BUILDING RESILIENCE TO CLIMATE CHANGE IMPACTS IN THE IKEL WATERSHED IN THE REPUBLIC OF MOLDOVA: A SYSTEM DYNAMICS APPROACH

by

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to my parents,

Galina and Nicolae

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ABSTRACT

BUILDING RESILIENCE TO CLIMATE CHANGE IMPACTS IN THE IKEL WATERSHED IN THE REPUBLIC OF MOLDOVA: A SYSTEM DYNAMICS APPROACH

Climate change threatens social-ecological systems (SES) across the globe. Developing countries where agriculture is a major income source for both local communities and the national economy are especially affected. In conjunction with their reliance on climatic resources, these countries face the challenge of data scarcity. Assessing and building the resilience of these communities to climate change impacts is equally important and challenging. As the relationship between science, policy, and practice changes, the demand increases on research to engage productively with stakeholders and ensure positive outcomes for all parties. Efforts are increasingly focusing on building the resilience of SES to climate impacts. In this research, I design, build and implement a client-based process under data scarcity conditions in a network governance setting within Republic of Moldova. The process includes analyzing a complex socio-ecological problem to identify policies helpful in meeting development objectives: improving crop yields, preserving groundwater resources and securing habitats for biodiversity conservation. To this end, I first develop a computer simulation model – Ikel CliRes – using a participatory approach that combines several methods, techniques and tools from two related fields: system dynamics and resilience of socio-ecological systems. I then use Ikel CliRes to design policy interventions that increase the desirable resilience of Ikel SES to some climate impacts. Ongoing implementation of several policies discussed with decision-makers is underway pointing to the effectiveness and usefulness of the process. Results should be regarded within the limitations of the model architecture and of the assumptions underlying both the model and the analysis.

ÖZET

MOLDOVA CUMHURİYETİ'NDEKİ İKEL HAVZASINDA İKLİM DEĞİŞİKLİĞİ ETKİLERİNE DAYANIKLILIK YARATMAK: SİSTEM DİNAMİKLERİ YAKLAŞIMI

İklim değişikliği, dünya genelinde sosyal-ekolojik sistemleri (SES) tehdit ediyor. Tarımın hem yerel topluluklar hem de ulusal ekonomi için önemli bir gelir kaynağı olduğu gelişmekte olan ülkeler özellikle etkilenmektedir. İklimsel kaynaklara olan bağımlılıklarıyla bağlantılı olarak, bu ülkeler veri kıtlığı sorunuyla karşı karşıyadır. Bu toplulukların iklim değişikliği etkilerine karşı direncini değerlendirmek ve inşa etmek eşit derecede önemli ve zorludur. Bilim, politika ve uygulama arasındaki ilişki değiştikçe, paydaşlarla verimli bir şekilde etkileşim kurmak ve tüm taraflar için olumlu sonuçlar sağlamak için araştırmaya olan talep artar. SES'in iklim etkilerine karşı dayanıklılığını artırmaya yönelik çabalar giderek artıyor. Bu araştırmada, Moldova Cumhuriyeti'ndeki bir ağ yönetişimi ortamında veri kıtlığı koşulları altında müşteri tabanlı bir süreç tasarlıyor, inşa ediyor ve uyguluyorum. Süreç, bu kalkınma hedeflerine ulaşmada yardımcı olacak politikaları belirlemek için karmaşık bir sosyo-ekolojik sorunun analiz edilmesini içerir: mahsul veriminin arttırılması, yeraltı suyu kaynaklarının korunması ve biyolojik çeşitliliğin korunması için habitatların sağlanması. Bu amaçla, ilk önce iki ilgili alandan çeşitli yöntem, teknik ve araçları birleştiren katılımcı bir yaklaşım kullanarak bir bilgisayar simülasyon modeli – İlkel CliRes – geliştiriyorum: sistem dinamikleri ve sosyo-ekolojik sistemlerin dayanıklılığı. Ardından, İlkel SES'in bazı iklim etkilerine karşı arzu edilen direncini artıran politika müdahalelerini tasarlamak için İlkel CliRes'i kullanıyorum. Karar vericilerle tartışılan çeşitli politikaların devam eden uygulaması, sürecin etkinliğine ve kullanışlılığına işaret etmektedir. Sonuçlar, model mimarisinin ve hem modelin hem de analizin altında yatan varsayımların sınırlamaları içinde değerlendirilmelidir.

