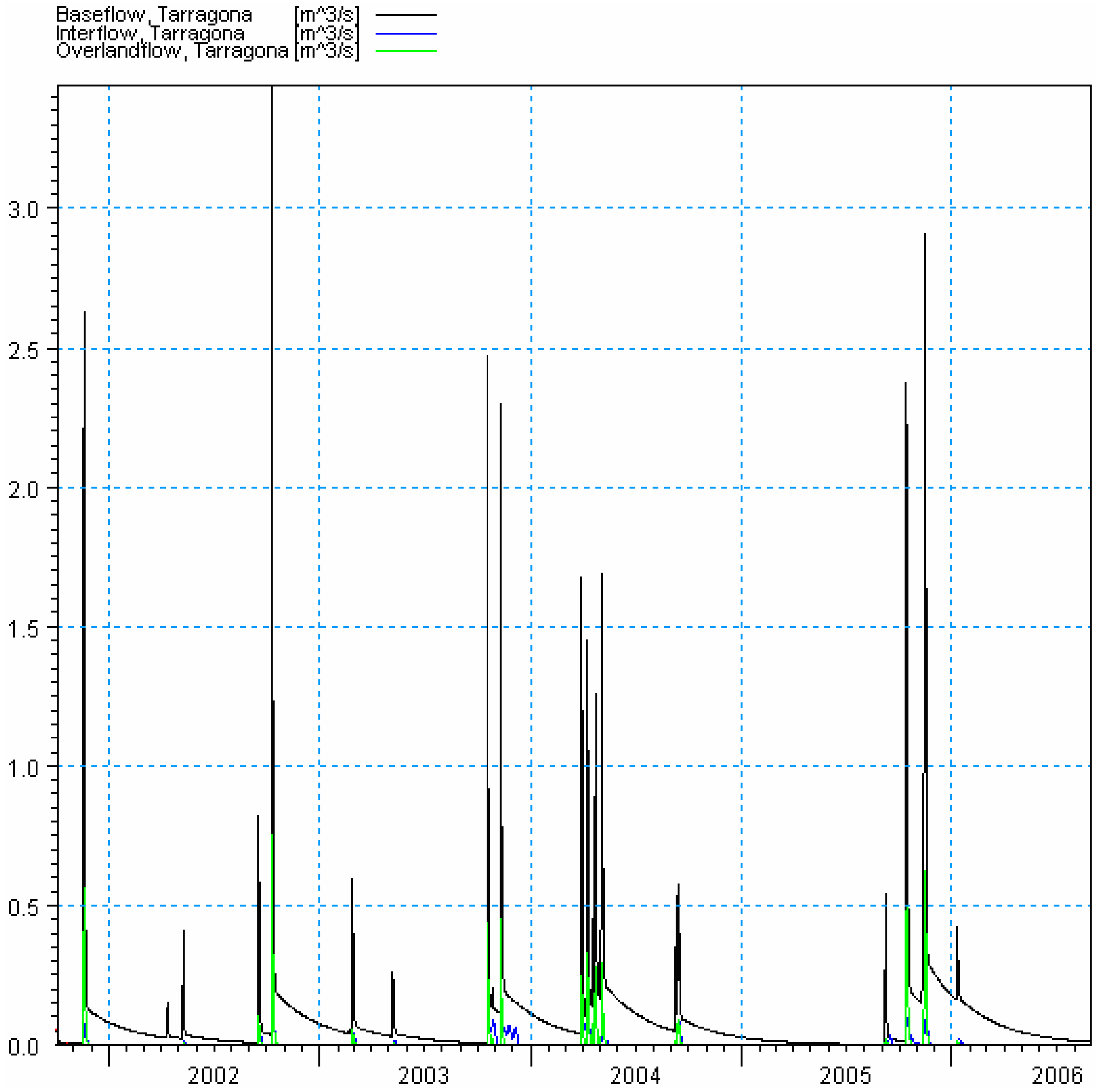


Fig. 3.4. NAM Simulated Base flow, Inter Flow and Overland Flow at Tarragona

The analysis of water availability in all the sub-watersheds considers surface water and groundwater, as the groundwater in the Francolí River basin is contributing to the total demand at most of the locations. Return flows are particularly important if the water for irrigation is imported from outside the catchment but in this study area the source of irrigation water is the same catchment. According to Catalan Water Agency (ACA) documents, about 70% of the total water demand is dependent on groundwater, and up to 40% of water initially abstracted for irrigation returns into the stream.

3.3.2. Calibration

Some degree of uncertainty is always expected in hydrological simulation models, as they are a simplification of reality. Uncertainties in model outputs can arise from conceptualization of the processes modeled, the quality and quantity of data, constraints of the modeling technology, and assumptions made in the tested scenarios (Caminiti, 2004). It was observed during calibration that the simulated hydrographs underestimated the water flow in the river. This was mainly due to insufficient data available to attempt to forecast actual outcomes. Some of the irrigation water and reservoirs information was not included in the network due to data unavailability.

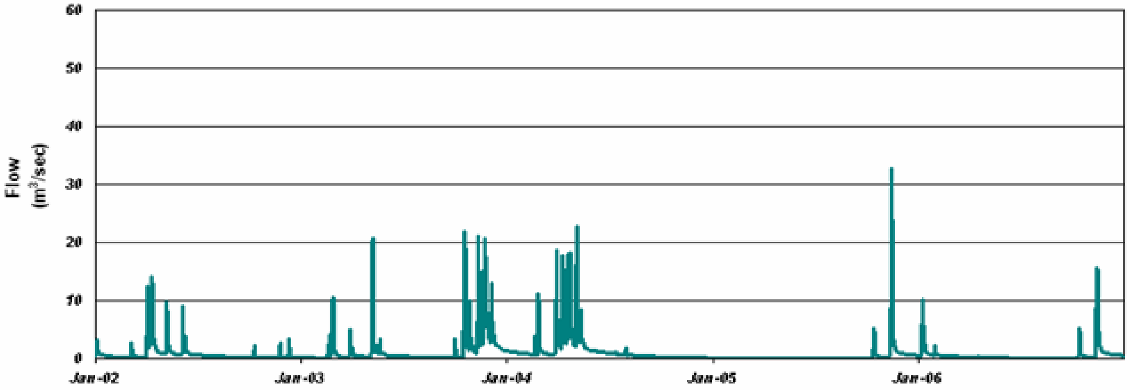
A standard performance metric, the Nash and Sutcliffe (1970) coefficient of efficiency, R Equation, was used to evaluate the model performance. A Numerical performance measure was applied in calibration process. A perfect match corresponds to $R^2 = 1$.

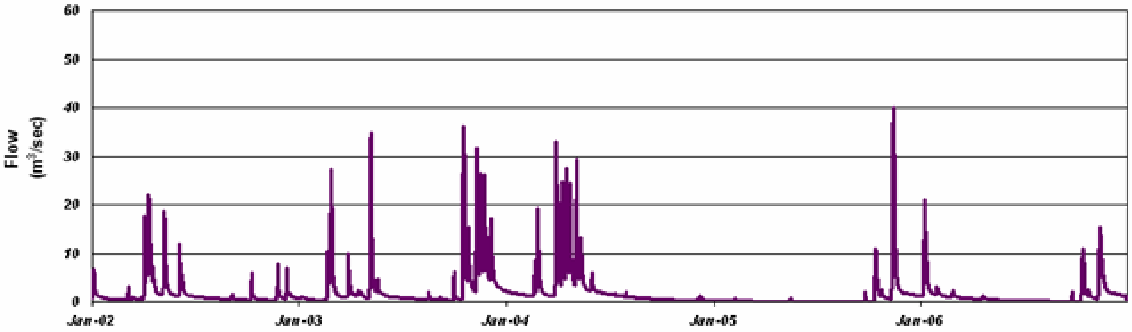
$$R^2 = 1 - \frac{\sum_{i=1}^{N}[Q_{obs,t} - Q_{sim,t}]^2}{\sum_{i=1}^{N}[Q_{obs,t} - \bar{Q}_{obs}]^2} \qquad \text{(Eq 3.1)}$$

Where Q_{obs} is the observed flow, Q_{sim} is the simulated flow, and $\bar{Q}_{obs}$ is the average observed flow.

As a physically-based model, the number of parameters needed for calibration should be kept to a minimum (Du et al., 2007). A trial-and-error parameter adjustment is made until satisfactory results are obtained. Each trial consists of two model runs; the first run is the NAM model followed by the MIKE BASIN run. The relevant model parameters are selected from Table 3.3, i.e. the parameters that mostly affect the considered process description. For example, the time constant for routing interflow and overland flow CK12 (hours) determines the shape of hydrograph peaks. The value of CK12 depends on the size of the catchment and how fast it responds to rainfall. The time constant can be inferred from calibration on peak events. If the simulated peak discharges are too low or arriving too late, decreasing CK12 may correct this, and vice versa.

Calibration over a continuous period from January 2002 to December 2006 for the entire hydrological years was performed. Model parameters are assigned based on soil textures, land use/land cover maps, and a combination of both. A calibration period even of a couple of months was also used by Senarath et al. (2000) and Beldring (2002), who assume that such period length may be sufficient when calibrating a model with daily and hourly time steps.


(a) Simulated Flow in Upper Francolí River


(b) Simulated Flow in Middle Francolí River

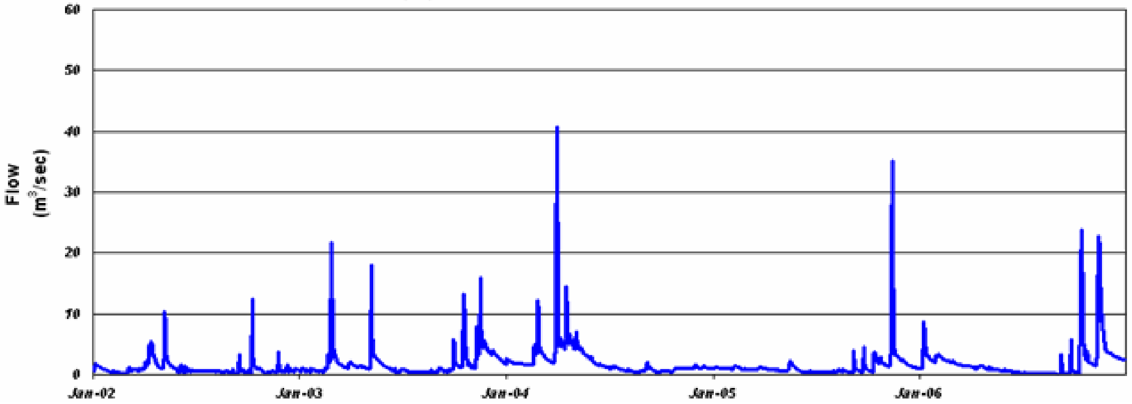

(c) Simulated Flow in Lower Francolí River

Fig. 3.5. Simulated flows observed at (a) Upper (b) Middle and (c) Lower river nodes

3.4. Results and discussion

3.4.1. NAM rainfall-runoff model

The NAM rainfall-runoff model has been used to estimate the runoff at a daily time step to the Francolí River sub-watersheds. The simulation period was from April 2001 to July 2006, and the highest flow values were observed in November 2005. However, by forcing the values of model parameters to vary within the pre-defined bandwidth during the simulation procedure, we may assume that the selected values of model parameters represent hydrological characteristics of sub-watersheds in the range of capabilities that the structure of NAM model allows. To simplify the rainfall–runoff modeling approach, while maintaining a spatial description of the catchment have produced a class of semi-distributed models that make use of a distribution function to represent the spatial variability of runoff generation (Croke et al., 2006).

A graphical evaluation of the NAM rainfall-runoff model's results for the sub-watersheds is shown in Fig. 3.3. The sub-watersheds along the main Francolí River include upper (Montblanc, La Riba), middle (Vallmoll), and lower (Selva and Tarragona) Francolí. The results show that NAM model simulates with precision both the timing and magnitude of the runoff peaks in most cases, and replicate the flow in the dry seasons.

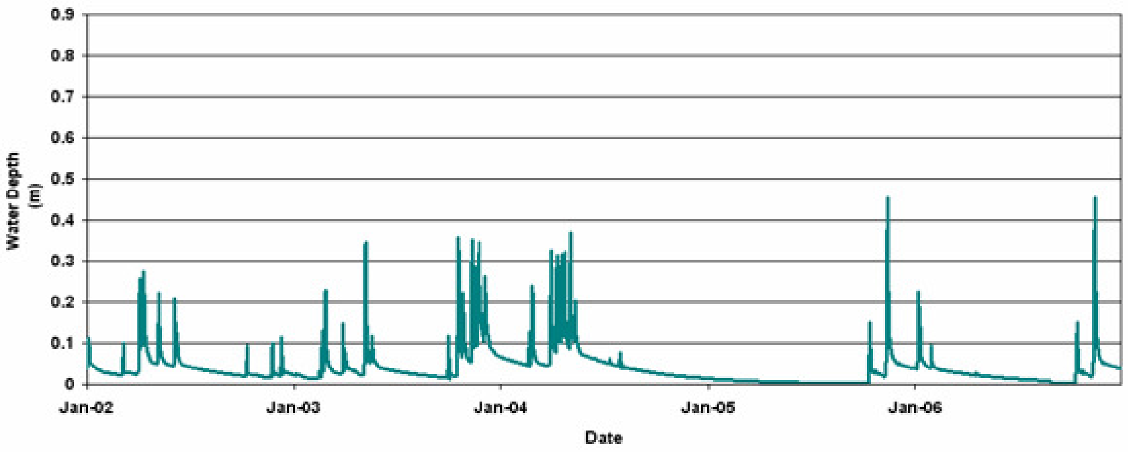
The time series of simulated total runoff obtained from rainfall-runoff modeling are specified as inputs of the respective sub-catchments for the MIKE BASIN simulations.

The recycle method, described earlier, calculates rainfall-runoff (relationship) automatically for the extended period in MIKE BASIN simulation. The total runoff includes the three components of flow regime: overland flow, base flow and inter flow. The soil porosity is higher in the lower part of River Francolí, which can be observed in the interflow simulation results. This phenomenon gives rise to higher base flow and lower overland flow (Fig. 3.4).

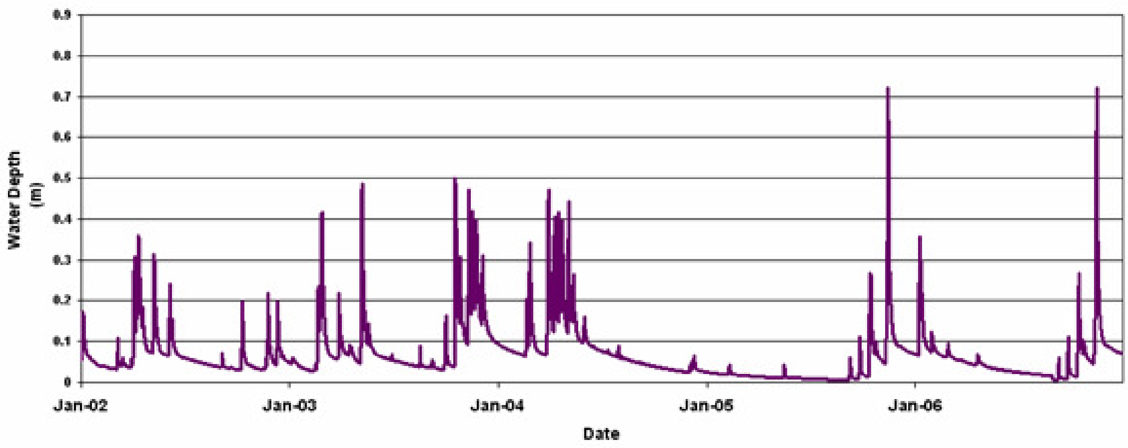
3.4.2. River flow model (MIKE BASIN)

The two sub-watersheds, Selva and Tarragona, encompass the lower Francolí, the Vallmoll sub-watershed is located in the middle Francolí, while La Riba and Montblanc sub-watersheds are situated in the upper Francolí basin. The timings of the peak flows observed at river node of different locations (upper, middle and lower) in the basement are similar (Fig. 3.5). However the peak values of the curves differ due to geographical variation, meteorological situation and different timings and amount of water demand in the sub-catchments. The period from April 2004 to January 2005 is observed as the longest dry period during the whole simulation phase that ranges from January 2002 to December 2006. The surface flow in the entire Francolí river basin reaches 0 m^3/sec during the dry season, thus encouraging water abstraction from deep aquifers. The lowest annual flow usually occurs in the same season each year. It can also be inferred from this result that wet season water availability must be high in order to preserve a significant amount of water for dry season, whereas dry season water availability is very low and cannot satisfy even a very low demand. It is possible to design modeling experiments to test whether hydrological models calibrated against historical stream flow data can be used to reliably predict runoff responses to changes in future climate inputs (Vaze et al, 2010).

(a) Water Depth in Upper River Francolí



(b) Water Depth in Middle River Francolí



(c) Water Depth in Lower River Francolí

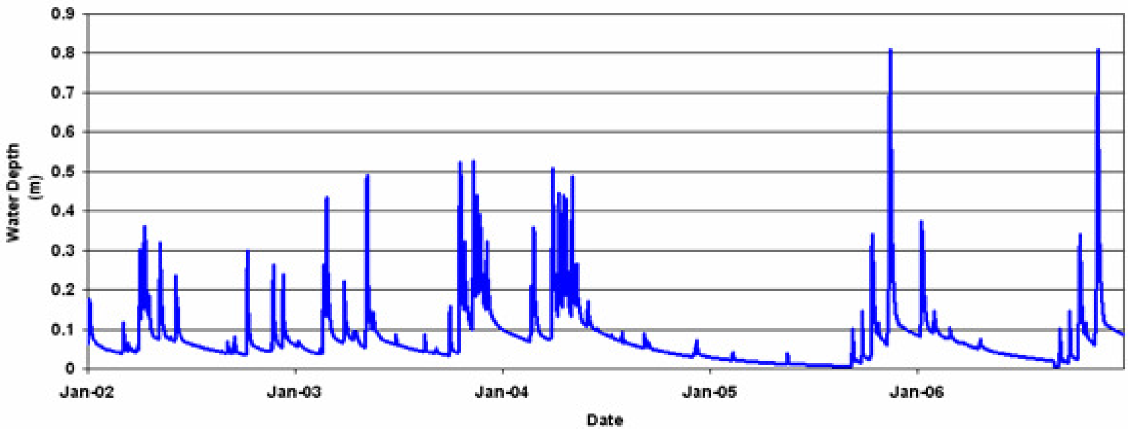


Fig. 3.6. Water Depth in (a) Upper, (b) Middle and (c) Lower River Francolí

The water depth varies seasonally at all three reaches of the Francolí River basin (upper, middle and lower) as shown in the Fig. 3.6. The maximum depth is 0.8 meters at Tarragona on 13th November, 2005, whereas the river remains waterless during the dry season. The dry season has a direct effect on the groundwater table by leading to water abstraction from ground aquifers for all the sectors. Due to the unavailability of surface water in the dry season, all sectors are seasonally dependent on the River Francolí.

The water demand is highest in the Lower Francolí but still there is some unallocated water in the sub-catchment, which is saline water and not suitable for domestic use (Fig. 3.7). The total water demand in Tarragona is found 10,400 m^3/year during the year 2002-2004, exceeding the amount of water available in the sub-catchment of Tarragona (Table 3.4). The available water is only 19 % of the total water demand and the main source is groundwater aquifers. This water deficit has been fulfilled by water supply from the neighboring Ebro River basin under an inter-basin management plan. Moreover, in the other sub-catchments, the available water satisfies the water demand for the domestic, agricultural and industrial sectors.

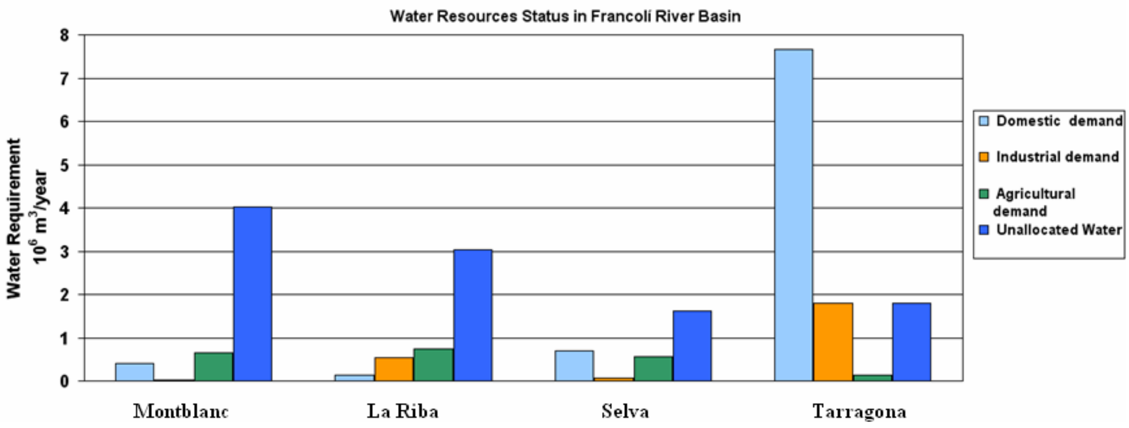


Fig. 3.7. Water demand and availability in upper and lower Francolí River sub-watersheds

Hydrological simulation leads to the question of an important characteristic of the physical system, which is the simulated profile of conjunctive flow of surface water and groundwater resources. To address this question, groundwater was also selected during the NAM simulation (Fig. 3.4). Integration of recharge and extraction of groundwater with surface water storage, artificial aquifer recharge and utilization in a coordinated manner can substantially increase basin-wide water-use efficiency and reliability of water use. Appropriate locations can be selected for reservoirs for the purpose of storage of surface water as well as for aquifer recharge to the groundwater system. It is observed that the sub-catchment runoff on the upper right (Sub-catchment Anguera Aigua in the east) side of the Francolí River do not apparently contribute to the main river. The effects of groundwater pumping near the head of a perennial river may result in groundwater table depletion through interception of recharge water and induced recharge of the aquifer from the river itself (Smakhtin, 2000). The two major reasons of this lower contribution are firstly, the lower elevation, and secondly, the increased area of agricultural land in this area (Fig. 3.2). While in terms of overland flow, however there is a significant contribution from the upper left (west) side springs like Brugent under the mountains.

Tarragona in the lower part of the Francolí River faces a considerable water deficit pressure compared to the upper parts (Montblanc and La Riba). In this manuscript, we intend to compare the water demand and water availability in the River Francolí basin by analyzing the hydrological condition of the basin. All the findings above are based on available data whereas the actual water demand is higher due to some missing irrigation water consumption at certain locations.

Table 3. 4
Water Demand Distribution by Area for the period 2002 - 2004

Summary	Upper Francolí	Lower Francolí
Demand* (m^3/year)	1,186,204	10,395,410
Demand* (m^3/year/km^2)	9,165	97,390
Availability (m^3/year)	8,307,849	6,701,064
Availability (m^3/year/km^2)	64,187	62,779

*Demand is the sum of domestic, agricultural and industrial demand.