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LIST OF ABBREVIATIONS

Abbreviation	Explanation
AMA	"Apele Moldovei" - Moldovan Water Agency
AGMR	Agency for Geology and Mineral Resources
CLD	Causal Loop Diagram
EC	European Commission
ECA	European Commission on Agriculture
ENVSEC	Environment and Security Initiative
ET	Evapotranspiration
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GMB	Group Model Building
HDI	Human Development Index
ICAS	Moldsilva Institute for Forestry Research and Landscaping
Ikel CliRes	Ikel Climate Resilience Model
ILRI	International Livestock Research Institute
IPCC	International Panel on Climate Change
MCA	Millennium Challenge Corporation from the United States, Account Moldova
ME	Ministry of Environment
MEA	Moldovan Environmental Agency
MSL	Mean Sea Level
NBS	National Bureau of Statistics
NEC	National Environmental Centre
NGO	Non-Governmental Organization
OECD	Organization for Economic Co-operation and Development
OSCE	Organization for Security and Co-operation in Europe
PET	Potential Evapotranspiration
RCP	Representative Concentration Pathway
SD	System Dynamics
SEI	Social Ecological Inventory

SES	Social Ecological System
SHS	State Hydrometeorological Service
UN	United Nations
UNDP	United Nations Development Program
UNECE	United Nations Economic Commission for Europe
UNEP	United Nations Environmental Programme
UNFCCC	United Nations Framework Convention on Climate Change
UNU-IAS	United Nations University Institute for the Advanced Study of Sustainability
USLE	Universal Soil Loss Equation
USSR	Union of Soviet Socialist Republics
VCT	Validation Cessation Threshold

1. INTRODUCTION

Possible climate change impacts are well acknowledged and increasing evidence of such impacts is well documented. The global community expects with high confidence that the average global temperature between 2030 and 2052 is likely to be equal or more than 1.5°C above pre-industrial levels if it continues to increase at the current rate (IPCC, 2018). The implications of this change are manifold for the natural and human systems alike. These include but are not limited to changes in the capacity of ecosystems to provide essential services, the loss of some of the ecosystems altogether, species loss and extinction, increase in intensity and frequency of extreme weather events, risks to livelihoods, food security, water supply, health, human security, economic growth and more (IPCC, 2018).

In this context, semi-arid agro-ecosystems are of particular concern, because local, national and in many cases regional food security depends on their productive capacity. Underdeveloped and developing countries where agriculture is a major income source for both local communities and the national economy are especially affected. In cases of crop failure, communities often resort to harvesting other ecosystem services and goods, to sustain their livelihoods. This, in turn, puts additional stress on ecosystem health, which further exacerbates the vulnerability to climate change of the socio-ecological system (SES) as a whole.

IPCC estimates that human activities have caused approximately 1.0°C of global warming above pre-industrial levels. Although relatively scarce, some studies suggest that other, non-human factors might have a significant stake in the warming of the Earth, such as the substantial role that the Sun might have on Earth's climate through its geomagnetic activity (Mufti and Shah, 2011). Nevertheless, while such debate addresses the natural or human causes of climate change, there is no doubt or debate about the need for adaptation to the changing climate. In the face of anticipated risks, adapting our social, ecological and economic systems to climate change has become imperative. As the IPCC (2018, page 5) highlights, besides the “magnitude and rate of warming, geographic location, levels of development and vulnerability”, the climate change risks also depend on “the choices and implementation of adaptation and mitigation option”.

1.1. Resilience to Climate Change Impacts in Developing Countries

Policies are already being developed and implemented across the globe to mitigate and adapt to climate change. Simultaneously, governments develop separate policies for biodiversity preservation, water and other resource management. Often, climate change adaptation policies are not well integrated into multiple sectors, are uncoordinated, too costly to implement, and come into conflict with other shortsighted policies. Among the main reasons is the complexity of relations within the social-ecological systems taking place at different spatial-temporal scales (Thomsen et al., 2012), and the incapability of human institutions to tackle with the complex interactions between ecological, economic and social aspects of the problems (Sterman, 2000; Underdal, 2010). These limitations often lead to maladaptation arising from reductionist approaches (Barnett and O'Neill, 2009; McEvoy and Wilder, 2012). Facing a problem, policymakers and tend to optimize the system for certain isolated purposes considered of interest or of higher priority.

An example to demonstrate this is the case of irrigation as maladaptation: the construction of extensive irrigation systems for agriculture purposes. The aim of such constructions is to compensate for the reduced amount of precipitation in the dry seasons rather than enhancing the resilience of the watershed as a system. Such a narrow approach might easily result in appropriation of the stock of the available water in the entire watershed that would otherwise be useful for other ecosystem and societal needs. Subsequently, a climate change adaptation policy in agricultural sector and a biodiversity conservation policy can thus easily come into conflict with each other rather than complement each other.

Another example of such adaptation measures might be the use of extensive agriculture as a measure to compensate for reduced crop yield. Land is a finite resource in a region, a country, and on the planet in general. New arable land is generated from converting other types of land use, such as meadows, forests or marshlands. Deforestation in the Amazon Forest is a well-known example of such conversion. Natural types of land use play multiple and important roles in ecosystem balance. Their conversion into arable land might solve a short-term problem of food shortage or revenue to corporate and state budget while generating a long-term weakening of the system's ability to withstand climate change impacts.

These examples highlight the risk of seeing climate change adaptation of individual sectors as a definitive solution to the challenges posed by climate change impacts. They also illustrate the need for building the resilience of the system rather than to optimize the system for certain isolated purposes.

Ecological resilience is a relatively new conceptual framework. It makes use of systems thinking to study the dynamics of linked social–ecological systems. In this context, it is defined as the capacity of a system to absorb disruptive changes (e.g., dry spells, prolonged droughts, sudden floods, etc.), but keep the same function, structure and feedbacks (Walker and Salt, 2006). From this perspective, the key to the sustainability of a social-ecological system is not optimizing it for more narrow, isolated purposes, but rather enhancing the resilience of the system as a whole. To do so, it is important to understand which properties of the complex system affect its capacity to avoid or facilitate drastic changes. This understanding of a system's adaptive capacity is done through the resilience assessment process. Based on this assessment, various stakeholders deploy efforts to build the system's resilience. Therefore, a good understanding of the system is an important prerequisite for building its resilience.

A considerable number of recent studies have been conducted to perform resilience assessment of various socio-ecological systems. For example, Nemec and colleagues conducted resilience assessment of the central Platte River SES in Nebraska, US to the construction of a major dam and to the implementation of an ecosystem recovery program (Nemec et al., 2013). Another team sought to assess the resilience of a South African pastoral SES to draughts (Linstädter et al., 2016). Members of Resilience Alliance and researcher have been especially active in conducting resilience assessments of various SES. Some of the research includes the resilience assessment of the Goulburn Broken Region in Victoria, Australia, of Kristianstads Vattenrike and Östra Vätterbranterna Biosphere Reserves in Sweden, of eleven catchment areas in New South Wales, Australia, and more (Resilience Alliance, 2020). Likewise, considerable number of studies have also focused on the resilience of socio-ecological systems in developing countries to various climate change impacts. Such studies include but are not limited to the resilience of wetlands in the Amudarya river delta in Central Asia to the climate induced changes in river runoff (Schlüter, 2013), adaptation and resilience to climate variability in north-east Ghana (Tambo, 2016), or the resilience of coastal communities to climate change in Bangladesh (Hoque et al., 2019).

Developing countries are particularly vulnerable to climate change impacts because of their greater reliance on climatic resources and natural systems-based economic activity. Currently, of the

7.7 billion people worldwide, over 80 % live in the developing countries (UN, 2019). The number of people in these countries is expected to reach ca 8 billion by 2050 (Coast, 2002). In Chapter 18 of the IPCC report (Smit et al., 2001) on adaptation to climate change in the context of equity, the authors underline the specific challenges of developing countries. Their social, economic and environmental vulnerabilities render them prone to more drastic effects of climatic events such as draughts. In terms of potential adverse effects of climate change on agricultural systems, developing countries suffer much greater losses than the developed countries. They fare worse than the developed countries in protecting and enhancing ecosystems and their services, they face limited availability of capital, poor access to technology, and absence of effective government programs when seeking to adapt in a timely manner, and they might also experience higher number of casualties due to extreme weather events because of differential adaptive capacity are.