Table 3.4 gives a clear picture of the water demand distribution by area. This indicates that demand in the upper Francolí is lower than the amount of water available in the sub-catchment. The amount of unallocated water is also high in the upper Francolí (Fig. 3.7). Larger volume of water availability of this part of the basin can accommodate increase in water demand through improved management options. Possibilities for new storage schemes need to be considered for this part of the basin to reduce the dependency on the other river basins in the lower Francolí. The demand in lower Francolí is in the need for management to trap the water, also the attention is required to manage the dry season water requirements. Drought and climate change place special stresses on water systems. Hydrological models may provide insights into flexible operations schemes that decrease negative effects of increased water scarcity or other changes (Harou et al., 2009). Stakeholders are able to gain additional benefits if they cooperate to reallocate water properly based on their water rights, either through water markets or regulated water transfers (Wang et al., 2008). One of the major reasons for insufficient groundwater exploitation is the presence of saline water in 5 % of the area. Removing or treating the salinity of water before the application is not considered sufficient; however, there are some ways to evade it. Production of salt-tolerant fodder crops and irrigation planning can eliminate and effectively reduce the causes of salinity. Unsuitable irrigation is often responsible for high saline drainage and long-term salt accretion in soils.

3.4.3. Calibration results

The calibration experiments described in this section are carried out using the river flow data recorded at Tarragona only. Not all gauges were contemporarily operative for all the events at other gauging stations. The coefficient of efficiency for river flow calibration at Tarragona was calculated as described in section 2.3.2 as, $R^2 = 0.75$. The values range between $-\infty$ and 1 and the higher the value the more efficient the calibration. The hydrograph of storm event in April 2004 has rising limbs with long and large pre-storm runoff rates that decrease the modeling efficiency. Nevertheless, the results in general are acceptable with the R^2 value higher than 0.7.

The flow simulations of the model were calibrated over five years, illustrated in the graph in Fig. 3.8, which reports the discharge predicted with the calibration over five years (2002 to 2006) versus the corresponding observed values. It is indicative of how well the manual calibration approaches simulated the range in magnitude of daily flows. It also shows that the calibration approach did equally well in simulating the magnitude of flow peaks from 2002 to 2003. Differences in hydrograph simulation were more pronounced in the comparison of daily river flow for the period of record from April 2004 to October 2006. A common feature among the data sets is that the maximum error between actual and calculated monthly runoff occurs in the month of maximum recorded runoff, due to the difficulties in measuring rainfall and runoff in big storms (Boughton, 2005). Nevertheless, with all environmental modeling, uncertainty and error propagation are especially challenging (Harou et al., 2009). The trial-and-error method makes additional use of expert knowledge through visual inspection of model performance but has to be done in a guided, step-wise way to avoid that the calibration process becomes too lengthy (e.g. Bandy and Willems, 2000).

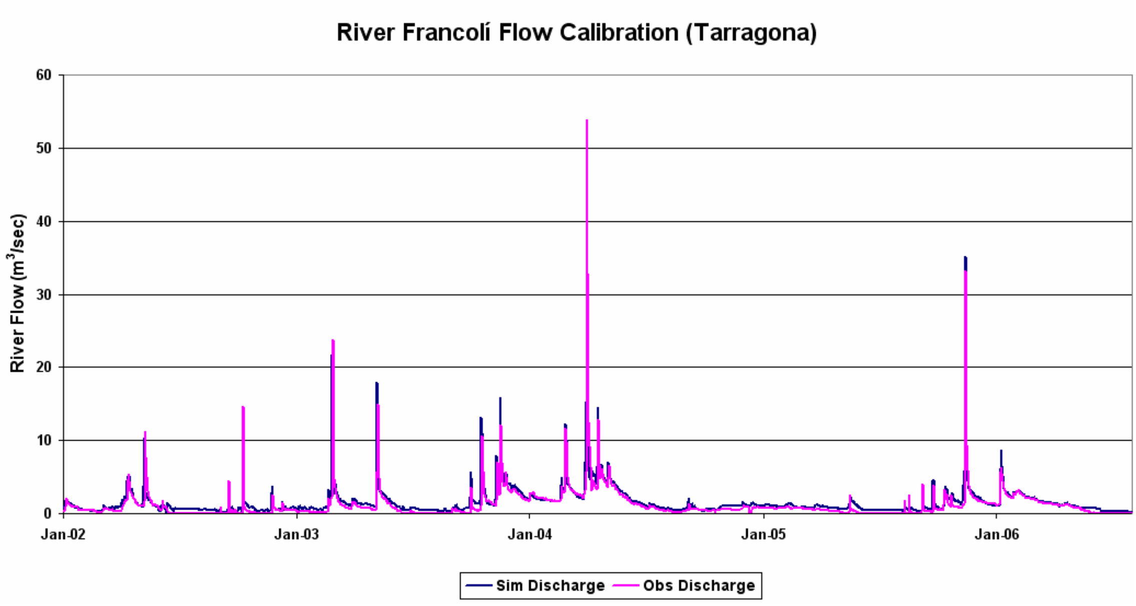


Fig. 3.8. Manual Calibration of river flow at Tarragona

The peak flow on record for the Francolí River at Tarragona occurred on 30th March 2004 and 13th November 2005. The same wet climatic period significantly influenced the computation of calibration values. Particular attention should be paid to the quality of the peak discharge which is heavily by the estimation of the direct runoff (Martina et al., 2010). Overall, the results indicate that the best out-of-sample performances are obtained calibrating the model periods possibly an entire hydrological year with wet and dry periods. The indication of a calibration period of peak discharge in 2004 and 2005 of data seems to be an improvement in comparison with the expected calibration of low flow discharge.

3.5. Conclusion

This paper illustrates the application of a basin-scale simulation model MIKE BASIN integrated with ArcGIS and has shown its capability to simulate even low flows, calculate runoff of the sub-watersheds, efficacy in analyzing the basin performance under data scarce conditions. The significant aspect of MIKE BASIN is that simulation process considered the conjunctive use of surface water and groundwater simultaneously. Moreover, it helps in establishing the best management approaches for the efficient use and allocation of water resources to different sectors. The model was applied in the low-flow Francolí River Basin of Northeastern Spain. Despite the data scarcity, the model demonstrates its usefulness in analyzing the basin performance. The analysis shows that there is inadequate water availability to satisfy even domestic and industrial uses in the lower part of the Francolí River. It also indicated that the wet season has increased water availability as compared to very little or no water availability in dry season. This disparity of water availability compels the municipality to remain dependent on inter-basin water resources. Based on the results, possibilities for new storage schemes or artificial aquifer recharge should be considered to store the excess wet season water and increase dry season reliability. Moreover, results obtained from this low-flow hydrological simulation are important to analyze other water related fields (e.g. ecosystem services in river basin), it would enable us to implement the River Basin Management Plan implementation, to quantify and identify the multiple ecosystem services at river basin scale.

Part III

HYDROLOGICAL ECOSYSTEM SERVICES

Chapter 4

Ecosystem services in Mediterranean river basin: Climate change impact on water provisioning and erosion control

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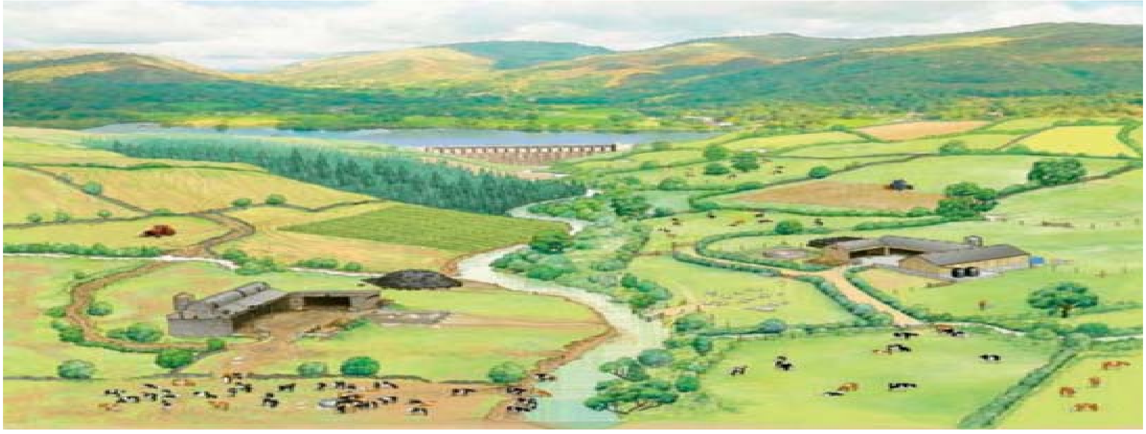

ABSTRACT

The Mediterranean basin is considered one of the most vulnerable regions of the world to climate change and such changes impact the capacity of ecosystems to provide goods and services to human society. The predicted future scenarios for this region present an increased frequency of floods and extended droughts, especially at the Iberian Peninsula. This paper evaluates the impacts of climate change on the water provisioning and erosion control services in the densely populated Mediterranean Llobregat river basin. The assessment of ecosystem services and their mapping at the basin scale identify the current pressures on the river basin including the source area in the Pyrenees Mountains. Drinking water provisioning is expected to decrease between 3 and 49%, while total hydropower production will decrease between 5 and 43%. Erosion control will be reduced by up to 23%, indicating that costs for dredging the reservoirs as well as for treating drinking water will also increase. Based on these data, the concept for an appropriate quantification and related spatial visualization of ecosystem service is elaborated and discussed.

Keywords: Hydrological ecosystem services, Ecosystem services mapping, Water scarcity, Sediment retention, Climate change

4.1 Introduction

Climate change has the potential to cause negative changes in ecosystems and their associated ecosystem services. Climate change is expected to bring several changes in global temperature and rainfall patterns, which are likely to present deep impacts on water availability and quality (Marcé et al., 2010; López Moreno et al., 2011). Indeed, the Mediterranean basin is considered one of the most vulnerable regions of the world to climate change (Schröter et al., 2005) and with a high potential to present important problems in water scarcity in the next few years. Under climate change, rainfall and runoff are expected to decrease in the Mediterranean area (Milly et al., 2005), as well as river flow (López-Moreno et al., 2011). Many research projects and several environmental assessments are currently addressing these concerns at all relevant scales, frequently in multidisciplinary collaborations. However, integrating this wealth of information across disciplines remains a considerable challenge (Millennium Ecosystem Assessment, 2003).

Ecosystem services are the benefits that people derive from nature. These include provisioning services such as food and water, regulating services such as flood and disease control, cultural services such as spiritual, recreational, and cultural benefits, and supporting services, such as nutrient cycling, that maintain the conditions for life on Earth (MEA, 2003). Many ecosystem services are derived from freshwater and are commonly referred to as hydrological ecosystem services. These benefits provided by ecosystems include provisioning services such as water supply for drinking, power production, industrial use and irrigation, as well as regulating services such as water purification and erosion control (de Groot et al., 2010). The provision of hydrological ecosystem services in the Mediterranean basin is likely to be impacted, as climate is one of the major shaping factors in semi-arid basins, which present larger extremes than more humid areas. Previous studies on the Llobregat basin (Catalonia, NE Spain) indicate that impacts on the delivery of services are especially important during dry conditions (Terrado et al., 2012). Hence, the application of future climate change predictions that consider the changes to rainfall and temperature patterns is essential to indicate the possible impacts on ecosystem services provision at the Mediterranean basin.

As a consequence of acute water shortages in the Mediterranean basin, competition for water and water stress are likely to increase, especially in summer (Falloon and Betts, 2010). Changes in sediment retention are also expected. According to the IPCC (2007), in southern Europe, runoff will decrease by up to 23% by to the 2020s and from 6 to 36% by to the 2070s. The projected changes in annual river basin discharge by the 2020s are likely to be affected by climate change. These estimations are based on global rather than regional climate models and a high uncertainty is related to those models. However, regionalized GCMs developed by CEDEX (2011) also projected runoff reduction (below 15%) in Mediterranean river basins.

In this work we used a conceptual framework that focuses on quantifying the benefits associated with changes in ecosystem services as a result of climate change, through a comparison of two climate change scenarios against a base scenario. This approach is in line with the emerging consensus about the importance of comparing alternative scenarios rather than a static analysis of current service provision (Nelson et al., 2009; Tallis et al., 2009). Another key feature of the approach adopted here is that it is spatially explicit, reflecting the fact that both the production and value of ecosystem services varies spatially (Tallis et al., 2009; Birch et al., 2010). Relatively few previous attempts have been made to analyze the spatial dynamics of ecosystem services in relation to climate change scenarios, although recent progress has been made by the Natural Capital Project and others (Nelson et al., 2009; Terrado et al., 2012).

In this paper we evaluated the impacts of climate change on provisioning (water) and regulating (erosion control) services, at the Mediterranean Llobregat river basin. When the river basin faces pressures from a high water demand while located in the semi-arid Mediterranean area, it is important to evaluate future scenarios and their effect on these services. Water scarcity can restrict activities dependant on water use, such as human and industrial consumption, electricity production, and agricultural irrigation. Water is already scarce in the region because of its extractive use for industry, human consumption, and agriculture; these activities have also contributed to water quality degradation (Sabater et al., 1987; Terrado et al., 2009; López-Doval et al., 2010). We applied Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST), a spatially explicit modeling tool for ecosystem services estimation (Tallis and Polaski, 2011). The model, integrated in a GIS platform, is applied to different future climate scenarios (ranging from 2001 to 2100) and further compared to a base scenario (1971-2000). We hypothesize that the provision of water for different uses, as well as the total sediment exported by the basin will decrease as a consequence of climate change, and the manuscript aims to determine the degree of change in these services, as well as to identify the areas of the basin that are most impacted by these changes. A limitation of this study is that the land use/land cover is considered constant over the whole period of analysis (2001 – 2100).

4.2 Methodology

4.2.1 Study area

The Llobregat basin (NE Spain) drains an area of 4,957 km^2, and is characterized as a typical Mediterranean basin, with a highly variable flow as a result of seasonal rainfall differences. The length of the river is 157 km and has three main reservoirs, Sant Ponç (24 hm^3), Llosa de Cavall (80 hm^3), and Baells (115 hm^3). It is one of the richest and most rapidly developing regions in Spain. The basin is heavily populated (more than 3 million inhabitants) and among one of Barcelona's major drinking water resources. Heavy anthropogenic pressures, characterized by extensive urban and industrial wastewater discharges as well as diffuse contamination from agricultural areas, are observed at the basin. Main watercourses are regulated by three large dams that impound around 35% of the basin's mean annual runoff.

4.2.2 Climate change scenarios data

The data applied in this study is acquired after a downscaling exercise performed by the Catalan Meteorological Service (2012). The typical resolution of general circulation models (between 100 and 300 km) is unsuitable for an evaluation at the basin scale, especially for Mediterranean regions with a complex orography such as Catalonia, which is influenced by polar and tropical air masses. The data provided for mean daily precipitation and temperature, compares the predictions of these parameters for the beginning (2001-2030), middle (2031-2070) and end (2071-2100) of the 21st century, with a base scenario (1971-2000). Specifically for the climate change scenarios, the raster resolution was 7.5km X 7.5km. The IPCC scenarios selected for evaluation of Llobregat basin are A2 and B1 (IPCC, 2000). The A2 scenario describes a very heterogeneous world, with a continuously increasing global population. Under this scenario economic development is primarily regionally oriented and *per capita* economic growth and technological changes are more fragmented and slower than in other storylines. The B1 storyline and scenario describes a convergent world with the same global population that peaks in mid-century and declines thereafter, with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social, and environmental sustainability, including improved equity, but without additional climate initiatives. Therfore, scenario A2 considers more severe changes, while scenario B1 considers moderate changes in global climate. These scenarios are calculated for three time spans and compared to a base scenario, as shows Table 4.1.

4.2.3 Ecosystem services modelling and mapping

Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) is a spatially explicit tool to model and map a suite of ecosystem services caused by land cover changes or climate change impacts (Tallis and Polasky, 2011). Model results can be reported in either biophysical or monetary terms, depending on the needs and the availability of information.

The ecosystem services of water provisioning (hydropower production and drinking water availability), and erosion control (dredging and water quality) are evaluated at the annual scale for the Llobregat basin, with a raster resolution of 200m X 200m. The definition of the subcatchments was made at the water body scale, as defined by the local environmental agency, based on the specifications of the Water Framework

Directive (European Council, 2000). Meteorological data are used to calculate annual evapotranspiration (ETo) and the rainfall erosivity index (R) for each scenario. Evapotranspiration was calculated based on the Hamon's equation (Tallis et al., 2011), as a function of temperature, and then calibrated with values from 2 stations at the Llobregat basin. The rainfall erosivity index (R) was calculated based on the work of Catari and Gallart (2010) that describes the erosivity at Llobregat basin as a function of mean precipitation (P) in summer months and in the other months of the year. The input data required for each model varies and depends on the service to evaluate. Most of the data formats are GIS raster grids, shapefiles and database tables. Input data requirements and outputs of the model for the selected services are given in Table 4.2. This study evaluates the changes in ecosystem services provision due to variation in the supply that are likely to be effected by climate change. However, increased water demand and population growth are not considered in scenario development.

Table 4.1

Input raster maps for the evaluated climate change scenarios.

Raster	Source	Time span			
		1971-	2001-2030	2031-2070	2071-2100
Temperature	Elaborated based on data from Catalan Meteorological Service (2012)	Base scenario	IPCC A2 and B1 scenarios	IPCC A2 and B1 scenarios	IPCC A2 and B1 scenarios
Rainfall	Elaborated based on data from Catalan Meteorological Service (2012)				
ETo	Own elaboration, as a function of temperature				
Erosivity (R)	Own elaboration, as a function of rainfall				

4.2.3.1 Water provisioning

InVEST biophysical models calculate the relative contribution of the different parts of the landscape to the provision of services. For the water provisioning service, the amount of water provisioned from each cell in the landscape (water yield) is calculated as the annual amount of rainfall that does not evapotranspire, and determined by the cell vegetation characteristics (Canadell et al., 1996).

The water yield model is based on the Budyko curve (Budyko 1974) and annual average precipitation. Annual water yield (Y_{jx}) is determined for each pixel on the landscape (indexed by x = 1,2,...,x) as follows:

$$Y_{xj} = \left(1 - \frac{AET_{xj}}{P_x}\right) . P_x \qquad (4.1)$$

Where, AET_{xj} is the actual evapotranspiration (annual) on pixel x for LULC j (LULC class code; e.g., 1 for forest, 3 for grassland, etc.), and P_x is the annual precipitation on pixel x. The evapotranspiration partition of the water balance, $1-\frac{AET_{xj}}{P_x}$, is an approximation of the Budyko curve developed by Zhang et al. (2001):

$$\frac{AET_{xj}}{P_x} = \frac{1 + w_x R_{xj}}{1 + w_x R_{xj} + \frac{1}{R_{xj}}} \qquad (4.2)$$

where, R_{xj} is the dimensionless Budyko Dryness index on pixel x with LULC $_j$, defined as the ratio of potential evapotranspiration to precipitation (Budyko 1974) and w_x is a modified dimensionless ratio of plant accessible water storage to expected precipitation during the year (Zhang et al. 2001). Finally, we define the Budyko dryness index, where Rxj values that are greater than one denote pixels that are potentially arid (Budyko 1974), as follows:

$$R_{xj} = \frac{(k_{xj} \cdot ETo_{x})}{P_{x}} \qquad (4.3)$$

where, ET_{ox} is the reference evapotranspiration from pixel x and k_{xj} is the plant (vegetation) evapotranspiration coefficient associated with the LULC $_j$ on pixel x. ET_{ox} represents an index of climatic demand while k_{xj} is largely determined by x's vegetative characteristics (Allen et al. 1998). The water yield model script generates outputs in form of total and average water yield at the sub-watershed level. The input data required for such calculations is described in Table 4.2.

Water demands for other consumptive uses (agricultural, industrial, forest) are removed from the total yield before assessing the benefit. The amount of water that actually reaches the reservoir for dam d (realized supply) is defined as the difference between total water yield from the watershed and total consumptive use in the watershed.

$$V_{\text{in}} = Y - u_d \qquad (4.4)$$

where u_d is the total volume of water consumed in the watershed upstream of dam d and Y is the total water yield from the watershed upstream of dam d. Hydropower production and available drinking water are the benefits assessed for the water provisioning services. Drinking water constitutes the most important annual consumptive demand of water resources in the Llobregat basin (65%), followed by industry (25%), agriculture (8%) and livestock (2%) (Catalan Water Agency, 2002). The fraction of water available for drinking purposes is calculated as the remaining water fraction after the removal of the demand for other consumptive uses (Catalan Water Agency, 2002) and the regulated environmental flow allocated at the basin outlet

(Catalan Government, 2006). To calculate the amount of energy produced by the three assessed hydropower stations, we performed a similar balance, discounting all the consumptive uses at the upstream of reservoirs. Although more than 100 small hydraulic plants exist in the Llobregat basin, the lack of information about diversion concessions forced us to use only power stations located in reservoir systems.

Table 4.2

Data requirements and outputs for the selected ecosystem services (ES)

ES	Step	Data requirements	Process	Output
Water provisioning	Water yield	DEM (m) Land use/land cover (LULC) Effective soil depth (mm) Average annual rainfall (mm) Average annual reference evapotranspiration (mm) Plant available water content PAWC (fraction [0,1]) Maximum root depth (mm) Evapotranspiration coefficient Zhang coefficient [0,10]	Calculates cell level yield as difference between rainfall and evapotranspiration	Annual average water yield (mm yr^{-1})
	Water scarcity	Consumptive use by LULC (m^3yr^{-1})	Subtracts water consumed for other uses	Annual average water yield available for drinking purposes (mm yr^{-1})
	Valuation	Turbine efficiency (fraction [0,1]) Average annual height (m)	Estimates power generated by water available for hydropower	Energy production (kWh y^{-1})
Erosion control	Soil loss	DEM (m) Land use/land cover (LULC) Rainfall erosivity (R) (MJ mm ha^{-1} yr^{-1}) Soilerodibility (K) (Mg h MJ^{-1} mm^{-1}) Sediment retention efficiency (%) Slope threshold (%) Threshold flow accumulation	Calculates sediment retention at each cell using USLE and routing	Annual average erosion (Mg y^{-1}) Annual average sediment retention (Mg yr^{-1})
	Valuation	Reservoir dead volume (m^3)	Subtracts sediment equal to dead volume	Annual average sediment retention to reservoirs (Mg yr^{-1})
		Allowed level of suspended solids pollution (kg yr^{-1})	Subtracts retention equal to amount of maximum allowed level	Sediment retention for water quality (kg yr^{-1})

4.2.3.2 Erosion control

The service of erosion control, which is the relative contribution of the different parts of the landscape to sediment retention, is estimated considering the land use patterns that affect sedimentation into downstream reservoirs, which can affect their water capacity and functioning for hydropower generation. Sediment retention service is calculated as the difference from received (from upstream cells) and exported sediment. Eroded soil from each cell is estimated using the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978), while the retained amount of sediment by each cell is a function of the retention coefficients associated to vegetation covers. Only sheet-wash erosion was included in the model (no rill-inter-rill, gully or stream bank erosion were considered), and the benefits of erosion control are calculated upstream of reservoirs for avoided reservoir sedimentation as the evaluated reservoirs are located in the upstream of the river Llobregat, while for water quality the whole basin is considered. We assumed that the landscape of upstream reservoir has a maximum export allowance, the reservoir dead volume, or the volume that, when filled with sediment, affects the reservoir's function. Given that any retention of sediment when fluxes are lower than the dead volume does not provide a reduction in dredging costs, infrastructure maintenance or production potential, this service was evaluated as the difference between total sediment production and maximum soil export allowance.

The InVEST model also calculates the total amount of sediment reaching a point of interest (water quality). In this study, the point of interest was a drinking water treatment plant near the outlet of the river basin. A threshold of total dissolved solids (US EPA, 2009) in drinking water is compared to the annual load of sediments that would arrive to the drinking water treatment plant near the outlet of the basin. These thresholds are applied where we considered that sediment retention is below the drinking water quality standard and does not provide human benefit.

Sensitivity analysis of the input parameters shows that the Zhang coefficient, a floating point value between 1 and 10, corresponding to the seasonal distribution of precipitation, is not an important factor in the geographical area. However, the precipitation is significant, especially in the more humid areas of the watershed (Sánchez-Canales et al., 2012). The main idea of the scenario approach is to analyse climate change impacts on selected ecosystem services with the constant land use maps of the river basin. Moreover, the sub-watershed is considered as the spatial unit of analysis to assess the performance of each ecosystem service. Model calibration for the Llobregat basin was performed as described by Terrado et al. (2012).

4.3. Results and discussion

4.3.1 Water provisioning

4.3.1.1 Water yield

Water yield represents the difference between the precipitation and the actual evapotranspiration (AET) in each land parcel. The contribution of each sub-watershed to the basin's total water yield varies along the territory (Fig. 4.1), with the major contribution from the North of the river basin. The yield of each sub-watershed varies between less than 500 $m^3ha^{-1}yr^{-1}$ (areas in dark red in Fig. 4.1) to more than 5000 $hm^3ha^{-1}yr^{-1}$ (areas in dark blue in Fig. 4.1), in the mountainous areas located in the Pyrenees (Northern). The Pyrenees area is the most important contributor to the basin's water yield (Fig. 4.1). These mountainous areas are functioned as regional "water towers" (Viviroli et al., 2007). This area presents hydrological changes that are already affecting inflows into the Pyrenees reservoir in two ways: (i) a reduction in the annual incoming water volume; and (ii) changes in the seasonal distribution of inflow, with a reduction in spring discharge and the earlier occurrence of the annual maximum monthly flow (López-Moreno et al., 2008). Changes in the hydrological cycle in the Pyrenees may have significant implications in water availability for different uses in the whole basin. From an ecosystem service perspective, the hydrological changes linked to the domestication of the Mediterranean forests have influenced the capacity of the study area to supply hydrologic ecosystem services at a wide range of scales (Willaarts et al., 2012).

Water yield in the Llobregat basin is expected to be affected at different extent by climate change (Fig. 4.2). Modest yield improvement is only expected in the southern part of the basin for the scenario B1 (2031-2070). The results of the remaining scenarios show that water yield values per sub-watershed are likely to be reduced by up to 60%. The northern part of the basin, which has the most significant contribution to the provision of freshwater to downstream areas, will be highly affected in the two scenarios (A2 and B1), especially for the time span 2071-2100.

The total annual water volume at the outlet of the basin is represented by the difference between the yield (hm^3) and consumptive uses (hm^3) of water and expected to reduce in all evaluated scenarios (Table 4.3). Significant reductions (between 42 and 69%) are observed for the scenarios of time span 2071-2100. These changes are a consequence of a reduced capacity of the river basin in terms of water yield. To increase the water yield, small reservoirs can significantly impact the hydrological regime of river basins (Wisser et al., 2010). Rainfall and Actual Evapotranspiration are the main drivers of change in water yield along with land use changes. But the land use changes are not evaluated in this work. The different degrees of rainfall reductions in the future scenarios are directly related to the reduced water yields for the respective scenarios. In a similar way, changes in Actual Evapotranspiration (AET) are directly linked to the changes in annual mean temperature. In this case, an increase is observed for 3 scenarios: A2 (2031-2070) and B1 (2031-2070 and 2071-2100). Rainfall decreases and AET increases are likely to impact negatively on water yield in the river basin. Another study of the basin (Sánchez-Canales et al., 2012) also observed that coupling exists between evapotranspiration coefficient and precipitation coefficient, with their correlation stronger in the central region of the watershed. Water yields were found to be most affected by Scenario A2 (2071-2100), with a yield reduction of 42%. Although reductions are more severe for the A2 scenario, a notable decrease in water yield is also expected for the moderate scenario (B1), with an annual yield reduction between 3 and 26%.

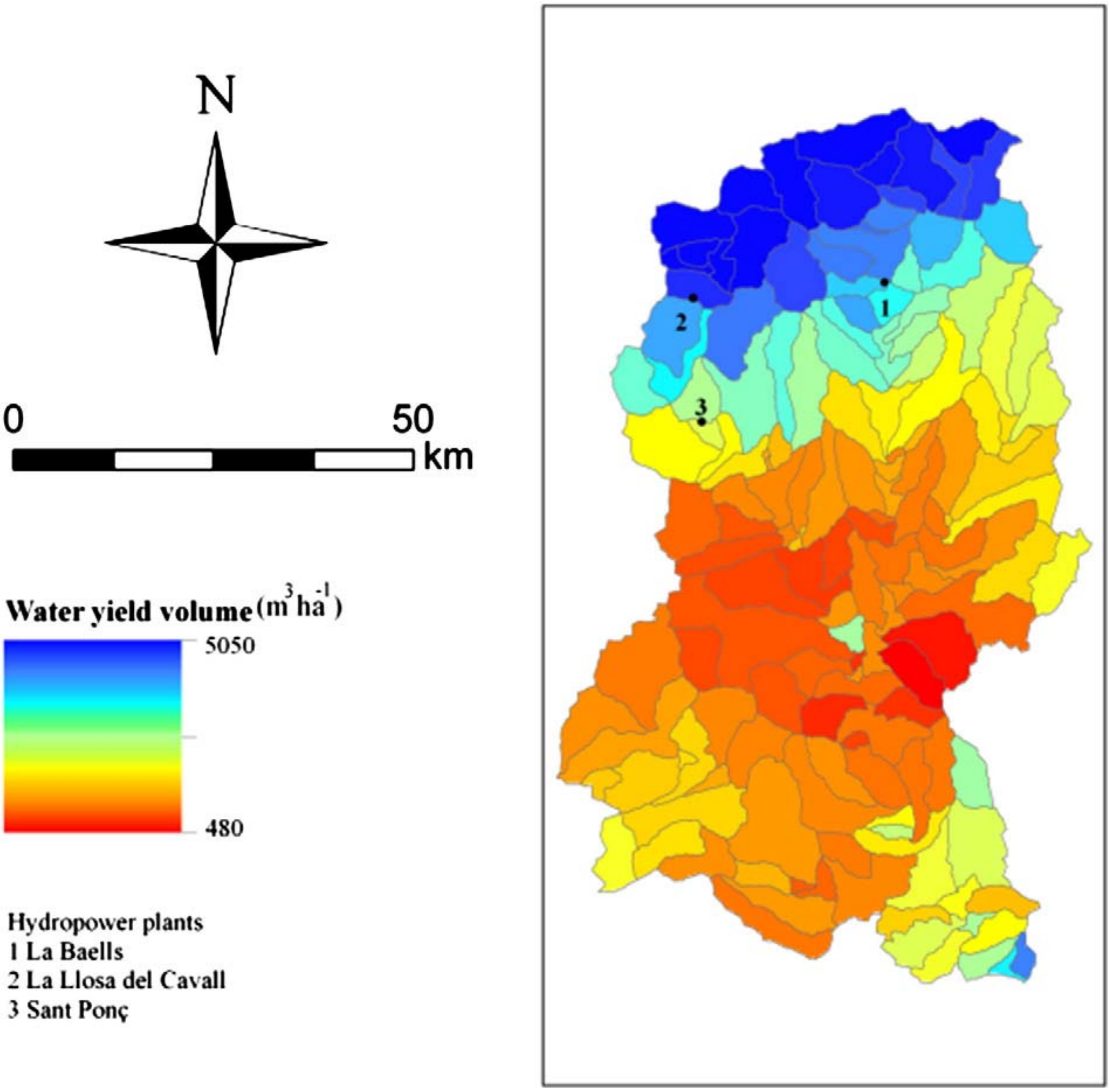

Fig. 4.1. Water yield volume (m3 ha−1 yr−1) per subwatershed for the base scenario (1971–2000).

An increase in forest area is observed around 14% between 1957 and 1993, as a consequence of improvement of forest from sparse to dense covers, and the change of land use from agriculture to pasture and forestry (Gallart et al., 2011). However, forest management is considered far less effective for water resource management than dam reservoir development (Komatsu et al., 2010).

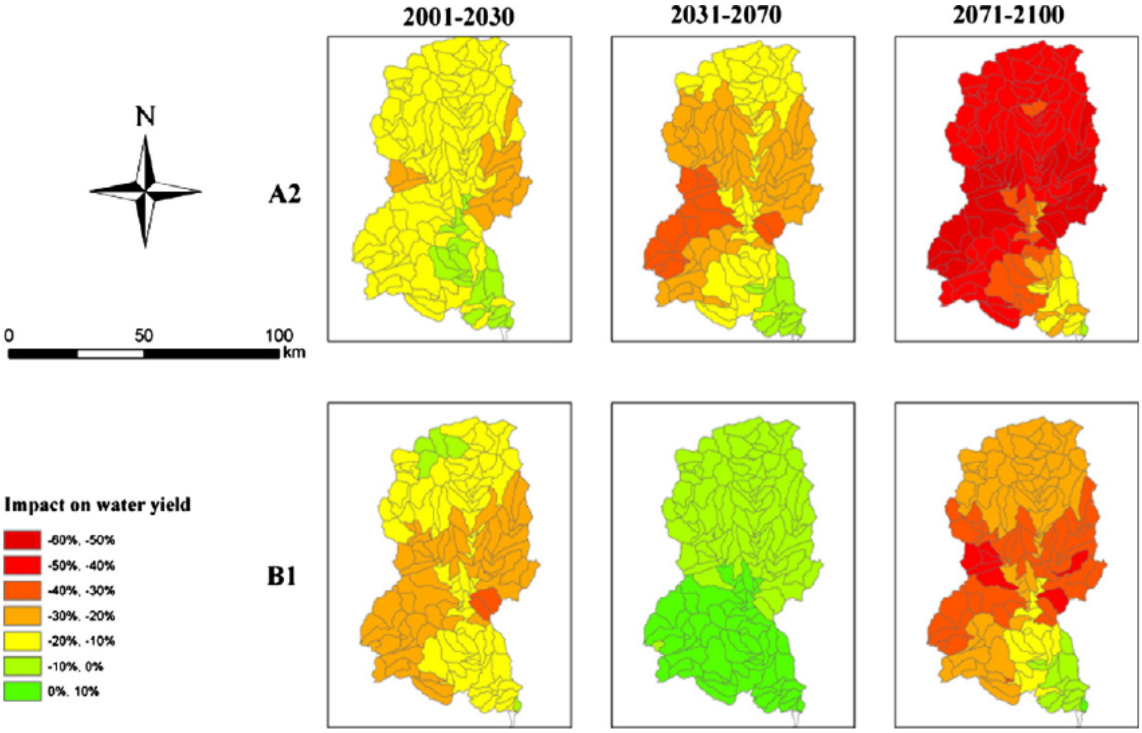

Fig. 4.2. Climate change impacts on water yield volume (m3 ha−1 yr−1) per subwatershed for the evaluated future scenarios.

The management of land cover with the aim of improving the availability of water resources is a complex task, as the goal is to obtain higher runoff coefficients while maintaining slope stability, ensuring low erosion rates, reducing reservoir siltation, and mitigating the risks associated with flood events (Beguería et al.,2006; López-Moreno et al., 2006). Water demand in the Llobregat region is increasing over time, especially in the low lands for agricultural purposes. To deal with this problem, an appropriate understanding of the importance of land cover management for water resource availability is needed, as has been confirmed in other studies of the basin (Beguería et al., 2003; López-Moreno et al., 2006). Trade-off analysis is needed to optimise river basin management, assuring the provision of key ecosystem services.

4.3.1.2 Water scarcity

Water yield reduction impacts negatively the basin capacity to provide drinking water and energy through hydropower production (Tables 4.3 and 4.4). Under climate change analysis, a reduction between 17 and 49% is observed for the drinking water service (Table 4.3), with the exception of scenario B1 (2031-2070), where an increase of 2% in rainfall leads to a reduction of only 3% in drinking water volume. For the base scenario, the Llobregat basin supplies $842 \cdot hm^3\ y^{-1}$ of water that could be used for drinking purposes, while the real drinking water demand in the basin is around $300 \cdot hm^3\ y^{-1}$ (Catalan Water Agency, 2002). The drinking water demand may also increase in the future as a consequence of land use change and population increase (Pouget et al., 2012), the factors that were not considered in this study. Differences encountered in the hydrologic ecosystem services provisioning capacity are intimately linked with the vegetation cover and management of the territory (Willaarts et al., 2012). However, the globe's most vulnerable regions are in need of more detailed analysis and the relative importance of population growth versus climate change in altering future freshwater supplies and future per capita water availability may be more a function of population change than climate change (Parish, 2012). A 2003 study by the World Resources Institute (WRI, 2003) concluded that 48% of the world's projected population (~3.5 billion people) will live in water-stressed river basins by 2025.

Water provisioning for drinking use is already an environmental problem in the Llobregat river basin, and water shortages are observed during drought periods. These water shortage periods are difficult to evaluate at an annual basin, and especially when the evaluation is based on the mean annual climate parameters for large time spans (between 30 and 40 years). More detailed studies are needed to evaluate the probability of having important impacts on water provision as a consequence of extended droughts, as the difficulty of supporting a prolonged drought period with the present consumption rates. Application of efficient water use systems is an important way to reduce water demand in a water-scarce region (Zhang et al., 2010). Due to the seasonal variations of the rainfall, efficient capture and retention of precipitation during rainy season and its recycling to water shortage periods as per the water requirements may be one of the best options to increase water availability during dry seasons.

One of the most important issues related to climate change in the basin is water security. Interactions between climate change and population growth are expected to increase water demand, and arid and semiarid regions will face additional challenges of absolute water scarcity (Vörösmarty et al., 2000). Water is a primary input to all goods and services either directly or indirectly. The available water quantity and quality can affect the production of goods and services and thus influences the level of economic activities, especially in quickly transforming societies, from agricultural based towards industrialized and modernizing economies (Guan and Hubacek, 2008). A recent study on the Llobregat basin showed that the total annual water volume had experienced an 80% decrease in dry conditions, while an increase of 160% was observed in wet conditions for the period 1970-2000. Drinking water demand remains approximately constant in the basin unless exceptional water demand restrictions are enforced during prolonged droughts (Terrado et al., 2012). These changes could lead to a reduction in drinking water availability to levels much lower than those observed in Table 4.3. According to these results, future challenges to water infrastructures and associated water challenges will potentially lead to important economic costs in the implementation of response alternatives. The imbalance between water demand and resources induces the pressure and degradation of the water quality. In such a case, the artificial recharge of water-table aquifers by water from dams is a credible alternative to improve the hydrodynamic and physicochemical conditions of the groundwater (Bouri and Dhia, 2010). However, the InVEST model is unable to account for deep groundwater recharge and water resource infrastructure that redistributes water flow (Vigerstol and Aukema, 2011).

4.3.1.3 Hydropower production

Similarly to drinking water availability, a decrease in hydropower production is observed in future scenarios developed for 3 reservoirs (Table 4.4). This agrees with the predicted reduction of hydropower potentials in Southern and South Eastern Europe (Lehner et al., 2005). For each future scenario, the degrees of reduction are compared for all three reservoirs. Two reservoirs (La Llosa del Cavall and Sant Ponç, Fig. 4.1) are located consecutively in the river basin and provide higher benefits to the region in terms of energy produced. It should be noted that the values reported in Table 4.4 correspond to the potential energy produced if all the available water is utilised for hydropower generation. However, the power stations are not working continuously and the actual amount of electricity produced is lower.

Table 4.3
Comparison between base and future scenarios (6 scenarios) of rainfall, actual evapotranspiration (AET), total water yield, drinking water provision and water volume at the outlet of the Llobregat basin.

Period	Scenario	Rainfall (mm yr^{-1})	Rainfall reduction (%)	AET[1] (mm)	AET reduction (%)	Water yield (hm^3 yr^{-1})	Water yield reduction (%)	Drinking water[2] (hm^3 yr^{-1})	Drinking water reduction	Water volume in the outlet (hm^3 yr^{-1})	Water volume reduction
1971-2000	Base	938.69	-	595.92	-	978.00	-	841.71	-	602.92	-
2001-2030	A2	879.81	6	587.65	1.39	833.52	15	697.23	17	458.44	24
2031-2070	A2	878.38	6	605.49	-1.61	778.01	20	641.72	24	402.92	33
2071-2100	A2	792.08	16	594.45	0.25	563.09	42	426.80	49	188.00	69
2001-2030	B1	869.12	7	583.76	2.04	814.01	17	677.72	19	438.93	27
2031-2070	B1	958.15	-2	625.65	-4.99	948.75	3	812.46	3	573.67	5
2071-2100	B1	863.37	8	608.62	-2.13	726.10	26	589.82	30	351.02	42

[1] AET: actual evapotranspiration
[2] Based on the assumption of a constant demand of 136.29 hm^3/year

Table 4.4
Climate change impacts in hydropower production at the Llobregat basin.

Period	Scenario		La Baells	La Llosa del Cavall	SantPonç	Total
1971-2000	Base	Provision (MWh yr^{-1})	39657	17910	21412	78979
2001-2030	A2	Provision (MWh yr^{-1})	33997	15366	18272	67635
		Reduction	14%	14%	15%	14%
2031-2070	A2	Provision (MWh yr^{-1})	32422	14325	16929	63675
		Reduction	18%	20%	21%	19%
2071-2100	A2	Provision (MWh yr^{-1})	22891	10319	12130	45340
		Reduction	42%	42%	43%	43%
2001-2030	B1	Provision (MWh yr^{-1})	35008	15987	18919	69914
		Reduction	12%	11%	12%	11%
2031-2070	B1	Provision (MWh yr^{-1})	37490	17237	20569	75296
		Reduction	5%	4%	4%	5%
2071-2100	B1	Provision (MWh yr^{-1})	30921	13660	16082	60663
		Reduction	22%	24%	25%	23%

The reduction in hydropower potential combined with the expected population growth in the basin indicates that either alternative energy sources should be considered, or to construct more dams in the studied area to meet the future demands. However, this fact could also lead to different impacts, such as fish biomass and biodiversity losses as a consequence of the barrier to fish migration routes (Ziv et al., 2012). In this regard, strategic analysis is needed to assess which should be the most suitable energy sources for this specific case, avoiding unnecessary risks to ecosystems and environmental services.

4.3.2 Erosion control

Total sediment retained by the basin was evaluated with two different approaches: (1) considering the sediment thresholds of each reservoir (avoided reservoir sedimentation), to calculate the avoided need of dredging reservoirs; (2) considering the threshold for suspended solids in the water treatment plant (water quality), to represent the avoided need to remove these solids from drinking water.

It is observed that the benefits from erosion control for water quality rang between 1070 and 1390 ton yr^{-1}. The higher values of mean sediment retention are observed in the upper part of the basin (Pyrenees mountains area, Fig. 4.3), and very low levels are observed close to the basin outlet (point 4 in Fig. 4.3). The estimated sediment export value of base scenario for the Llobregat basin is 1.37 10^{6} ton yr^{-1} (Table 4.5). These values are very similar to the levels reported in another study for the same basin (Liquete et al., 2009). Similar trends are observed for the mean sediment retention for dredging service. However, higher sediment retention amounts are observed at La Baells reservoir as compared to other two reservoirs in the basin (Fig. 4.3).

Similar to water provisioning, the effect of climatic change on soil erosion is also not homogeneous throughout the basin. The analysis of climate change scenarios showed that the sediment retention at upstream of the reservoirs will be reduced in all cases (Fig. 4.4) but more drastic reductions are expected for the period 2071-2100. Reduction of sediment retention could also affect the water quality at the basin outlet (Fig. 5). Significant impacts are observed in the Northern part of the basin (Pyrenees area) with the highest sediment retention values.

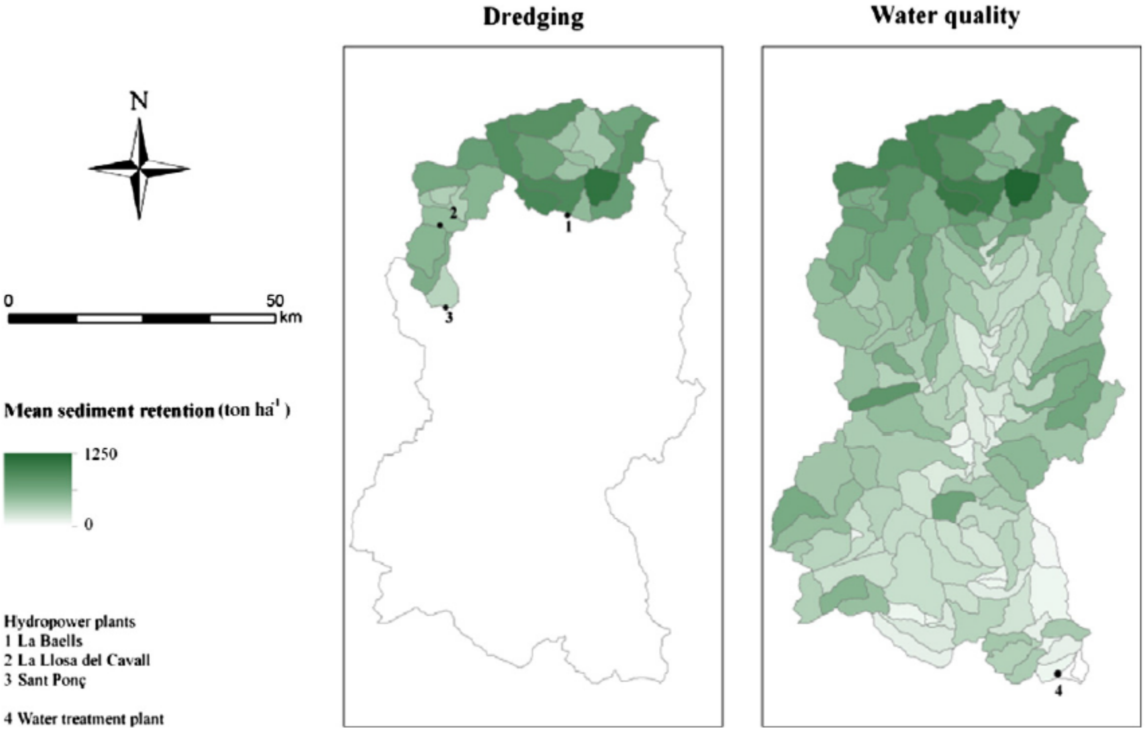

Fig. 4.3. Mean sediment retained per year on each subwatershed, including sediment retained that originates from upslope subwatersheds as well as sediment that originates on the subwatershed itself. The results represent the sediment retention service for avoided dredging (hydropower plants) and water quality (water treatment plant) regulation.

Table 4.5
Comparison between the amounts of sediment exported and retained per year at the Llobregat basin.

Period	**Scenario**	**Sediment exported (ton yr^{-1})**	**Export reduction**	**Sediment retained (ton yr^{-1})**	**Retention reduction**
1971-2000	Base	1.37E+06	-	2.04E+08	
2001-2030	A2	1.34E+06	2%	1.98E+08	3%
2031-2070	A2	1.27E+06	8%	1.87E+08	8%
2071-2100	A2	1.07E+06	22%	1.57E+08	23%
2001-2030	B1	1.28E+06	7%	1.90E+08	7%
2031-2070	B1	1.39E+06	-1%	2.03E+08	0%
2071-2100	B1	1.19E+06	13%	1.77E+08	13%

The amount of sediments exported (Table 4.5) is also expected to decrease, agreeing with the predictions reported by Milly et al. (2005) for the same period in the region. For this reason, erosion control results are interpreted considering both sediment retention and exports (Table 4.5). For all the scenarios, the amount of sediment retained is two orders of magnitude higher than that exported, and most of the sediment produced in the basin is retained by existing vegetation. Results of this study illustrate the same trends as reported by Terrado et al. (2012), and higher export values are observed close to the main stream, while higher retention values are observed far from the stream. As a result of the lower erosion values, sediment retention also decreased in the evaluated periods. The same tendency is observed by López-Moreno et al. (2008), revealing that climate trends are leading to more restrictive conditions for runoff generation due to an increase in evapotranspiration and a decrease in rainfall during certain periods of the year. Catalan Water Agency (ACA) has planned several interventions in the basin to ensure the sustainable water supply and improve water quality. For example, river bank plantation at lower and upper part of the river will minimize the erosion values along with other environmental objectives. However, a quantified analysis of each intervention is required with the perspective of ecosystem services.

At the reservoir level, dam managers are assumed to generate their profits by providing irrigation water and hydroelectric power, which are dependent on the reservoir storage capacity (Lee et al., 2011). The life of a reservoir is reduced significantly when there is high sediment deposition, and periodic sediment removal can recover reservoir storage capacity. The primary controls on temporal change in reservoir sedimentation rates include climate, land use or land cover, geologic materials and internal fluvial system operations (Graf et al., 2010). A study (Shi et al., 2012) shows that soil conservation measures taken in fields effectively reduce on-site soil loss and sediment yield. However, off-site sediment control measures appear to be much less effective at reducing sediment yield. The sediment delivery processes are complex in nature, and inputs of reservoir sediment may have periods of very different rates of delivery separated by short periods of rapid change. In the case of the Llobregat basin, temporal variation of sedimentation is related to seasonal variations in the rainfall erosivity index, which in turn is a function of the variability in rainfall within a one year period.

Rainfall seasonality is considered in the study only to differentiate mean rainfall values for summer months and the other months of the year. As the study is based on yearly data, with mean values for large periods, the existence of isolated rainfall events is not assessed by the model. An important drawback of the model used in the present study is that it runs on an annual basis and seasonal climate variations are not assessed. Further studies will consider evaluating these climate change scenarios for the wettest and driest year of each period. These studies would allow evaluating the real impact of extreme future climatic conditions.

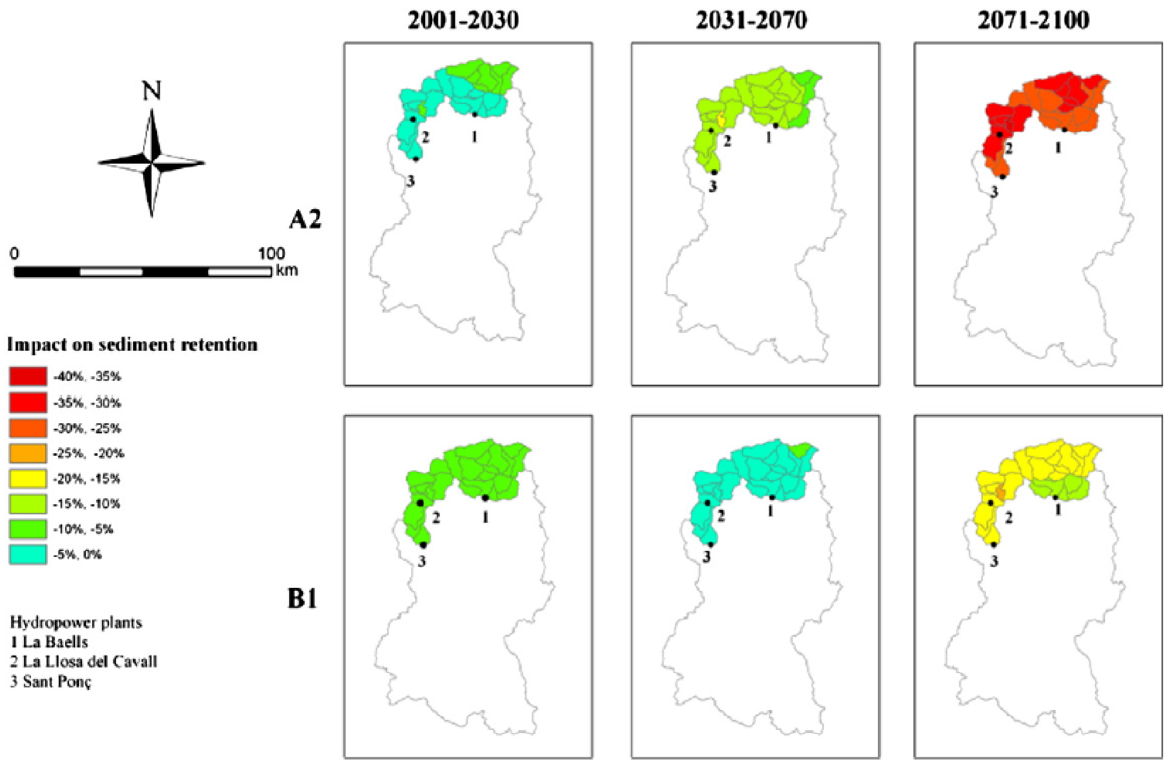

Fig. 4.4. Climate change impacts on avoided reservoir sedimentation per reservoir for the evaluated future scenarios.

4.4. Conclusions

The evaluation of climate change impacts on ecosystem services provision shows that water provisioning and erosion control are highly sensitive to climate change in the Llobregat river basin. A review study (Gosling, 2013) found a proportionally larger amount of evidence to suggest that ecosystem services are vulnerable to changes in the large-scale climate-earth system in the Mediterranean region. Services supply and delivery are likely to reduce by significant amounts, indicating that urgent measures must be taken to avoid future water stress in the basin. The sub-watersheds from the Pyrenees region are responsible for most of the services provision, and are also the most impacted areas regarding climate change. Interventions to enhance the provision of regulating services should focus in certain areas where obtained benefits per surface area are estimated to be the highest. For the protection of these areas, interventions such as restoration and measures suitable for increasing or maintaining resilience in rivers are essential to assure future water use in the basin. The groundwater–surface water interplay and the temporal nature of water demands in the Mediterranean region also lend complexity to the system (Bangash et al., 2012). The aim of the study was the detection of change in trends over time and the quantification of ecosystem service provisioning under climate change impact. The results show clear trends over time, with decreases in water yield and the amounts of sediment retained being two orders of magnitude higher than that exported. Climate change is the only variable and driving force considered in this study. Other important drivers of change, as land use and land cover, and the increase in demand by different sectors are considered constant for the whole catchment. However, it is obvious that the protection of water resources is not sufficient if the levels of consumption continue to increase in the future. Proactive management of basin should be implemented for adapting to climate change as mitigating measures taken in the present may avoid long-term future consequences.

Chapter 5

The impact of climate change on water provision under a low flow regime: A case study of the ecosystems services in the Francoli river basin

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ABSTRACT

Mediterranean basin is considered one of the most vulnerable regions of the world to climate change and with a high potential to present problems related to water scarcity in the next years. Francolí River basin (NE Spain), located in this vulnerable region is selected as a case study to evaluate the impact of climate change on the delivery of water considering the IPCC scenarios A2 and B1 for the time spans 2011-2040, 2041-2070 and 2071-2100. InVEST model is applied in a low flow river as a new case study, which reported successful results after its model validation. The studied hydrological ecosystem services will be highly impacted by climate change at Francolí River basin. Water yield is expected to be reduced between 11.5 and 44% while total drinking water provisioning will decrease between 13 and 50% having adverse consequences on the water quality of the river. Focusing at regional scale, Prades Mountains and Brugent Tributary provide most of the provision of water and also considered highly vulnerable areas to climate change. However, the most vulnerable part is the northern area which has the lowest provision of water. Francolí River basin is likely to experience desertification at this area drying Anguera and Vallverd tributaries.

Keywords: Climate change scenarios, Water scarcity, Mapping freshwater, Ecosystem services, InVEST

5.1 Introduction

Changing Climate is an intrinsic characteristic of the Earth's system. During the Quaternary, long cold and dry periods alternated with relatively short warm periods (García-Ruiz et al., 2011). Each of these periods was affected by climatic variability at different temporal scales (Bradley, 1999; Alley, 1953). Climate change may be due to natural internal processes or external forcing, or to persistent anthropogenic changes in the composition of the atmosphere or in land-use (VijayaVenkataRaman et al., 2012). The Mediterranean region lies in a transition zone between the arid climate of North Africa and the temperate and rainy climate of central Europe and it is affected by interactions between mid-latitude and tropical processes (Giorgi and Lionello, 2008). This area has been globally identified as one of the most vulnerable to climate change (Schröter et al., 2005). Climate change will intensify the hydrological cycle in semi-arid areas through global increases in temperature, rainfall concentration in short periods of the year, and more extended droughts (Hisdal et al., 2001).

Ecosystems services are the benefits that humans derive from ecosystems, which include provisioning, regulatory, supporting and cultural services (MEA, 2003). It is well known that the services of natural ecosystems are clearly important to our societies: probably there would not be life without them. Climate change has the potential to cause abrupt negative changes in ecosystems and associated ecosystem services (Gosling, 2012). It is likely that first impacts will be felt in the Mediterranean water resource system through increased frequency of water shortages and decline in water quality (Bangash et al., 2012).

The variety of ecosystem services which are derived from freshwater are commonly referred to as hydrological ecosystem services. They are often regulated by terrestrial ecosystems (Brauman et al., 2007) and include provisioning services such as water supply for drinking, power production, industrial use and irrigation, as well as regulating services such as water purification and erosion control (Groot et al., 2010). Their provision depends on watershed characteristics, such as topography, land use and land cover (LULC), and climate, parameters which have governing roles on the delivery of services. It is important to note that climate has greater determination in semi-arid basins like Mediterranean area. However, the quantity and quality of freshwater flows and hydrological ecosystem services supply is closely related to the management of the territory (Willaarts et al., 2012) .

The low flow regime characteristic of some Mediterranean river basins also results from natural factors besides anthropogenic effects that includes the hydraulic characteristics and extent of the aquifers, infiltration characteristics of soils, frequency and amount of recharge, evapotranspiration rates, vegetation types, topography and last but not least the climate. On one hand a low flow is a seasonal phenomenon, and an integral component of a flow regime of any river. On the other hand, a drought is a natural event resulting from a less than normal precipitation for an extended period of time (Bangash et al., 2012). Mapping of ecosystem services has been a major topic at the regional to global scale (Eigenbrod et al., 2010). Low flow river provides same ecosystem services as provided by high flow rivers, however modelling low flow river basin has always been a challenge due to lack of sufficient data. Low flow hydrological features are crucial for efficient development and integrated water resources management and a lot of effort has been made by the scientific community to deal with low flow parameters estimation in ungauged sites (Longobardi and Villani, 2008). Several studies have assessed the anthropogenic effect on land use and cover, but few have focused on the impact of climate change on the reduction of hydrological ecosystem services. Moreover, lack of policy and regulation interests for low flow river basins also hinders the consistency of the links between decisions and the parallel analysis of the hydrological processes.

This manuscript aims to evaluate the impacts of climate change on water provisioning services, at the Mediterranean basin of Francolí River, showing the degree of reduction as well as the areas of the basin that will be more impacted. Estimated results for the future climate change scenarios A2 and B1 for the time spans 2011-2040, 2041-2070, 2071-2100 are obtained and compared to the base scenario 1971-2000. This study is inevitable in a situation when the river basin is already under high pressure and located in semi-arid Mediterranean area, where water scarcity can restrict activities dependant on water consumption. Adequate freshwater supplies are fundamental in ensuring the sustainability of agriculture, industry and the natural environment. Results of this study can be used to compare alternative management options in terms of biophysical measures of services (Bai et al., 2012).

5.2 Materials and methods

5.2.1 Study site

Francolí River in the Mediterranean area of northern Spain is about 85 km in length, and including main tributaries is 109 km long, constituting approximately a basin of 855 km^2. The mainstream flows from Espluga de Francolí and leads into Mediterranean Sea through coastal mountains passing by cities like Montblanc, La Riba and Vallmoll (Fig. 5.1). Coastal mountains are a source area for river basins where precipitation is scarce, evapotranspiration is intense and there is marked seasonality of rainfall, often causing drought periods during summer (Delgado et al., 2010). In this case, Brugent River flows through Prades mountains being the major tributary of Francolí River.

The low flow is a special characteristic of Francolí River which can be subject to high inter-annual and seasonal variability of precipitations, with long and intense dry periods or extreme rainfall and floods. Thus, the flow depends on the rainfall intensity: spring and autumn rains and dry summers. Consequently, even though water is relatively scarce throughout most of the year, there have been some flash floods such as one occurred on 10th October 1994, during the rainy season in the Mediterranean area, a major flood event that lasted 24 h caused severe damage throughout the Francolí basin (Roca et al., 2009).

Regions in Mediterranean basins could suffer even more frequent regional shortages due to the twin problems of climate change and rising demand. Francolí River basin has been under considerable pressure for water availability and water quality over the last decades because of the low flow and the prolonged drought period. The main anthropogenic factors have been the population growth and related increasing demand in cities like Montblanc, Valls, La Selva, Constantí and Tarragona. Household water constitutes the most important annual consumptive demand of water resources (88%) followed by industry (11%) and agriculture (1%) (ACA, 2008). The watershed was solely dependent on groundwater and surface water before the inter-basin transfer water supply schemes from Ebro River was started in 1989. Moreover, climate change is becoming an added key factor to worsen the already existing water stress situation in the Francolí watershed. Less precipitation will cause less watershed runoff and lower availability of water in the river basin (Bangash et al., 2012). Moreover a flow decrease may have an obvious direct effect on the dilution factor, giving rise to an increase in the concentration of pollutants and thus to a corresponding increase in risk for the aquatic ecosystems (Patrovic et al., 2011). Consequently, it is expected that the hydrological ecosystem services in terms of water provisioning are being affected enormously causing water scarcity and a decrease of the river flow quality.

5.2.2 Model application

Natural Capital Project, a group based at Stanford University in California, has developed models that quantify and map the values of environmental services, such as Integrated Valuation of Environmental Services and Tradeoffs (InVEST). InVEST 2.4.2 has been used for this study.

InVEST 2.4.2 model runs as script tool in the ArcGIS 10 ArcToolBox on a gridded map at an annual average time step, and its results can be reported in either biophysical or monetary terms, depending on the needs and the availability of information. It is most effectively used within a decision making process that starts with a series of stakeholder consultations to identify questions and services of interest to policy makers, communities, and various interest groups. These questions may concern current service delivery and how services may be affected by new programs, policies, and conditions in the future. For questions regarding the future, stakeholders develop scenarios of management interventions or natural changes to explore the consequences of potential changes on natural resources (Guerry et al., 2012). This tool informs managers and policy makers about the impacts of alternative resource management choices on the economy, human well-being, and the environment, in an integrated way (Daily et al., 2009). The spatial resolution of analyses is flexible, allowing users to address questions at the local, regional or global scales.

5.2.2.1Data preparation

Data collection and processing is a rigorous and basic activity in ecosystem services model development. For this study, we used projected coordinate system of European Datum: Zone 31N of UTM Year 1950. The data inputs required for each model development vary depending on the service to be analysed. But most of the input data formats are in GIS raster grids, GIS shapefiles, database tables (Vigerstol and Aukema, 2011) or constants (Table 5.1).

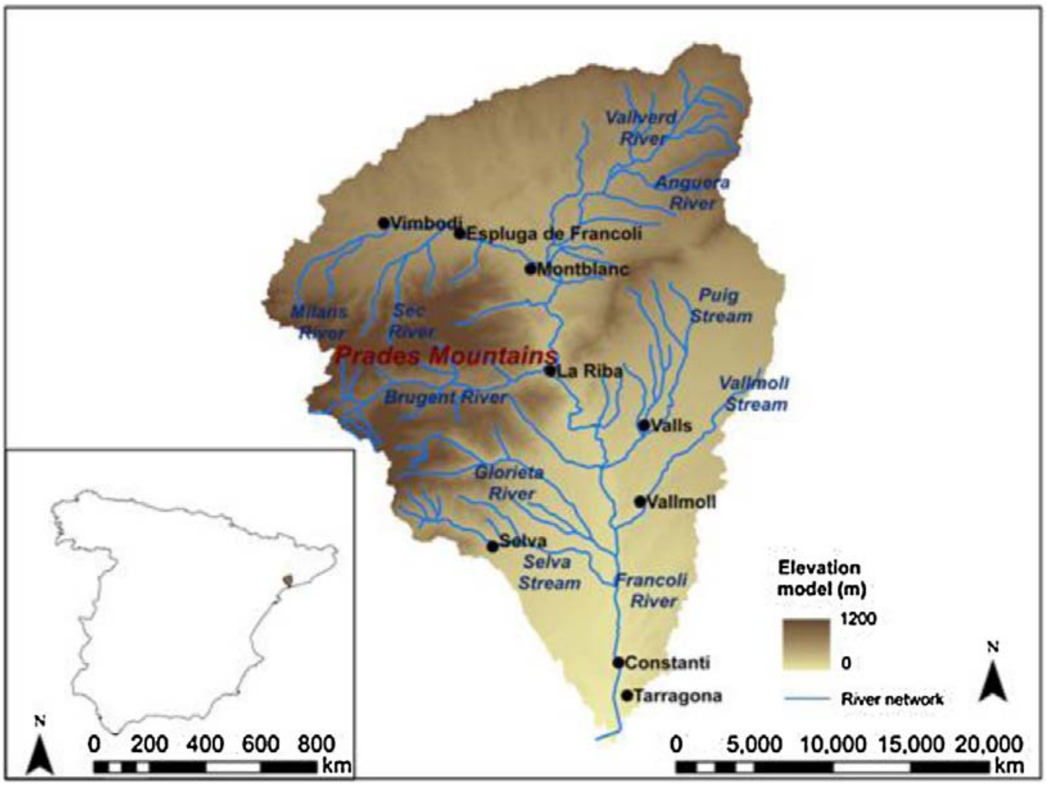


Fig. 5.1. Francolí river basin.

The greatest sensitive input parameter is precipitation and the least are Zhang coefficient and evapotranspiration as it is explained by Sánchez-Canales et al. (2012). However, it is required to use the precipitation map that best represent the region under study, due to the fact that this input becomes crucial as a result of the sensitivity analysis performed.

5.2.2.2Water provisioning models

InVEST hydrological models are based on simplifications of well-known hydrological relationships (Vigerstol and Aukema, 2011) of the natural ecosystems. The biophysical models calculate the relative contribution of the different parts of the landscape to the provision of services.

This work is focused on the water provisioning service, included in the InVEST freshwater module. This service brings information about the total amount of water available in a basin (Sánchez-Canales et al., 2012). Freshwater module is based on development of two interlinked models; water yield model and water scarcity model. In water yield model, the amount of water provisioned from each cell in the landscape was obtained by calculating the net hydrological balance (Terrado et al., 2014) as the difference between precipitation and evapotranspiration, determined by the cell vegetation characteristics (Canadell et al., 1996) (Fig. 5.2). In water scarcity model, the amount of water available for drinking uses was obtained by subtracting the water demand by each land use/land cover from the already calculated water yield.

Table 5.1

Maps, tables and constants used as input to InVEST with reference to the source and the spatial discretization.

Data type	Data source	Spatial discretization
GIS raster grids maps		
Topography/DEM	ICC (Institut Cartogràfic de Catalunya, www.icc.cat)	30 x 30 m^2
Average annual rainfall	Catalan Water Agency data	20 sub-watersheds
Average annual rainfall for the future scenarios	Catalan Meteorological Service	20 sub-watersheds
Average annual reference Evapotranspiration	Climatic atlas of Catalonia temperature data. Calculated (Hamon 1961, Wolock and McCabe 1999) and interpolated.	30 x 30 m^2
Average annual reference Evapotranspiration for the future scenarios	Catalan Meteorological Service	30 x 30 m^2
Land use/land cover	Centre for ecological research and forestry application	30 x 30 m^2
Effective soil depth	European Soil Database	30 x 30 m^2
Plant available water content	European Soil Database Calculated with Bech et al., 2008	10 x 10 km^2
GIS shapefiles maps		
Watershed boundary	Extracted from Digital Elevation Model (DEM) using ArcGIS hydrological tools	As DEM, 30 x 30 m^2
Sub-watershed boundary	Provided by Catalan Water Agency	As DEM, 30 x 30 m^2
Database tables		
Maximum root depth	Canadell et al., 1996	
Evapotranspiration coefficient	Extracted from InVEST User's guide. Tallis et al., 2011. Literature review of Mediterranean area	
Water demand table	Catalan Water Agency and Catalan Statistics Institute	
Constant		
Zhang coefficient	Zhang and McFarlane, 1995; Zhang et al., 2001, 2004; Milly, 1994	

Table 5.2

Components and description of two steps of the water provisioning module

Step	**Data requirements**	**Process**	**Outputs**
Water yield	Land use/land cover Annual average precipitation Annual average reference evapotranspiration Plant available water content Evapotranspiration coefficient Root depth Effective soil depth Zhang coefficient	Calculates yield as difference between precipitation and actual evapotranspiration $Y = P - AET$ where: Y= water yield P= precipitation AET= actual evapotranspiration	Annual average water yield (mm·watershed^{-1} · year^{-1}, mm·subwatershed^{-1} year^{-1})
Water supply for drinking purposes	Water demand by each land use/land cover	Substracts water consumed by each land use/land cover as below: $V_{in} = Y - u_d$ where: V_{in}= water supply Y= water yield u_d= water consumption by each land use/land cover	Annual average water supply (mm·watershed^{-1} · year^{-1}, mm·subwatershed^{-1} year^{-1})

The first step (water yield) uses data on average time span precipitation, annual reference evapotranspiration, soil depth, plant available water content, land use and land cover, root depth, evapotranspiration coefficient by each land use and land cover and a seasonality factor of rainfall (Zhang coefficient). Regarding the model sensitivity to parameters performed in previous studies, high changes in the precipitation input values causes significant changes in water yield, especially in more humid areas of the watershed where precipitation is high and evapotranspiration low. Hence, decrease in water yield expected for the future scenarios is mainly related to the precipitation decrease while the evapotranspiration increase has a minor influence. On the other hand, the Zhang coefficient in Mediterranean basins does not seem to be an important factor in water yield calculations that gives values within a range of same output (Sánchez-Canales et al., 2012).

The second step (water scarcity) adds water demand by each land use/land cover to determine the water available for drinking purposes (water supply) (Table 5.2).

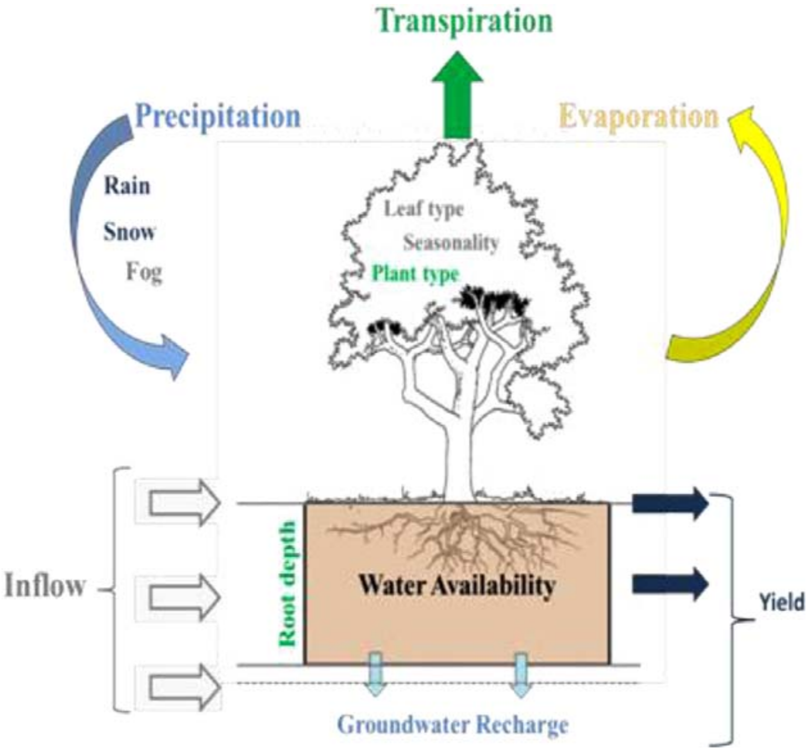


Fig. 5.2. Water balance model used in InVEST hydrological models. Only parameters shown in color are included, and parameters shown in grey are ignored.

InVEST water provisioning models are applied for each scenario and time span for climate change impact assessment. The model was run seven times, changing in each run the inputs related to the climatic factors. Thus, the average annual reference evapotranspiration and the average annual rainfall were different according to the projected variations in temperature and precipitation patterns (Table 5.3) established by regionalized IPCC scenarios. A2 scenario expects severe changes in temperature and precipitation schemes, while B1 scenario expects more moderate variations. Land use and water demand are kept constant for all the scenarios because the main objective of this paper is to assess exclusively the impacts related to climate change.

InVEST model does not differentiate between surface, subsurface and base flow, but assumes that the water yield from each and every pixel reaches the point of interest via one of these pathways. The model calculates the sum and averages of water yield at sub-watershed level. The pixel-scale calculations allow representing the heterogeneity of key driving factors in water yield such as soil type, vegetation and temperature. InVEST ensures good interpretation of these models at sub-watershed scale, and all outputs are summed and/or averaged to the watershed scale.

Water yield model is based on the Budyko curve (Budyko and Miller, 1974) and annual average precipitation. First, the annual water yield (Y_{jx}) for each pixel on the landscape (x=1, 2, 3…X) is determined in Eq. 5.1.:

Eq. (5.1) $$Y_{xj} = \left(1 - \frac{AET_{xj}}{P_x}\right) \cdot P_x$$

AET_{xj} is the annual actual evapotranspiration on the pixel x with land use land cover (LULC) j. P_x is the annual precipitation on the pixel x.

Table 5.3

Temperature and precipitation variations at Francolí watershed for selected scenarios and time spans

Scenario	Time span	Average annual temperature variation (ºC)	Average annual precipitation variation (%)
A2	2011-2040	+ 0.8	- 8
	2041-2070	+ 2.1	- 8
	2071-2100	+ 3.6	- 16.5
B1	2011-2040	+ 0.9	- 1.4
	2041-2070	+ 1.4	- 3.8
	2071-2100	+ 2.5	- 10.5

Table 5.4

Required data for Sacramento and InVEST models

Sacramento model		**InVEST model**	
Inputs	***Outputs***	***Inputs***	***Outputs***
Precipitation Temperature Evaporation	Snow retention Evaporation Surface flow Groundwater flow	Precipitation Evapotranspiration Land use/land cover Plant available water content Evapotranspiration coefficient Root depth Effective soil depth Zhang coefficient	Water yield (surface, subsurface and groundwater flow)

The evapotranspiration partition of the water balance shown in the Eq. 5.2 (AET_{xj}/P_x) is an approximation of the Budyko curve developed by Zhang et al. (2001):

Eq. (5.2) $$\frac{AET_{xj}}{P_x} = \frac{1 + w_x R_{xj}}{1 + w_x R_{xj} + \frac{1}{R_{xj}}}$$

Where R_{xj} is de dimensionless Budyko Dryness index on pixel x with land use land cover (LULC) j, defined as the ratio of potential evapotranspiration to precipitation (Budyko and Miller, 1974) and w_x (Eq. 5.3) is a modified dimensionless ratio of plant accessible water storage to expected precipitation during the year. As defined by Zhang et al. (2001) is a non-physical parameter to characterize the natural climatic-soil properties.

$$w_x = Z\frac{AWC_x}{P_X} \quad \text{Eq. (5.3)}$$

Where AWC_x is the volumetric (mm) plant available water content and Z is the Zhang coefficient which has already been explained before.

Finally, the Budyko dryness index was defined with Eq. 5.4, where R_{xj} values which are greater than one denote pixels that are potentially arid (Budyko and Miller, 1974), as follows:

$$R_{xj} = \frac{k_{xj} \cdot ETo_x}{P_x} \quad \text{Eq. (5.4)}$$

Where ETo_x is the reference evapotranspiration from pixel x and k_{xj} is the plant (vegetation) evapotranspiration coefficient associated with the land use land cover j on pixel x. ETox represents an index climatic demand while k_{xj} is largely determined by x's vegetative characteristics (Allen-Wardell et al., 1998).

Afterwards, the water supply for drinking purposes is calculated as the difference between water yield and water consumptive use in the watershed.

5.2.2.3Model validation

The wide-spread use of numerical models for the study of ecological and environmental phenomena requires some means of assessing model correctness (Power, 1993). Validation is an attempt to increase the degree of confidence that the events inferred by a model occur under the assumed conditions.

The validation of InVEST application was performed by comparing InVEST water yield results with Sacramento model runoff values which were validated with observed values by Catalan Water Agency (ACA). Sacramento is a conceptual model which generates the flow as surface runoff from waterproof and porous basin areas, together with the subsurface flow and low levels of base flow. The model represents the basin as a set of storages with specific capacities which retains water temporarily and then gradually yield, as their content decreases because of percolation, evapotranspiration and lateral drain (Figueroa Leiva, 2008). As it is shown in Table 5.4, the required input data for Sacramento model is precipitation, temperature and evaporation in order to calculate the basin flow. As such, the model analyse the hydrological behaviour of the basin, through the determination of different percentages of water layers like snow retention, evaporation, surface flow or groundwater flow. InVEST requires input data of climatic and regional parameters of the land and generates a single water yield which includes surface, subsurface and groundwater flow.

Catalan Water Agency (ACA) provided average values of surface and groundwater flow for twelve different sub-watersheds evenly distributed in the Francolí River basin for a base period from 1970-2000. To validate InVEST performance, both model values were compared through the calculation of Nash-Sutcliffe model efficiency index (Nash and Sutcliffe, 1970).

5.3 Results and discussion

5.3.1 Water yield

InVEST tool calculates water yield as the difference between precipitation and the actual evapotranspiration (AET). The actual water yield volume for Francolí River basin is 47.77 hm^3yr^{-1}, but as it is shown in the Fig. 5.3, each sub-watershed contributes in different proportion as a consequence of the variation of the parameters like precipitation and AET, through the watershed. The highest water yield contribution comes from the western part of the watershed with the course of Brugent River which flows through the Prades Mountains. These mountains, which are situated at the Coastal Mountains chain, have high annual rainfall and low average annual evapotranspiration causing a total water yield of 1,150 $m^3ha^{-1}yr^{-1}$. On the other hand, the lowest water yield values, which are around 300 $m^3ha^{-1}yr^{-1}$, belongs to the northern sub-watersheds.

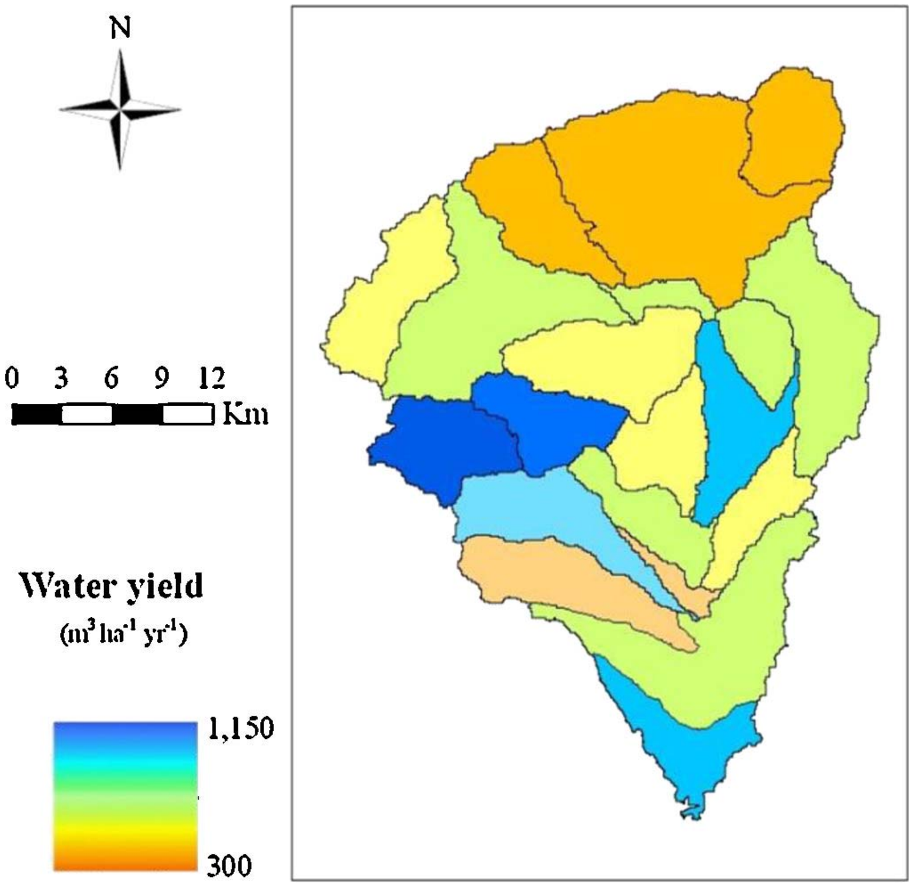


Fig. 5.3. Actual water yield in Francolí river basin.

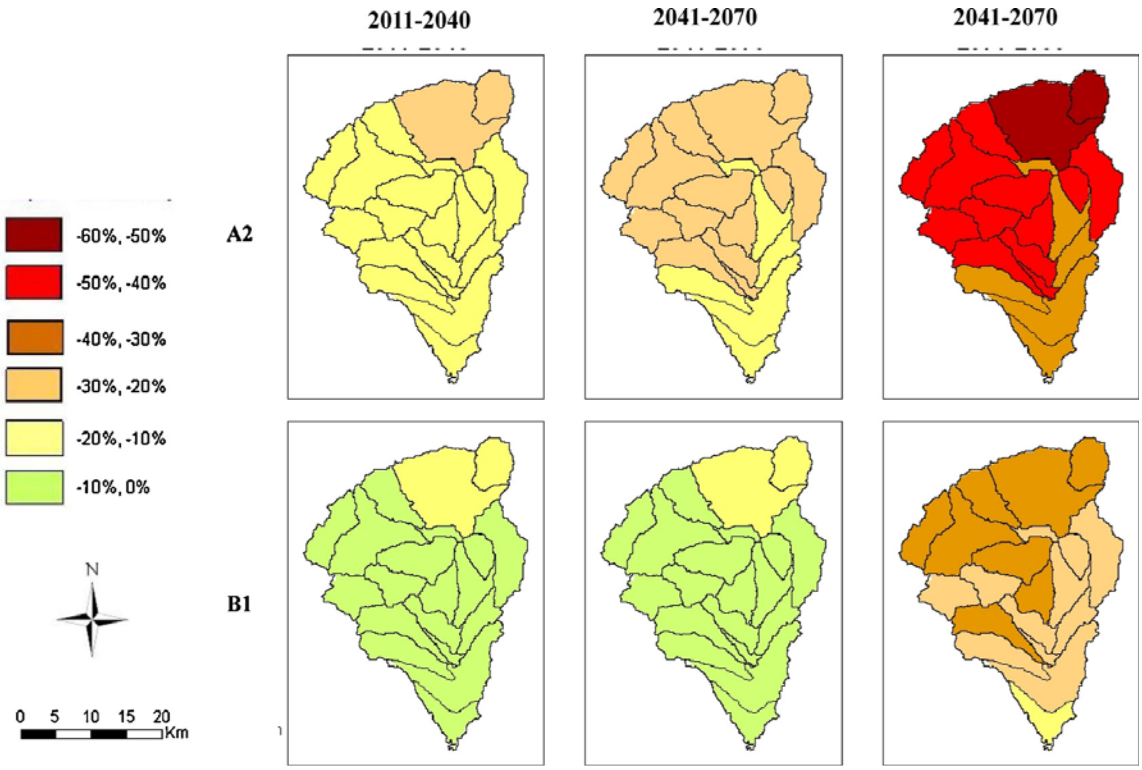


Fig. 5.4. Percentage of reduction of the actual water yield

This area is confluence of two low flow tributaries of Francoli River, called as Anguera and Vallverd River, and both are under water stress situation. This part of the watershed is characterized for having low annual rainfall as well as high average annual evapotranspiration. Tarragona sub-watershed, located at the southernmost region of the Francolí River basin, has a water yield volume of 800 $m^3ha^{-1}yr^{-1}$. Although the low annual rainfall and the high average annual evapotranspiration, this area has this high water yield volume as a result of the groundwater that flows through the watershed recharging the aquifer of this sub-watershed.

Climate change impact on water yield varies from watershed to watershed in Francolí River basin. The Fig. 5.4 shows the expected percentages of reduction of the actual water yield volume considering two different regionalized IPCC scenarios (A2 and B1) for the time spans 2011-2040, 2041-2070 and 2071-2100.

The scenario A2 expects the highest impacts with an average reduction from 21% to 44% (Table 5.5) in terms of water yield for the whole watershed. However, each sub-watershed has a different percentage of decrease as a result of regional differences of the land showing reductions from above 0% to 60%. As it is shown in the Fig. 5.3, for all time spans more impact is observed in the northern part, less impact in the southern area, and medium-high impact in the western part. Water yield from northern part will decrease a total of 30% for the time spans 2011-2040 and 2041-2070, and up to 60% for the time span 2071-2100. Western sub-watersheds expect reductions of 20%, 30% and 50% for the time spans 2011-2040, 2041-2070 and 2071-2100 respectively. Southern part will be the less impacted area in Francolí watershed. Total reductions of 20% for the time spans 2011-2040, 2041-2070 and 30% for the time span 2071-2100 are expected.

Considering B1 scenario, the expected impacts are lower than scenario A2, with an expected average reduction from 11.5% to 33% in terms of water yield for the whole watershed. The projected reduction for each sub-watershed will be the same for the time spans 2011-2040 and 2041-2070, with a total decrease of 20% in the northern area, and 10% for the rest of the watershed in comparison with the base scenario. For the time span 2071-2100, highest impacts on water yield are expected at the northern, north-western and central area with a reduction of 40%, whereas western and southern part will decrease up to 30%.

Each region of Francolí river basin undergoes different percentage of reductions as a consequence of the regional differences of the land. Both selected scenarios agree to show the most impacted area is at the northern sub-watersheds, followed by western, central and southern ones as a consequence of the difference in the land characteristics. Northern sub-watersheds match up with the lowest water yield part; this poor area in terms of water yield will be the most affected part of Francolí watershed. Two rapidly drying low flow related tributaries in this part, Anguera and Vallverd, are causing water stress situation in this area. Western sub-watersheds, region which belongs to Francolí River source and Francolí tributary Brugent River, are expected to be highly impacted. Any change in precipitation patterns in these sub-watersheds will highly affect the whole watershed, threatening the water availability for different uses. However, the Tarragona sub-watershed has a medium-high water yield volume being mainly groundwater, and medium-low reduction impact in this region is expected. This area is considered as the most preserved region at Francolí watershed in terms of water yield, and similar finding are observed in another study carried out by Bangash et al. (2012).

5.3.2 Water supply for drinking purposes

Reductions in water yield impacts negatively the basin capacity of providing water for drinking purposes. This value is defined by water scarcity analysis as the difference between the yield and consumptive uses of water by each land use. This actual value in Francolí watershed is 41.86 hm^3yr^{-1}. However, as it is shown in Fig. 5.5, these values vary at sub-watershed scale from 250 $m^3ha^{-1}yr^{-1}$ in Anguera and Vallverd sub-watersheds to 1,100 $m^3ha^{-1}yr^{-1}$ in Prades and Brugent River sub-watersheds. Water supply for drinking purposes is slightly lower than the actual water yield as a result of the water demand defined by each land use, but it is important to note that sub-watersheds of urban areas and irrigated crop land undergo higher decreases in availability of water for drinking purposes.

Table 5.5
Comparison between base and future scenarios (6 scenarios) of rainfall, actual evapotranspiration (AET), total water yield and drinking water provision in Francolí river basin**.**

Time span	**Scenario**	**Rainfall**	**Rainfall reductio**	**Actual evapotranspirati**	**AET reductio**	**Water yield**	**Water yield**	**Drinking water supply**	**Drinking water**
		$\text{mm} \cdot \text{yr}^{-1}$	%	$\text{mm} \cdot \text{yr}^{-1}$	%	$\text{hm}^3 \cdot \text{yr}^{-1}$	%	$\text{hm}^3 \cdot \text{yr}^{-1}$	%
1971-2000	Base	565.42	-	416.67	-	47.77	-	41.86	-
2011-2040	A2	528.66	6.5	404.59	2.9	37.81	21	31.90	24
2041-2070	A2	535.45	5.3	416.92	-0.06	36.09	24.5	30.18	28
2071-2100	A2	484.56	14.3	396.29	4.89	26.81	44	20.90	50
2011-2040	B1	555.80	1.7	418.7	-0.49	41.83	12.5	34.92	14
2041-2070	B1	548.09	3.06	427.06	-2.49	42.20	11.5	36.29	13
2071-2100	B1	511.7	9.5	406.85	2.36	31.86	33	25.95	38

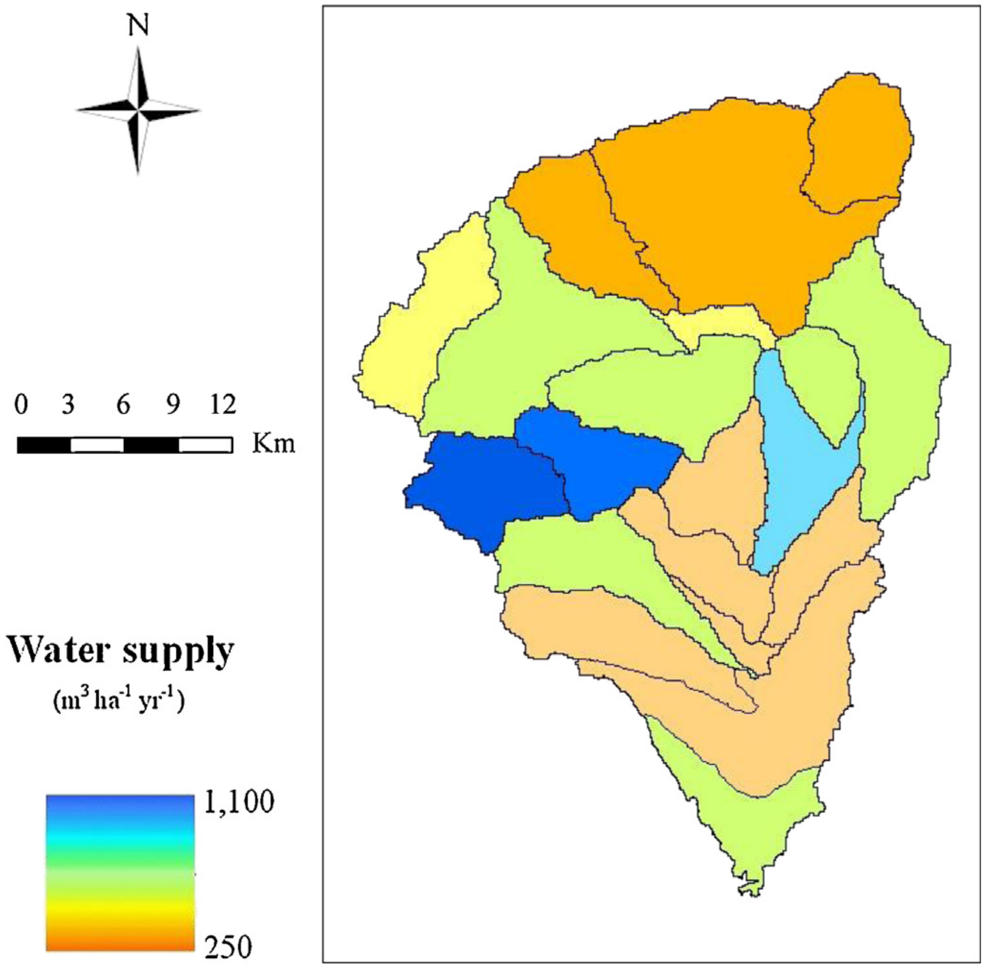


Fig. 5.5. Actual water available for drinking purposes in Francolí river basin

Climate change will also impact on Francolí River basin by affecting negatively the basin capacity of providing drinking water. As it is shown in Table 5.5, as well as in the impact assessment maps shown in Fig. 5.6, the total annual volume of water for drinking use is expected to reduce in all the selected scenarios but with greater percentages in comparison to the water yield assessment.

For the A2 scenario, reductions from 24% to 50% at watershed scale are expected as mentioned in Table 5.5. At sub-watershed scale, the same impacts are expected for the time span 2011-2040 and 2041-2070, showing reductions up to 40% at three sub-watersheds located at the northern area and one of the central part, as well as 30% of reduction for the others sub-watersheds. However, the time span 2071-2100 expects higher impacts with reductions up to 60% at the northern and central sub-watersheds, as well as reductions up to 50% for the rest of the watershed. In general, each sub-watershed of urban and irrigated crops lands undergo higher decreases. The main reason is because more water is needed as a result of the high water demand by domestic and agricultural uses. These results (Fig. 5.6) show these higher expected negative impacts in the projected future scenarios in comparison with expected impacts on water yield (Fig. 5.4). In this study, water demand has been considered constant for future scenarios because this study aims to assess only the impact related to climatic factors.

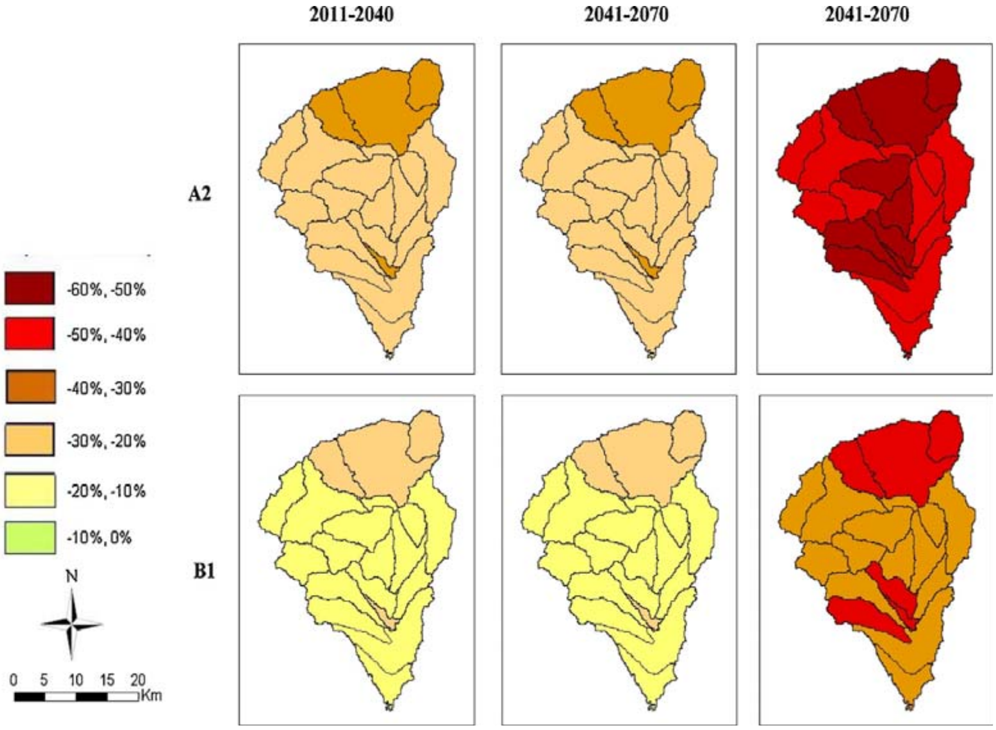


Fig. 5.6. Percentage of reduction of the actual water available for drinking purposes.

In the B1 scenario assessment, reductions from 13% to 38% of the actual water supply (41.86 $hm^3\ yr^{-1}$) are expected. As well as for the A2 scenario, the same degree of reduction at sub-watershed scale is expected for the time span 2011-2040 and 2041-2070 but they are slightly lower. There is a group of three northern sub-watersheds and one sub-watershed located at the central part which expects decrease up to 30% whereas the rest of the watershed expects 20% of reduction. The last time span, 2071-2100, expects impacts up to 50% of reduction at the northern sub-watersheds and three sub-watersheds located at the central area, while the rest of the watershed expects decrease up to 40%.

Following the same pattern as in water yield assessment, northern and western sub-watersheds are the most impacted area, and the time span 2071-2100 is the worst expected scenario in terms of availability of water for drinking purposes. However, in A2 scenario as well as in B1 scenario, there are some sub-watersheds which become more impacted in water supply for drinking purpose assessment than in water yield as a consequence of the different land use and land cover and its related water demand. For each time span, the northern area, which is always the most impacted region, is formed by three sub-watersheds instead of two in water yield case. The reason is because in this added sub-watershed there is urban area which belongs to Espluga de Francolí which causes a high water demand depending on Francolí supply, and consequently has a higher impact. Regarding to these higher impacts, central sub-watersheds also become more impacted than in water yield case because of its irrigated crop land and urban areas such as La Selva, Vallmoll and Valls.

InVEST works on annual basis and the climate trend of Mediterranean river basins is to undergo an average precipitation decrease and an average temperature increase over the years. However, it is important to note that climate change expects to concentrate the rainfall in shorter periods of the year, and suffer more extended droughts. Hence, it could be interesting to consider the impact of extreme wet and dry years on the delivery of hydrological ecosystem services. As it has been studied by Terrado et al. (2014), for the Llobregat watershed in the same Mediterranean region, the basin capacity of providing drinking water is likely to experience reductions up to 80% in dry years and to be increased up to 160% at least in wet years. In a similar way for Francolí river basin during a dry season, it is assumed that water supply for drinking purposes will be reduced up to 8.37 hm^3 while during a wet season an increase of 108.84 hm^3 is expected.

5.3.3 Validation results

As it has been explained in the methodology part, after plotting the regression line resulting from InVEST and Sacramento values, the validation was measured through the calculation of coefficient of Nash-Sutcliffe model efficiency index (Nash and Sutcliffe, 1970) in order to decide if linear adjustment is enough or if it is necessary to apply alternative models using eq. 5.5. The obtained index result was 0.92 (Fig. 5.7), value that shows the proper application of InVEST in the low flow Francolí River.

$$\frac{R^2 = 1 - \sum_{t=1}^{N}[Q_{obs,t} - Q_{sim,t}]^2}{\sum_{t=1}^{N}[Q_{obs,t} - \bar{Q}_{obs}]^2} \qquad \text{(Eq 5.5)}$$

Where Q_{obs} is the observed flow, Q_{sim} is the simulated flow, and Q¯$_{\text{obs}}$ is the average observed flow.

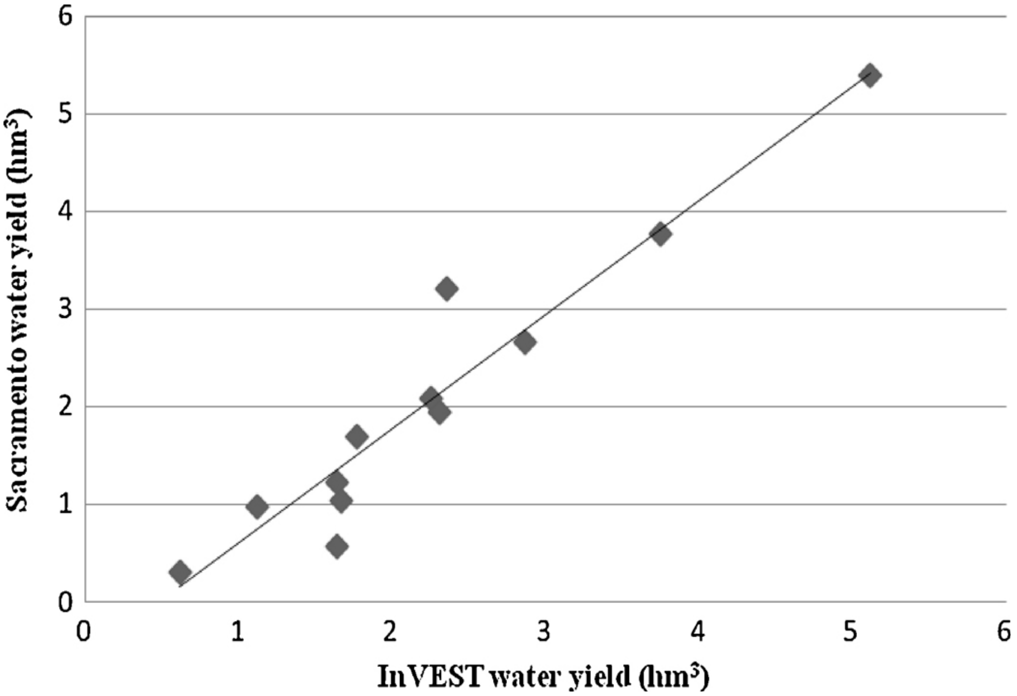


Fig. 5.7. InVEST versus Sacramento annual water yield at different sub-watersheds distributed along Francolí river basin.

5.4Conclusions

This paper illustrates the application of the ecosystem services model InVEST in Francolí River basin (NE Spain) to assess how changes in temperature and precipitation patterns related to climate change impact on water provisioning ecosystem services. Future attention will be focused on predict the water quality of the river flow considering these expected impacts. InVEST has been largely applied to map ecosystem services in a high flow rivers (Bai et al., 2012; Sánchez-Canales et al., 2012). After model validation, InVEST seems to be a valuable tool to map ecosystem services in a river with a low flow hydrological regime.

The evaluation of climate change impacts on the selected hydrological ecosystem services shows that water provisioning is highly sensitive to climate change in Francolí River basin. In terms of water provisioning, the analysis shows that areas responsible for least and most of the provision of water service will be the most impacted, causing desertification in the low flow areas and at the same time reductions in the source areas are expected which cause flow decreases at the whole watershed. In terms of water supply for drinking purposes, in addition to these mentioned impacted areas, the central region will be also highly impacted because of the water consumption demand by urban areas and irrigated crops land showing the importance of the land use in this second analysis. A reduction in stream flow might lead to increase in peak concentrations of certain chemical compounds (Belgiorno et al., 2013). Therefore, the highest impacted regions are likely to undergo the highest decreases in water flow quality.

Because of all these expected impacts mentioned above, urgent measures should be taken to mitigate the already existing water stress in the basin. Decision making and policy aimed at achieving sustainability goals can be improved with accurate and defendable methods for quantifying ecosystem services (Kareiva et al., 2011). The approach is designed to enhance on-site benefits, contribute to state-wide policy initiatives, and also inform the mitigation of negative impacts where necessary (Goldstein et al., 2012) through the introduction of River Basin Management Plan to assure the provision of water in the basin.

Part IV
DECISION SUPPORT TOOLS

Chapter 6

Decision support system for water supply in a low-flow Mediterranean river watershed

Rubab Fatima Bangash, Marta Schuhmacher

ABSTRACT

Adaptation to alternate water resources in Mediterranean region has become a practice of heightened interest, as a consequence of water scarcity caused by climate and global change. This practice has benefits to ensure water availability for different water users and environmentally efficient, however users may have to pay higher costs, depending on the type of alternate water resource. Stakeholder participation is incorporated in planning and in the process of making decision support system (DSS) for the development of suitable water resources management strategies at the river basin level. This study applies the Analytical Hierarchy Process (AHP) method to identify stakeholders' preferences regarding alternate water resources for different water users, to include it in the design of water resources management plans at the river basin level. The study is focused in Mediterranean low flow Francolí river basin (NE Spain) considering climate change scenarios. AHP used in this study is five step approach: 1) indicators prioritization and normalization, 2) assign preferences to the indicators in each group, 3) assign preferences to the groups, 4) weighting prioritization and 5) sustainability ranking. This analysis revealed that use of reclaimed water (RW) for industry has a better sustainability ranking as compared to other two scenarios of agriculture and domestic water supply. Moreover, to aggregate different scenarios regarding cost effectiveness, a simple spreadsheet is elaborated. The application of this approach gives insights to decision makers, guiding them to more confident decisions at the river basin level and higher commitments of stakeholders to the proposed objectives.

Keywords: Stakeholders, Decision support system, AHP, Alternate water resources

6.1Introduction

Demand for the world's increasingly scarce water supply is rising rapidly. Even as demand for water by all users grows, groundwater is being depleted, other water ecosystems are becoming polluted and degraded, and developing new sources of water is getting more costly (Mark et al., 2002). Changes in water supply conditions for economic activities and environmental uses are likely to be affected by hydrological changes, including altered frequency of extreme events, such as droughts (Varies et al., 2004; Jacobs et al., 2000). Lack of additional water resources for increasing urban demand poses new challenges to water resource managers. Such a rise in demand coupled with increased awareness on environmental issues and adverse effects of climate change are becoming more complex for decision makers.

In the arid and semi-arid regions like Mediterranean, where current fresh water reserves are already at risk due to scarcity, the use of recycled wastewater is an alternative water resource for agricultural, industrial and urban non-potable purposes. Water reuse is likely to develop rapidly along the Mediterranean coast and, more especially, on Mediterranean islands (Lazarova, 2001). However, for the proper water distribution from different resources, formal methods need to be developed to help policy makers for water resource sustainability.

Stakeholder's workshop facilitates the decision process among the multiple relevant actors in order to arrive at one or several shared objectives. However, these objectives become conflicting in certain situations. An appropriate way to have a balance between these conflicting objectives is to incorporate the stakeholder preferences in the decisions. There is a growing shift towards the methodical inclusion of stakeholder preferences in practical decision-making situations related to sustainable water resources management (e.g., Ghanbarpour et al., 2005; Larson and Denise, 2008; Water Resources Strategy Committee, 2002). De Marchi et al. (2012) also provided a survey of formal methods available to help decision makers improve their decisions.

Decision support system (DSS) has also proven to be a useful and widely applied tool in environment and urban water management (Aulinas et al., 2011; Gualtieri, 2011). Various strategies have been developed over the years in response to growing water demand, such as alternate water resources and inter-basin transfer water to deficient areas. However, such interventions require much time and money. It is important to examine not only technical solutions but also socio-economic issues, as well as the environmental impacts. A study carried out for the European Commission in December 2008 assessing the risks and impacts of four alternative water supply options (desalination, wastewater re-use, groundwater recharge, and rainwater harvesting) revealed that it is not possible to provide an EU-wide set of best available mitigation options. The potential problems and mitigation options differ between locations and technologies – meaning that mitigation measures have to be designed to deal with local conditions. Alternative water supply options may be more expensive than conventional options, but subsidies to compensate for price differences should serve only to help users in the transition towards more sustainable use of water.

To determine the weights of water resource indicators, the evaluators are often confronted with a lack of data. Therefore, the pair-wise comparison technique based on the Analytic Hierarchy Process (AHP) is used in order to derive relative weights of each indicator practically (Krajnc and Glavic, 2005). AHP is a decision making tool intended to help people set priorities and make decision when both qualitative and quantitative aspects of a decision need to be considered (Cziner, 2006). It reduces complex decisions to a series of one-to-one comparisons, then synthesizing the results. The Analytic Hierarchy Process (Ong et al., 2001), is chosen for the analysis of stakeholder's workshop output. The methodology is incorporated into DSS for the prioritization and normalization of each indicator of environmental, economical and technical groups for different water user sectors of the Francolí River Basin (NE Spain). This study also incorporates cost analysis for proposed alternate water resources.

6.2Study area

Francolí river (NE of Spain) is about 109 km long low flow Mediterranean stream, with a drainage basin of 853 km^2 and covering the needs of a population of approximately 190,000 inhabitants (IDESCAT, 2011).

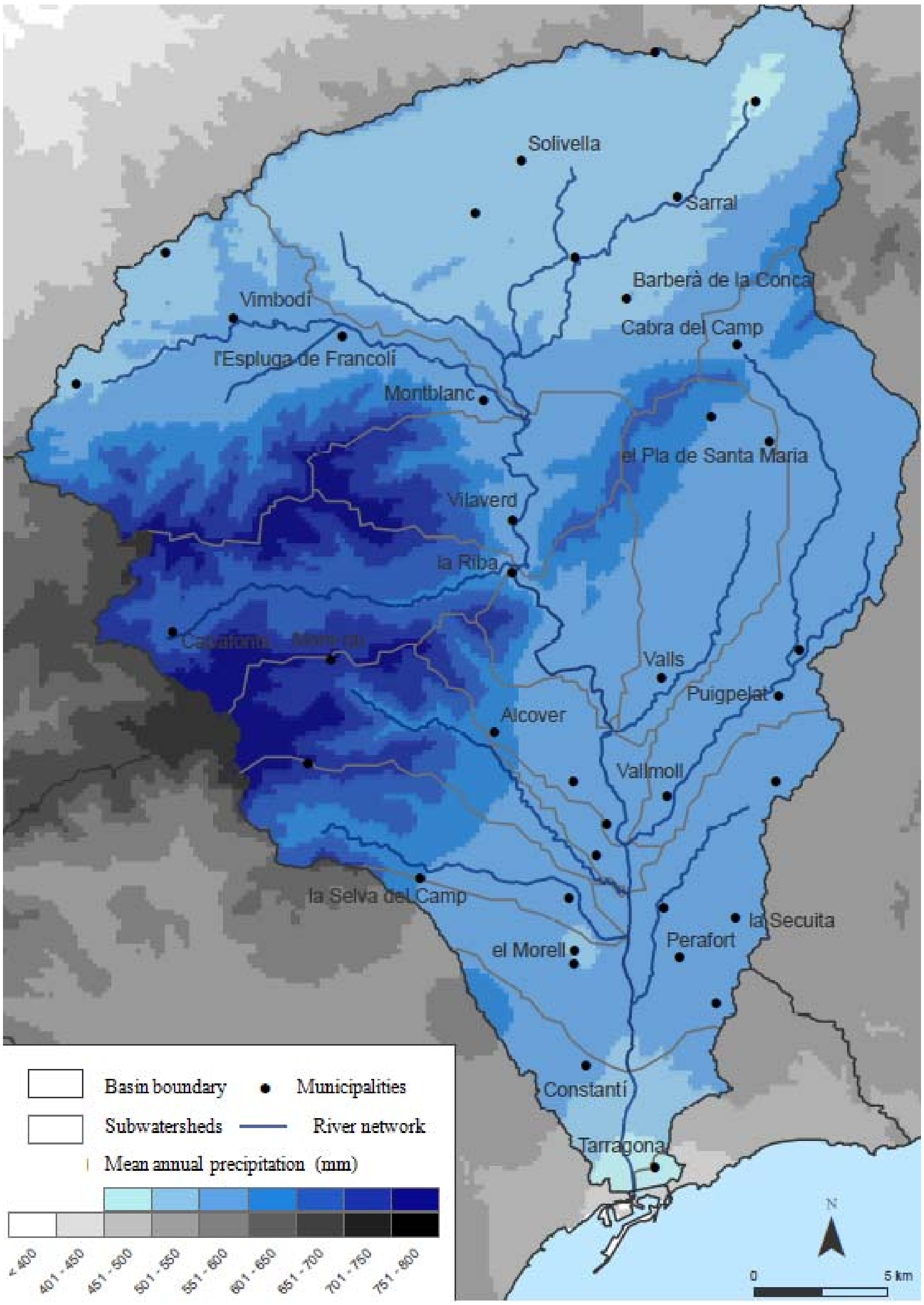


Fig 6.1. Francolí river basin

The Francolí River Basin has been under considerable pressure for water availability and water quality over the past few decades due to the population growth, climate change and increased water demand in industrial cities like Montblanc, La Riba and Tarragona. The river is the main collector of industrial and municipal treated wastewater and provides irrigation water to the seasonal farms.

The main river starts from Espluga del Francolí (Conca de Barbera), flowing through coastal Prades mountains range and finally leads to the west of the port of Tarragona (Figure. 6.1). Climate change effect is already observed in this area, as the precipitation is scarce, evapotranspiration is intense and there is marked seasonality of the rainfall, often causing drought periods during summer. This phenomenon is causing water stress and results in reduced watershed runoff and lower availability of water in the river basin.

Water management along the Francolí River and its tributaries is complex because it is a Mediterranean environment and there is a limited supply of water to satisfy the demand of all sectors and environmental needs (Bangash et al., 2012). City of Tarragona, located at the mouth of Francolí River, was solely dependent on its own water resources before 1988. Sea water intrusion in the groundwater aquifers compelled the municipalities to meet the water demand by inter-basin transfer from neighbouring river basins (Ebro River and Gaia River). Moreover, Tarragona is second largest industrial area of Catalonia and most of the industries in Francolí River basin are located close to Tarragona including a large petrochemical industry. Many other small industries are situated in the upper part of the river basin. The agricultural demand varies all along the river basin depending on the crop type and cultivated area.

6.3Development of decision support tool

6.3.1 Problem definition

Effective water allocation is an activity that manages the use of the scarce water resources. Water scarcity is expected to rise in the Mediterranean, greatly increasing the need for efficient water allocation systems. Efficiency requires that the water consumers and stakeholders are involved in decision making, and prioritise water users for alternate water resources, since only this provides a true incentive to avoid conflicts. Each of these groups of stakeholders is concerned about different issues regarding alternate water resources. For example, farmers wish to increase their production without compromising the quality of their product and cost to be paid for each cubic meter of water consumed. This poses major social, economic and environmental challenges. These will only be addressed when stakeholders are involved in decision making and effective ways can be found to allocate water between competing needs within a catchment, while sufficient water is retained to ensure the continuation of ecosystem functions.

6.3.2 Output of stakeholders' workshop

The scenario analysis is first complemented on by a stakeholder analysis. Actors involved in the workshop conducted for water supply situation in Francolí River basin—i.e. stakeholders as well as decision makers and their executive authorities—are asked to provide information of water quantity consumed by each sector. Two annual workshops were organized for a group of experts from government management, industrial distribution management, agricultural sector representatives, experts on river ecology and academic researchers. An activity designed to describe stakeholder's perception and plans of the increasing future water demand and adaptation to water scarcity situation expected to increase as climate change impact on different sectors. The outcome of scaling (Low-Medium-High-Very High) climate change impact on different sectors during workshop is described in Table 6.1 considering cost as well as future water demand.

In Table 6.1, the future water demand for industry is marked as very high by the representatives of industry as the increasing trend has been observed over the last couple of decades. However, adaptation to alternate water resources to meet the future water demand increases the cost of water but ensure reliability of water supply. It is assumed from this approach that the industry is not prone to severe water stress induced by climate change as they are planning to increase water reuse source by 80% in the future.

Table 6.1
Stakeholder's perception of climate change impact on different sectors

Sector	Climate change	Cost	Future demand
Industrial	Low	High	Very high
Agriculture	High	High/Very high	High/Very high
Domestic	Low	Medium	Medium

Moreover, a general form of a hierarchical model using AHP of a decision problem is developed with the help of stakeholders. Analytic Hierarchy Process (AHP) is a procedure that enables the decision makers to decompose and describe elements of a problem hierarchically. The problem is divided into smaller parts and the procedure guides decision makers through a series of pair wise comparison judgments to give the relative dominance (importance or preferences) of the elements in the hierarchy. The judgments (even if given verbally) are expressed in numbers. A decision maker does not need to give any numerical judgment; instead, a relative verbal appreciation is sufficient. The different dominances determined at every level are finally synthesized into an overall rating of the indicators, which have to be prioritised.

AHP has been used successfully by companies and governments in diverse areas for making choices, setting priorities, allocating resources, measuring performance, resolving conflict, and also when dealing with quality management, public policy, health care, strategic planning, etc (Hongre, 2006).

AHP is a multi-criteria decision analysis (MCDA) methodology that allows objective as well as subjective factors to be considered in a decision making process. Basically, AHP helps to determine which variable has the highest priority and should be acted upon to influence the decision outcome. AHP relies on the supposition that humans are capable of making relative judgments than absolute judgments; and it is based on the key principles of decomposition, comparative judgement, and synthesis of priorities (Dey, 2003).

6.3.3 Analytic Hierarchy Process (AHP) model development

The hierarchy starts with broad overall objective (or goal) at the highest level. The lower levels list the criteria and respective sub-criteria used to choose among alternatives. At the lowest level are the alternatives to be evaluated. Each element of the hierarchy in a given level is necessarily connected to at least one element of the next higher level, which is considered as a criterion according to which we compare the elements of the next level below. Graphically it is displayed with a hierarchy tree where the goal is at the top (first level), then successively from top to bottom, levels of factors (criteria, sub criteria), then alternatives as shown in Figure 6.2.

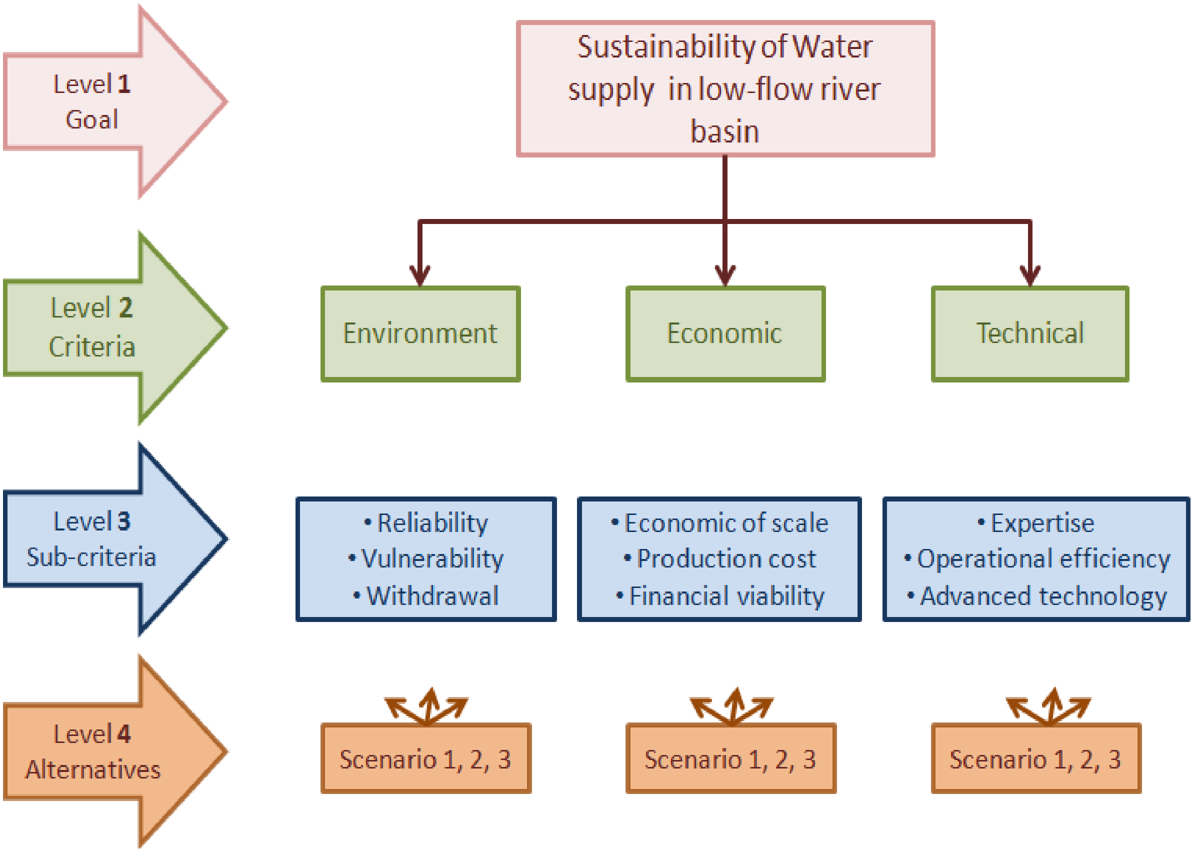


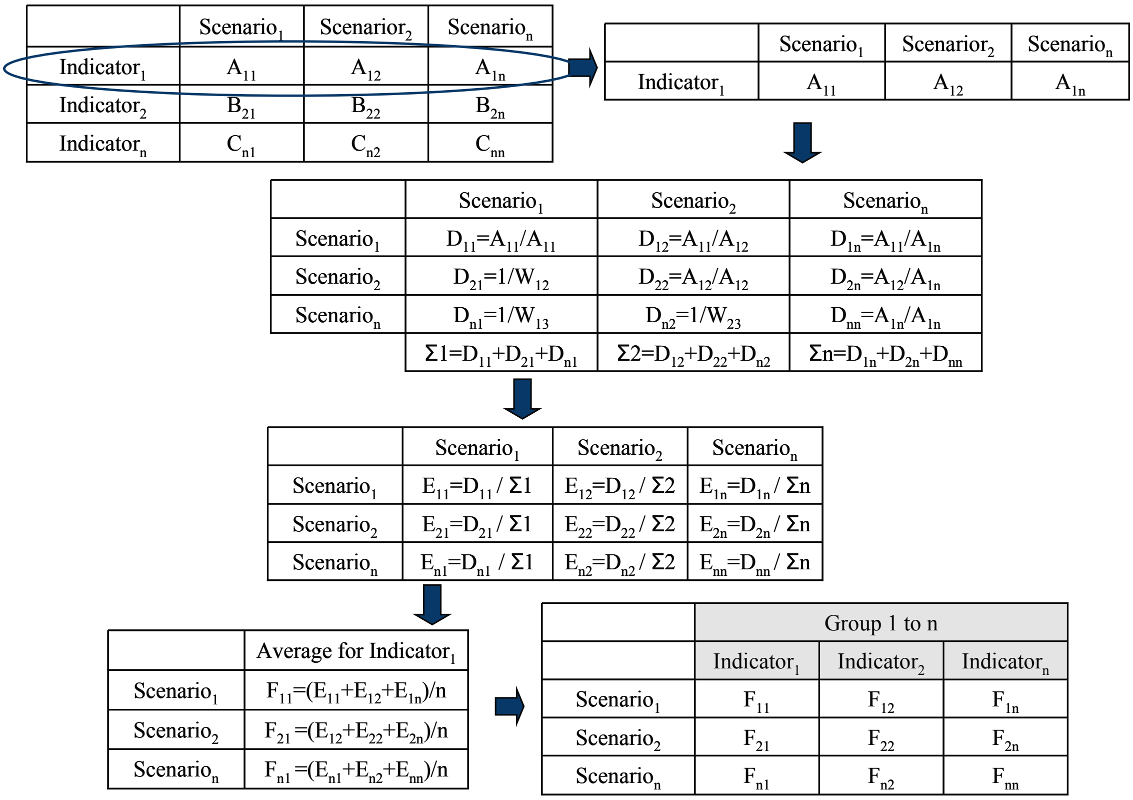
Fig 6.2. The top down rating process through the hierarchy

Indicators Aggregation

The integration part of the methodology consist of five steps: 1) indicators prioritization and normalization, to prioritize and normalize the indicators results, 2) weighting per indicators, to assign preferences to the indicators in each group, 3) weighting per groups, to assign preferences to the groups, 4) weighting prioritization, to obtain the global weighting value of each indicator, 5) sustainability ranking, to obtain the overall sustainability index.

1) Indicators prioritization and normalization

A pair wise comparison per indicator is done by using nine-point scale mentioned in Table 6.2 (Saaty, 2000). This procedure has to be done for each indicator to obtain the prioritization and normalization per indicators. Figure 6.3 shows the pair wise comparison per indicators procedure.



	$Scenario_1$	$Scenarior_2$	$Scenario_n$
$Indicator_1$	A_{11}	A_{12}	A_{1n}
$Indicator_2$	B_{21}	B_{22}	B_{2n}
$Indicator_n$	C_{n1}	C_{n2}	C_{nn}

	$Scenario_1$	$Scenarior_2$	$Scenario_n$
$Indicator_1$	A_{11}	A_{12}	A_{1n}

	$Scenario_1$	$Scenario_2$	$Scenario_n$
$Scenario_1$	$D_{11}=A_{11}/A_{11}$	$D_{12}=A_{11}/A_{12}$	$D_{1n}=A_{11}/A_{1n}$
$Scenario_2$	$D_{21}=1/W_{12}$	$D_{22}=A_{12}/A_{12}$	$D_{2n}=A_{12}/A_{1n}$
$Scenario_n$	$D_{n1}=1/W_{13}$	$D_{n2}=1/W_{23}$	$D_{nn}=A_{1n}/A_{1n}$
	$\Sigma1=D_{11}+D_{21}+D_{n1}$	$\Sigma2=D_{12}+D_{22}+D_{n2}$	$\Sigma n=D_{1n}+D_{2n}+D_{nn}$

	$Scenario_1$	$Scenario_2$	$Scenario_n$
$Scenario_1$	$E_{11}=D_{11}/\Sigma1$	$E_{12}=D_{12}/\Sigma2$	$E_{1n}=D_{1n}/\Sigma n$
$Scenario_2$	$E_{21}=D_{21}/\Sigma1$	$E_{22}=D_{22}/\Sigma2$	$E_{2n}=D_{2n}/\Sigma n$
$Scenario_n$	$E_{n1}=D_{n1}/\Sigma1$	$E_{n2}=D_{n2}/\Sigma2$	$E_{nn}=D_{nn}/\Sigma n$

	Average for $Indicator_1$
$Scenario_1$	$F_{11}=(E_{11}+E_{12}+E_{1n})/n$
$Scenario_2$	$F_{21}=(E_{12}+E_{22}+E_{2n})/n$
$Scenario_n$	$F_{n1}=(E_{n1}+E_{n2}+E_{nn})/n$

	Group 1 to n		
	$Indicator_1$	$Indicator_2$	$Indicator_n$
$Scenario_1$	F_{11}	F_{12}	F_{1n}
$Scenario_2$	F_{21}	F_{22}	F_{2n}
$Scenario_n$	F_{n1}	F_{n2}	F_{nn}

Fig. 6.3. Indicators prioritization and normalization scheme

By using nine-point scale mentioned in Table 6.2, indicators prioritization and normalization is carried out and convert individual comparative judgements into a ratio scale of measurements. However, these values selected from the Saaty scale represent linguistic and somewhat fuzzy and do not represent strict algebraic ratios.

Table 6.2.
Scale for pair wise comparison

Equal	1
Equal to moderate	2
Moderate	3
Moderate to strong	4
Strong	5
Strong to very strong	6
Very strong	7
Very strong to extreme	8
Extreme	9

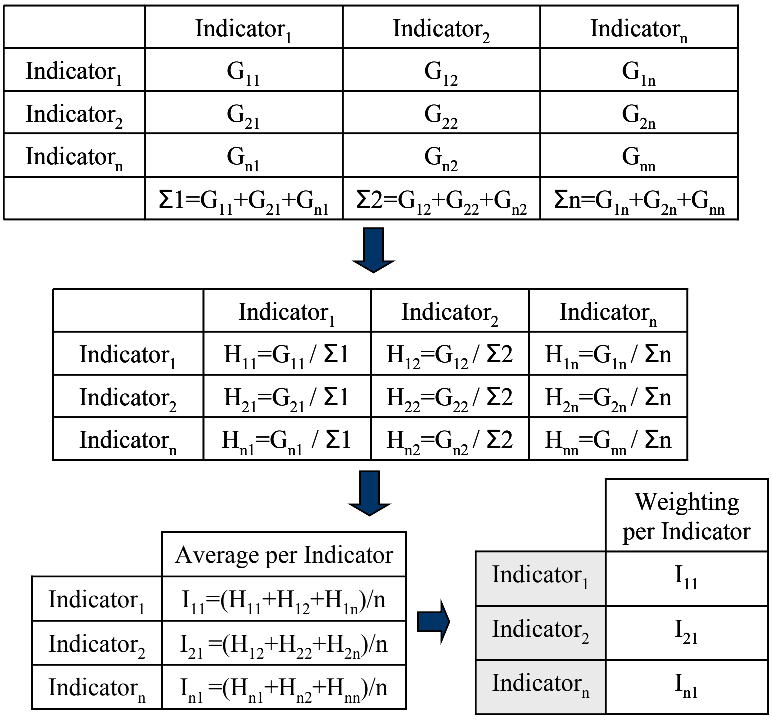
(Source: Saaty, 2000)

Usually, the main scale defined by the odd numbers is used. Intermediate values (even numbers) are used to compromise between two judgments.

Set of objectives are determined for all major concerns on sustainable water supply. The experience of stakeholders also aided in identification of sustainability factors/objectives for evaluation of the goal. A total of 9 Performance Indicators (PIs), that summarize the performance of the sustainability of water supply objectives are identified and listed as sub-criteria in Fig. 6.2.

2) Weighting per indicators

The indicators selected must be weighted. The assignment of the weighting factors is based on expert judge and bibliography. The weighting procedure is based on a pair wise comparison between indicators per groups (environment, economic, technical). This means that the indicators of each group must be compared with the other indicators of the same group. It is assumed that indicators with different units are not comparable. Figure 6.3 shows the weighting per indicators procedure. It is important to note that the weights can vary according to the case study.



	Indicator$_1$	Indicator$_2$	Indicator$_n$
Indicator$_1$	G_{11}	G_{12}	G_{1n}
Indicator$_2$	G_{21}	G_{22}	G_{2n}
Indicator$_n$	G_{n1}	G_{n2}	G_{nn}
	$\Sigma1=G_{11}+G_{21}+G_{n1}$	$\Sigma2=G_{12}+G_{22}+G_{n2}$	$\Sigma n=G_{1n}+G_{2n}+G_{nn}$

	Indicator$_1$	Indicator$_2$	Indicator$_n$
Indicator$_1$	$H_{11}=G_{11}/\Sigma1$	$H_{12}=G_{12}/\Sigma2$	$H_{1n}=G_{1n}/\Sigma n$
Indicator$_2$	$H_{21}=G_{21}/\Sigma1$	$H_{22}=G_{22}/\Sigma2$	$H_{2n}=G_{2n}/\Sigma n$
Indicator$_n$	$H_{n1}=G_{n1}/\Sigma1$	$H_{n2}=G_{n2}/\Sigma2$	$H_{nn}=G_{nn}/\Sigma n$

	Average per Indicator
Indicator$_1$	$I_{11}=(H_{11}+H_{12}+H_{1n})/n$
Indicator$_2$	$I_{21}=(H_{12}+H_{22}+H_{2n})/n$
Indicator$_n$	$I_{n1}=(H_{n1}+H_{n2}+H_{nn})/n$

	Weighting per Indicator
Indicator$_1$	I_{11}
Indicator$_2$	I_{21}
Indicator$_n$	I_{n1}

Fig. 6.4. Weighting per indicator scheme

Three alternatives scenarios for the AHP assessment are identified by stakeholders as shown in Table 6.3.

Table 6.3.
Description of scenarios

Scenario 1
Increased quantity of inter-basin water supply for domestic purpose
Reclaimed water for public water supply (excluding domestic)

Scenario 2
Storage reservoir for agricultural water use
Artificial aquifer recharge for agricultural water use

Scenario 3
Reclaimed water for industrial water use
Less dependancy on inter-basin transfer for industrial water use

3) Weighting per groups

The groups analyzed (environment, economic, technical) are weighted and the weighting factors are based on expert judgement and bibliography. The weighting procedure is based on a pair wise comparison between groups. It is assumed that different groups are not comparable. Fig. 6.5 shows the weighting per group procedure. It is important to note that the weights can vary according to the case study.

	Group$_1$	Group$_2$	Group$_n$
Group$_1$	J_{11}	J_{12}	J_{1n}
Group$_2$	J_{21}	J_{22}	J_{2n}
Group$_n$	J_{n1}	J_{n2}	J_{nn}
	$\Sigma 1=J_{11}+J_{21}+J_{n1}$	$\Sigma 2=J_{12}+J_{22}+J_{n2}$	$\Sigma n=J_{1n}+J_{2n}+J_{nn}$

	Group$_1$	Group$_2$	Group$_n$
Group$_1$	$K_{11}=J_{11}/\Sigma 1$	$K_{12}=J_{12}/\Sigma 2$	$K_{1n}=J_{1n}/\Sigma n$
Group$_2$	$K_{21}=J_{21}/\Sigma 1$	$K_{22}=J_{22}/\Sigma 2$	$K_{2n}=J_{2n}/\Sigma n$
Group$_n$	$K_{n1}=J_{n1}/\Sigma 1$	$K_{n2}=J_{n2}/\Sigma 2$	$K_{nn}=J_{nn}/\Sigma n$

	Average per Group
Group$_1$	$L_{11}=(K_{11}+K_{12}+K_{1n})/n$
Group$_2$	$L_{21}=(K_{12}+K_{22}+K_{2n})/n$
Group$_n$	$L_{n1}=(K_{n1}+K_{n2}+K_{nn})/n$

	Weighting per Group
Group$_1$	L_{11}
Group$_2$	L_{21}
Group$_n$	L_{n1}

Fig. 6.5. Weighting per group scheme

4) Weighting prioritization

The weight per indicator is multiplied by the weight per group to obtain the global weighting prioritization. Fig. shows the weighting prioritization scheme.

		Weighting Prioritization
Group$_1$	Indicator$_1$	$M_{11}=I_{11}*L_{11}$
	Indicator$_2$	$M_{21}=I_{21}*L_{11}$
	Indicator$_n$	$M_{n1}=I_{n1}*L_{11}$
Group$_n$	...	...

Fig. 6.6. Weighting prioritization scheme

5) Sustainability Ranking

The sustainability ranking of the indicators is obtained by multiplying the indicators prioritization by the weighting prioritization of each scenario by following the sustainability ranking scheme shown in Fig. 6.7.

	Group$_1$			…	Sustainability Ranking
	Indicator$_1$	Indicator$_2$	Indicator$_n$	…	
Scenario$_1$	$N_{11}= F_{11} * M_{11}$	$N_{12}= F_{12} * M_{21}$	$N_{1n}= F_{1n} * M_{n1}$	…	$R_{11}=N_{11}+N_{12}+N_{1n}$
Scenario$_2$	$N_{21}= F_{21} * M_{11}$	$N_{22}= F_{22} * M_{21}$	$N_{2n}= F_{2n} * M_{n1}$	…	$R_{21}=N_{21}+N_{22}+N_{2n}$
Scenario$_n$	$N_{n1}= F_{n1} * M_{11}$	$N_{n2}= F_{n2} * M_{21}$	$N_{nn}= F_{nn} * M_{n1}$	…	$R_{n1}=N_{n1}+N_{n2}+N_{nn}$

	Sustainability Ranking
Scenario$_1$	R_{11}
Scenario$_2$	R_{21}
Scenario$_n$	R_{n1}

Fig. 6.7. Sustainability ranking scheme

6.3.4 Alternate water resource analysis

It is required to assess cost os available water resources to enforce the sustainable water allocation process. Initially, sufficient water was available to meet the needs of all water users within a Francolí River basin without jeopardising ecosystems. As a consequence, little management was required for distribution. However, increases in agricultural and industrial activity coupled with population growth lead to ever increasing water withdrawals from different sources. Some augmentation of supply through engineering approaches is usually possible to meet increased water demand, for example, construction of increased storage capacity reservoirs and inter-basin transfer. However, arid and semi-arid areas where climate change effect is also predominant and causing water scarcity, multi-disciplinary management is required to avoid unsustainable water use as mentioned in Figure 6.8.

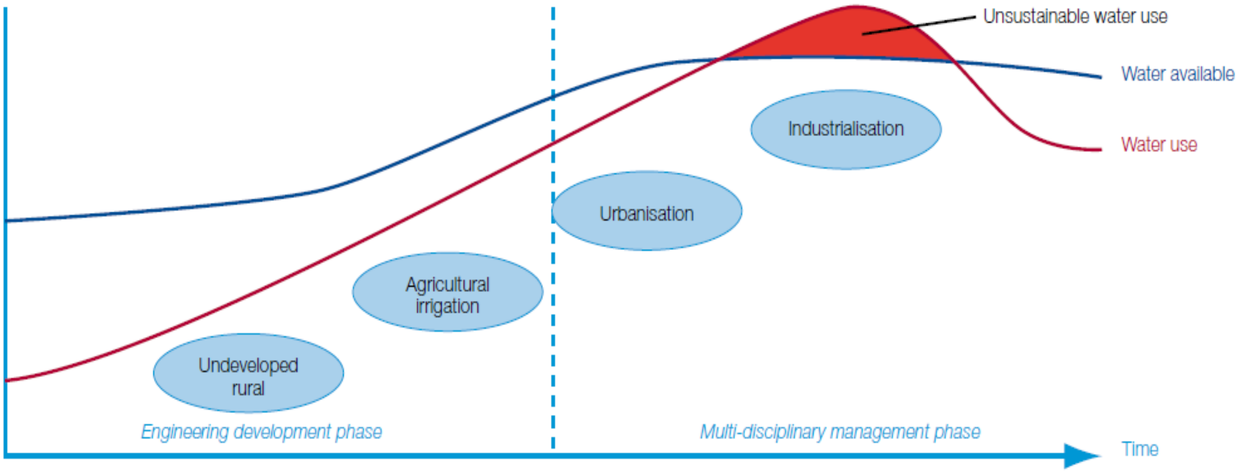


Fig: 6.8. Changing risk and management requirements with use

Source: (WWF, 2007)

A simple spreadsheet is used for cost analysis of alternate water resource for each and every proposed scenarios developed with the help of stakeholder's contribution.

6.4 Results and discussion

6.4.1 Indicators aggregation

The main advantage of the AHP methodology is that it allows comparison between different processes and disciplines. Three different scenarios mentioned in Table 6.4 are analysed by using AHP. A sustainability index is obtained by aggregating the results from the environmental, economic and technical impact assessments by following five different stages, as explained in the methodology.

For the first stage, indicators prioritization and normalization, the indicators to be compared were selected:

- Environmental assessment: Reliability, vulnerability and withdrawal
- Economic assessment: Economic of scale, securing of investment resources and financial viability
- Technical assessment: Expertise, operational efficiency and advanced technology

Table 6.4 to Table 6.11 presents the indicators aggregation results of each step mentioned in the methodology to obtain sustainability index of three scenarios.

Table 6.4.

Indicators results

Area	Indicator	Units	Scenario 1	Scenario 2	Scenario 3
Environmental	Reliability	Quality	5	6	3
	Vulnerability	Quality	3	4	3
	Withdrawal	Quality	2	5	4
Economical	Economic of scale	Quality	4	5	3
	Securing of investment resources	Quality	5	5	4
	Financial viability	Quality	6	3	3
Technical	Expertise	Quality	5	4	3
	Operational efficiency	Quality	6	5	3
	Advanced Technology	Quality	5	6	5

A pair wise comparison per indicator is done for all three scenarios by using nine-point scale mentioned in Table 6.2. For example, reliability is given 5, 6 and 3 for scenario 1, scenario 2 and scenario 3 respectively. Scale 5 represents strong importance and judgment strongly favours one. While scale 6 for scenario 2 shows intermediate values between adjacent scale values (5-strong and 7-very strong) where compromise is needed between two judgements for agricultural water use. However, scale 3 for scenario 3 represents weak importance and experience and judgment slightly favor one activity over another activity. All the indicators are given specific scale by stakeholder during a workshop.

Table 6.5.

Indicators prioritization

	Environmental			Economical			Technical		
	Reliability	Vulnerability	Withdrawal	Economic of scale	Securing of investment resources	Financial viability	Expertise	Operational efficiency	Advanced Technology
Scenario 1	0.36	0.30	0.18	0.33	0.36	0.50	0.42	0.43	0.31
Scenario 2	0.43	0.40	0.45	0.42	0.36	0.25	0.33	0.36	0.38
Scenario 3	0.21	0.30	0.36	0.25	0.29	0.25	0.25	0.21	0.31
	1.00	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**

A comparison between indicators not together but per groups was made. In the environmental area (Table 6.6), the same weigh was given to vulnerability and withdrawal as they are interlinked with each other.

Table 6.6. Environmental Weighting Calculation

	Environmental		
	Reliability	Vulnerability	Withdrawal
Reliability	1	2	2
Vulnerability	0.5	1	1
Withdrawal	0.5	1	1
	2	4	4

	Environmental			
	Reliability	Vulnerability	Withdrawal	Mean
Reliability	0.5	0.5	0.5	0.5
Vulnerability	0.25	0.25	0.25	0.25
Withdrawal	0.25	0.25	0.25	0.25
	1	1	1	1

In the economic aspects (Table 6.7), the same weigh was given to all indicators, since they were considered equally important.

Table 6.7. Economical Weighting Calculation

	Economical		
	Economic of scale	Securing of investment resources	Financial viability
Economic of scale	1	1	1
Securing of investment resources	1	1	1
Financial viability	1	1	1
	3	3	3

	Economical			
	Economic of scale	Securing of investment resources	Financial viability	Mean
Economic of scale	0.33	0.33	0.33	0.33
Securing of investment resources	0.33	0.33	0.33	0.33
Financial viability	0.33	0.33	0.33	0.33
	1.00	1.00	1.00	1.00

For the technical area as shown in Table 6.8, the same weigh was given to all indicators, since they are all considered equally important.

Table 6.8. Technical Weighting Calculation

	Technical		
	Expertise	Operational efficiency	Advanced Technology
Expertise	1	1	1
Operational efficiency	1	1	1
Advanced Technology	1	1	1
	3	3	3

	Technical			
	Expertise	Operational efficiency	Advanced Technology	Mean
Expertise	0.33	0.33	0.33	0.33
Operational efficiency	0.33	0.33	0.33	0.33
Advanced Technology	0.33	0.33	0.33	0.33
	1.00	1.00	1.00	1.00

Then, a comparison between the groups of indicators was made (Table 6.9). The same weigh was assigned to each group and 0.33 was given to each one. It is important to note that the weighs can vary according to the case study.

Table 6.9. Indicators Group Weighting Calculation

	Environmental	Economical	Technical
Environmental	1	1	1
Economical	1	1	1
Technical	1	1	1
	3	3	3

	Environmental	Economical	Technical	Mean
Environmental	0.33	0.33	0.33	0.33
Economical	0.33	0.33	0.33	0.33
Technical	0.33	0.33	0.33	0.33
	1	1	1	1

After the calculations, the indicators prioritization was obtained. The weigh per groups was multiplied by the weigh per indicator to obtain the indicators prioritization (Table 6.10).

Table 6.10:
Indicators weighting factors

Area	**Indicator**	**Weight/group**	**Weight/indicator**	**Indicators Prioritization**
Environmental	Reliability	0.33	0.5	0.17
	Vulnerability	0.33	0.25	0.08
	Withdrawal	0.33	0.25	0.08
Economical	Economic of scale	0.33	0.33	0.11
	Securing of investment resources	0.33	0.33	0.11
	Financial viability	0.33	0.33	0.11
Technical	Expertise	0.33	0.33	0.11
	Operational efficiency	0.33	0.33	0.11
	Advanced Technology	0.33	0.33	0.11

Sustainability ranking of the indicators was obtained by multiplying the indicators prioritization by the weighting factors of each scenario as shown in Table 6.11.

Table 6.11:
Sustainability ranking

	Environmental			**Economical**			**Technical**			
	Reliability	Vulnerability	Withdrawal	Economic of scale	Securing of investment	Financial viability	Expertise	Operational efficiency	Advanced Technology	**Sustainability Ranking**
Scenario 1	0.061	0.024	0.01	0.036	0.0396	0.055	0.0462	0.0473	0.0341	**0.36**
Scenario 2	0.073	0.032	0.036	0.0462	0.0396	0.0275	0.0363	0.0396	0.0418	**0.37**
Scenario 3	0.036	0.024	0.029	0.0275	0.0319	0.0275	0.0275	0.0231	0.0341	**0.26**

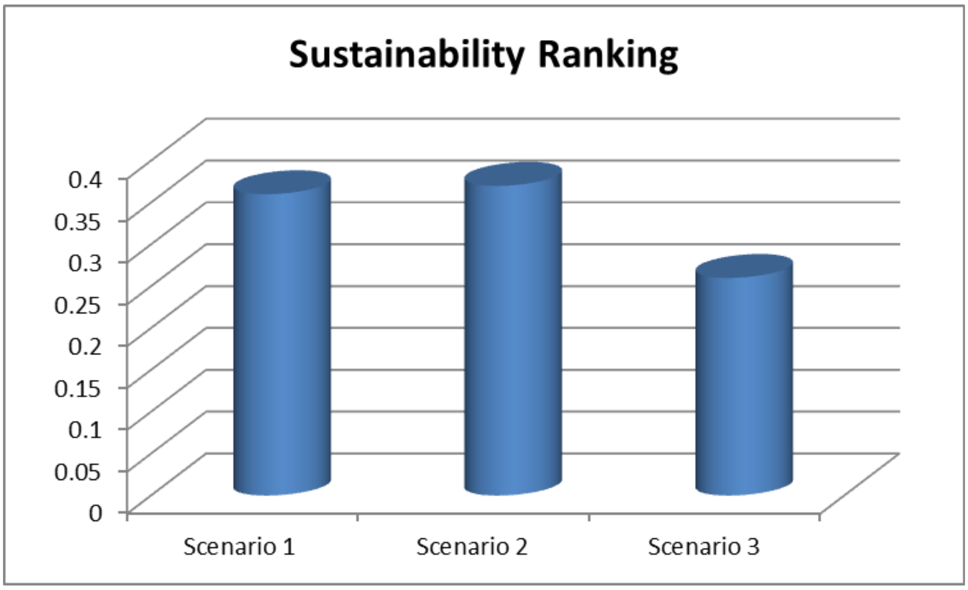


Fig 6.9. Sustainability ranking of three scenarios

From the sustainability ranking, shown in Figure 6.9, it can be concluded that the interventions to increase water supply for agriculture has better sustainability ranking than other two scenarios. Agriculture is the only sector that is solely dependant on water avaialable in Francolí River basin, whereas industry and domestic sectors are already taking water through inter-basin water supply. When we rank descending order to proposed scenarios, the alternatives are ordered as Scenario 2 > Scenario 1 > Scenario 3. Hence, the combination of storage resservoir and artificial aquifer recharge for agricultural use is selected as the best among other alternatives. In addition, use of alternate water resources for domestic purpose is found to be as the second best alternative.

The comparison of scenario 1 and scenario 2 shows that there is not a significant difference in their sustainability ranking and present almost similar results, slightly better for scenario 2. However, it might have a different impact if the type of intervention is changed that costs more than the inter-basin transfer or reclaimed water use. However, these priorities of interventions were set with the collaboration of stakeholders and compared with other scenarios.

All the competing sectors cannot be satisfied simultaneously and need to be prioritised after conducting an analysis based on survey or a stakeholder's workshop. The prioritisation of interventions for a specific sector depends on the local and regional situation. In case of Francolí River basin, which is the second largest industrial area of Catalonia, the stakeholder emphasis is observed to use more percentage of reclaimed water for industrial consumption although carrying the lowest sustainability ranking as mentioned in Figure 6.9. Industry is one of the major water consumers in Francolí River basin and reducing water intake from inter-basin results in higher impact environmentally as well as economically. Approximately 70% to 80% of increase in the use of reclaimed water for industry is mentioned in the stakeholders' workshop.

6.4.2 Cost analysis of alternative water resources

The climate change impact on water yield in Francolí River basin is simulated in Marquès et al. (2013), described under chapter 5. These values of reduction in water yield are used as threshold to develop scenarios for future water supply as mentioned in the Table 6.12. For example in case of scenario 1a, the water supply from primary source is kept below 67.47 hm^3/year where the total demand is increased to 113.85 hm^3/year for all three sectors during the next 30 years. Primary source can provide 66.90 hm^3/year and the remaining water demand is met by alternate water resource (reclaimed water) for industry and agricultural uses.

The water from primary source is already less than the total demand for the current situation as mentioned in Table 6.12. This deficiency is fulfilled by using reclaimed water for industrial sector. Following the trend of Catalonia water demand for future, total water demand for Francolí River basin is also assumed to be increased by 21% for future scenarios.

In several Mediterranean countries, reclaimed water is the significant low-cost alternative resource for irrigation and industry. The scenario 1a is estimated as a lowest cost option as shown in the Figure 6.12. This scenario is a combination of primary source and reclaimed water for irrigation and industrial use as an alternate water resource.

Table 6.12 Alternate water resource scenarios and respective costs

Scenarios	Action id	Sector	Demand (hm^3/yr)	Primary source (hm^3/yr)	RW (%)	AAR (%)	SR (%)	DS (%)	Cost per sector (€/yr)	Total Cost (€/yr)
Current	0	I	31.35	85.40					16,631,325	47,438,655
		D	45.6						23,964,577	
		A	17.1						6,842,753	
Scenario A2 with 21 % reduction in water yield (Threshold yield < 67.47 hm^3/yr)*										
1	a	I	37.95	66.90	50				17,363,200	45,641,830
		D	55.2						23,964,577	
		A	20.7		50				4,314,053	
1	b	I	37.95	61.28	70			10	17,934,665	47,437,945
		D	55.2				5		23,193,149	
		A	20.7		10				6,310,132	
1	c	I	37.95	61.97	70				17,679,370	46,549,294
		D	55.2		5		5		22,709,614	
		A	20.7			10			6,160,310	
Scenario B1 with 12 % reduction in water yield (Threshold yield < 75.15 hm^3/yr)*										
2	a	I	37.95	73.32	30				17,049,958	46,322,698
		D	55.2		5		5		22,709,614	
		A	20.7		5				6,563,127	
2	b	I	37.95	66.01	70				17,685,225	47,823,009
		D	55.2			2			23,574,657	
		A	20.7		5				6,563,127	
2	c	I	37.95	67.60	60			10	17,759,015	48,566,345
		D	55.2						23,964,577	
		A	20.7						6,842,753	

*Marquès et al., 2013
** Reclaimed Water (RW), Artificial Aquifer Recharge (AAR), Storage Reservoir (SR), Desalination (DS)
*** Industrial (I), Domestic (D), Agricultural (A)

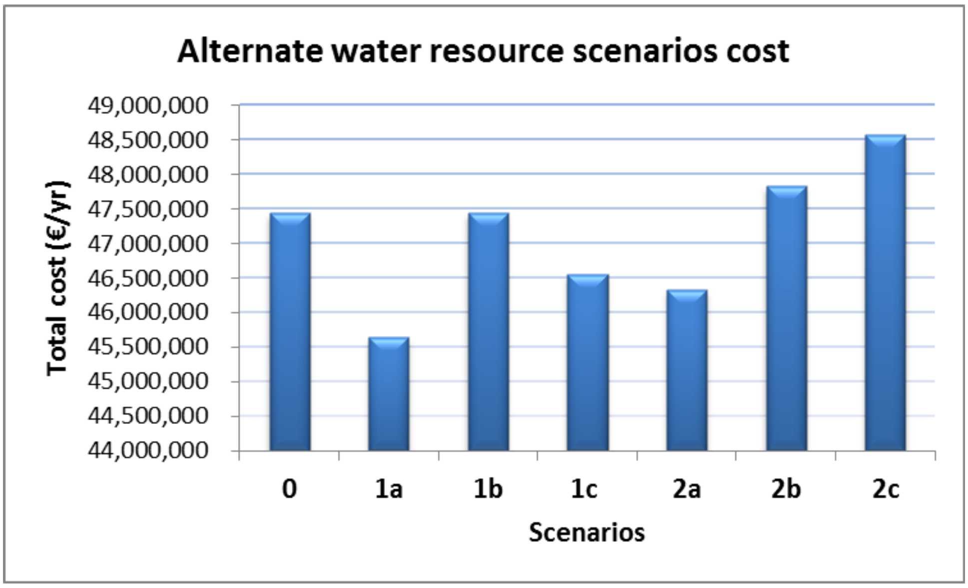


Fig. 6.10. Estimated cost of alternate water resource scenarios

Use of alternate water resource has a vital part to play in environmental sustainability. For example, recycled water has been proven to be a reliable alternative resource and wastewater reuse prevents degradation of receiving water bodies and the environment.

Ranking a finite set of alternatives evaluated on multiple conflicting criteria is not a trivial task. The ELECTRE-III model is proposed as future task to solve the ranking problematic using a hierarchical structure of criteria and also consider global change scenarios.

6.5 Conclusions

This study showed the applicability of the AHP method to integrate stakeholder groups' preferences in the decision making process of alternate water resource management. The use of the AHP as a participatory tool can improve both stakeholders' participation and at the same time it increases transparency in decision making process based on the sustainability ranking. More effective avenues of communication for interventions could be designed that suit different stakeholders' groups and knowing beforehand the stakeholder priorities.

All the competing sectors cannot be satisfied simultaneously. Prioritisation of the sectors is a necessity after conducting a survey or a stakeholder's workshop. For the selection of combination of alternate water resources, environmental, economic and technical aspects are considered. The scenario that has best sustainability ranking includes storage reservoirs and artificial aquifer recharge (AAR). This is followed by use of reclaimed water and inter-basin water supply for domestic purpose with slightly lower sustainability ranking. Moreover, industrial activities are more dominant in Francolí River basin and stakeholders also showed promising increased use of reclaimed water in the future. These results can be used by the relevant authorities to customize their interventions.

An imbalance between water resources and demand make comprehensive alternate water resource analysis a necessity. The water reuse option is often not only the most cost-effective solution, but it has the advantage of valorising the social and environmental value of water, enhancing a region's resource availability and minimising wastewater outflow with additional environmental benefits (Lazarova et al., 2001). Moreover, greater conservation, more efficient water systems, desalination and artificial aquifer recharge (especially for industrial agriculture) will also help to meet increased water without deteriorating environment.

Finally, it is recommended that this research be extended to cover the rest of the possible global change scenarios, in order to understand to what extent alternate water resources are environmentally safe and cost effective. That certainly would make the intervention plans more transparent and increase the acceptability of the final decision by all parties, thus avoiding potential future conflicts.

Part V

GENERAL CONCLUSIONS AND FUTURE RESEARCH

Chapter 7

Conclusions

7. Conclusions

It is important to understand the implications of climate change for sustainable water resource management. In this research study, the possible impacts of climate change in the Mediterranean regions of NE Spain for hydrology and hydrological ecosystem services were holistically explored in its regional context given that a changing climate and rising water demand are the only pressures on the regions.

Climate change have already affected some elements of hydrological ecosystem services (e.g. effects of floods and droughts on water balance) and that some are vulnerable to climate change (e.g. water provisioning; sediment retention) in the Mediterranean river basins. Together these effects determine the need of a correct approach for water allocation system and the appropriate alternate water resources at a catchment level due to water scarcity. Some of the evidence for recent changes in hydrological ecosystem impacts presented in this study is inline with what could be expected from climate change. To this end, this represents a worthy avenue for further research.

7.1 Overall conclusions

Analysis is carried out for the water resource allocation to different sectors by developing a data scarce hydrological simulation model for a low flow Mediterranean river basin. This section was mainly focused to know the applicability of the hydrological simulation model for a low flow river analysis, and concluded with the following observations:

-Abstraction of groundwater increases during dry periods in low flow river basins.

-Unallocated and wet period excessive water should be stored for the dry period.

-MIKE BASIN is an efficient tool for low flow and data scarce hydrological simulation.

Adverse climatic conditions are expected to occur more frequently in the future with the onset of global warming, which will bring reduced precipitation in addition to higher temperatures. To maintain and improve the essential functions of our hydrological ecosystems and provide water for all essential uses even under aggravated climatic conditions, we need to manage them well and introduce a water saving culture in the Mediterranean river basin and achieve a drought resilient society.

The role of alternative water supply options will grow in the future due to reduction of water availability as a negative consequence of climate change, requiring particular attention to be paid to their implementation and the continuous improvement of knowledge in the field. Moreover, water reuse is inevitable in regions with temperate climate in order to protect sensitive areas, recreational activities and water intensive economic sectors, and to cope with water crises caused by repeated droughts.

7.2 Specific conclusions

7.2.1 Water allocation assessment in a low flow Mediterranean river

In order to analyze the water allocation simulation in a low flow river, a model was developed that was integrated with rainfall-runoff model. Pre-existing modelling approaches that allow the development of a basin-scale simulation model were used given the data scarcity constraints. Criterion for the model selection includes catchment scale models that have been calibrated and validated and sensitive to the relevant input variables and that output impact indicators.

-The NAM rainfall-runoff model for River Francolí was developed with several parameters specified for each representative sub-catchment. The main input data required are precipitation, evapotranspiration and NAM parameters. The NAM model was prepared with the input of surface root zone and groundwater parameters. Initial values of overland flow, interflow, base flow and groundwater are also specified for each of the MIKE BASIN sub-catchment that required rainfall-runoff modelling. The type of model selected for simulation is NAM RR, 2-Layer GW, which considers both shallow as well as deep aquifers. The NAM model was successfully calibrated against measured river flow statistics with the correlation coefficient obtained was 0.75.

-A basin-scale hydrological simulation model using MIKE BASIN integrated with ArcGIS was developed for a low flow river basin analysis. It helps in establishing the best management approaches for the efficient use and allocation of water resources to different sectors and the model showed its efficacy in analysing a low flow river basin. The model was applied in the low-flow Francolí River Basin located in NE Spain. The missing input data was regenerated from neighboring sub-catchment statistics. The trend of simulated flow hydrographs and observed hydrographs at river nodes was found similar.

NAM rainfall-runoff model (inside MIKE BASIN) is found helpful tool to calculate runoff of each and every sub-catchment. Based on the results, possibilities of new storage schemes or artificial aquifer recharge should be considered to store the excess wet season water and increase dry season reliability. The analysis shows that there is inadequate water availability to satisfy even domestic and industrial uses in the lower part of the Francolí River. It also indicated that the wet season has increased water availability as compared to very little or no water availability in dry season. This disparity of water availability compels the municipality to remain dependent on inter-basin water supply. Based on the results, possibilities for alternate water resources or new storage schemes should be considered to store the excess wet season water and increase dry season reliability. The water scarcity caused by climate change is apparent in many Mediterranean river watersheds. In the further studies, it is insight to analyze the emerging interactions of low-flow hydrological simulation results with other water related fields to comply with European Water Framework Directive (WFD) (EC, 2000) to achieve good water status for all waters by implementing River Basin Management Plan.

7.2.2 The importance of climate change effect on hydrological ecosystem services

Climate change will have a large influence on important hydrological ecosystem services in Mediterranean river basins. Vulnerability to climate change differs across European Mediterranean regions and between hydrolgical ecosystem services. While projected climate changes can be negative for one sector, other sectors could benefit.

In this study, a spatially explicit tool, InVEST, is used to model and map a suite of hydrological ecosystem services caused by climate change impacts. Model results can be reported in either biophysical or monetary terms, depending on the needs and the availability of information. The data applied in this study is acquired after a downscaling exercise performed by the Catalan Meteorological Service (2012). The typical resolution of general circulation models (between 100 and 300 km) is unsuitable for an evaluation at the basin scale, especially for Mediterranean regions with a complex orography such as Catalonia, which is influenced by polar and tropical air masses. The data provided for mean daily precipitation and temperature, compares the predictions of these parameters for the beginning (2001–2030), middle (2031–2070) and end (2071–2100) of the 21st century, with a base scenario (1971–2000). Specifically for the climate change scenarios, the raster resolution was 7.5 km × 7.5 km. The IPCC scenarios selected for evaluation of Llobregat basin are A2 and B1 (IPCC, 2000).

-The ecosystem services of water provisioning (hydropower production and drinking water availability), and erosion control (dredging and water quality) are evaluated at the annual scale for the Llobregat basin, with a raster resolution of 200 m × 200 m. The Llobregat basin (NE Spain) drains an area of 4957 km^2, and is characterized as a typical Mediterranean basin, with a highly variable flow as a result of seasonal rainfall differences. The length of the river is 157 km and has three main reservoirs, Sant Ponç (24 hm^3), Llosa de Cavall (80 hm^3), and Baells (115 hm^3). It is one of the richest and most rapidly developing regions in Spain. The basin is heavily populated (more than 3 million inhabitants) and among one of Barcelona's major drinking water resources. The evaluation of climate change impacts on ecosystem services provision shows that water provisioning and erosion control are highly sensitive to climate change in the Llobregat river basin. The results show clear trends over time, with decreases in water yield and the amounts of sediment retained being two orders of magnitude higher than that exported.

-The ecosystem services of water provisioning (water yield and water scarcity) are evaluated at the annual scale for the Francolí river basin, with a raster resolution of 30 m × 30 m. Francolí River in the Mediterranean area of northern Spain is about 85 km in length, and including main tributaries is 109 km, constituting approximately a basin of 855 km^2. The mainstream flows into Mediterranean Sea through coastal mountains, which is a source area for river basins where precipitation is scarce, evapotranspiration is intense and there is marked seasonality of rainfall, often causing drought periods during summer. Regions in Mediterranean basins could suffer evermore frequent regional shortages due to the twin problems of climate change and rising demand. Household water constitutes the most important annual consumptive demand of water resources (88%) followed by industry (11%) and agriculture (1%). In terms of water provisioning, the analysis shows that areas responsible for least and most of the provision of water service will be highly impacted and causing desertification in the low flow areas. At the same time reductions in the source areas are expected which causes flow decreases at the whole watershed. In terms of water supply for drinking purposes, in addition to these mentioned impacted areas, the central region will also be highly impacted due to higher water demand by urban areas and irrigated crops land.

Collectively, the findings emphasize that hydrological ecosystem services are very sensitive to climate change in semi-arid basins where water demand is very high. Services supply and delivery are likely to reduce by significant amounts, indicating that urgent measures must be taken to avoid future water stress in the basin. There is too much at stake, and water is too precious of a resource need to implement policies and adapt to the coming changes. Proactive management of basin should be implemented for adapting to climate change as mitigating measures taken in the present may avoid long-term future consequences.

7.2.3 Analysis of alternate water resources for different water users

To analyse the different combination of alternate water resource for competitive water users, a decision support tool was developed. The Analytic Hierarchy Process (AHP) was used to solve the multi-criteria decision-making problem of alternate water supply to competative users in Francolí river basin. AHP is a procedure for describing elements of a problem hierarchically. The problem is divided into smaller parts and the procedure guides decision makers through a series of pair-wise comparison that gives the relative importance of the elements in the hierarchy.

In those regions where water demand still exceeds the availability of resources, despite having exhausted all possible options to reduce water demand in line with the water hierarchy, alternate water resources for the mitigation of drought effects could be considered.

The different combinations of alternate water resources for different water users are also elaborated by simple spreadsheet analysis for cost effectiveness. Prioritization of intervention action is done through stakeholder's workshops, by keeping in mind criteria of cost, technical and environment. Interventions to increase water availability for agricultural use (storage reservoir and artificial aquifer recharge) are found more economical, with better sustainability ranking and pose less damage to the environment.

7.2.4 Suggestions for further work

The models developed by this study are useful for water resource planners to address water shortage problems such as those experienced during drought periods in the Mediterranean region. Future studies should focus on refining the water supply term to include flow exchanges between watersheds and constraints of environmental flows to water availability for human use.

It is recommended that the modeling community give special attention to developing new and improved methodologies for simulating hydrological ecosystems. Possible actions are: (i) developing and using more detailed local or regional models of ecosystem services that are able to integrate with other models of neighboring regions, (ii) developing integrated model that includes both terrestrial as well as aquatic component (iii) developing nested models that combine the capabilities of regional and global models.

Incorporating traditional and indigenous methods of water reuse and sustainable usage that is applicable to each community and/or region will be needed. But what is most needed is dissemination of research outputs on climate change to reduce future water demand by adapting to new methodologies and thereby put the world on a path toward a more sustainable future.

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