In addition to their reliance on climatic resources, developing countries also face the challenge of data scarcity. One of the major reasons these countries lack data is because they lack either technological means or funds available to collect it. This hinders the full understanding of the socio-ecological systems in those countries and the accurate assessment of their resilience (Ndzabandzaba, 2015; UNDP, 2017). Attempts to address this challenge include initiatives to map data ecosystems and make available reliable and actionable data (UNDP, 2017) and investing in statistical systems (OECD, 2017). Such initiatives are rather resource-intensive and require longer periods to succeed. Other initiatives tackle the possibility to do policy- and decision-making in data scarce conditions. One example is sharing data held by private entities towards development practice (Williams, 2018). Another, more common example is harnessing expert knowledge (Scholten et al., 2013; Shen et al., 2015; Sayyad et al., 2015).

These things considered, assessing and building the resilience of these communities to climate change impacts is equally important and challenging, on the one hand because of the size of the population affected, and on the other - because of widespread data scarcity in the developing countries that limits the decision-makers' capacity to take data-based action.

1.2. Watersheds as Geographical Units in Addressing Environmental Management Problems

In his article on the progress of debate on Gaia hypothesis (2002) Kirchner welcomes the idea of considering Earth as a coupled system and stresses the need to figure out how that system works rather than assuming it works according to a desired scenario. Since von Bertalanffy's development of General System's Theory in the early 1920s (1972), a considerable number of scientists have embarked on the process of trying to understand the way both nature and human society work by using a systems approach. In 1950s J.W. Forrester proposed a system dynamics methodology to study the behavior of complex systems (System Dynamics Society, 2020).

In their review of theoretical and practical application of system dynamics over the last 50 years in regional planning, watershed and urban water management, Winz et al. argue that qualitative data analysis and techniques may be used in the challenging process of quantification of qualitative variables. In the same article they appraise the suitability of system dynamics methodology as a tool for integrative resource management (Winz et al., 2009).

Problems in regional planning and watershed management often have counterintuitive short-term and long-term effects and are all too often contentious issues. System dynamics modeling provides an appropriate methodology to effectively address such issues as the complex character of a SES and of the fact that our normal way of thinking about complex systems is often limited and misguided (Ford, 1999; Winz et al., 2009).

Watersheds are commonly regarded as the spatial unit for water resource management (European Commission, 2015). They contain a relatively stable, easily identifiable and functional boundary, making them appropriate basic units for natural resources management. The European Union's Water Framework Directive, for example, requires member, candidate and associate countries to develop and implement River Basin Management Plans with the overall aim to maintain the good quality of waters and to improve the quality of the aquatic environment in the European Community. The text of the Directive states that its purpose is "primarily concerned with the quality of the waters […]. Control of quantity is an ancillary element in securing good water quality and therefore measures on quantity, serving the objective of ensuring good quality, should also be established" (EU Directive 2000/60/EC). The European Commission thus acknowledges the fact that "the best model for a single system of water management is management by river basin - the natural geographical and hydrological unit - instead of administrative or political boundaries (European Commission, 2015).

Looking at a watershed as a hydrological unit presents a wide range of advantages. Limiting it to only managing water resources limits the opportunities for integrated management of land ecosystems and social sustainability.

Many scientists have been addressing coupled socio-ecological problems at watershed scale. Some of them make use of system dynamics modeling for issues ranging from changes in water quality and availability (Saysel, 2007; Rivers et al., 2011; Kroeze et al., 2012; Wang et al., 2021) to impact of water scarcity on potential conflict situations (Haraldsson et al., 2002; Huerta, 2004; Pluchinotta et al., 2018; Yuan et al., 2021).

Effects of climate change at watershed scale was also tackled through system dynamics modeling approach by Koca and Svedrup in a stakeholder workshop on developing preventive strategies within Seyhan river basin in Turkey. They made use of system dynamics methodology to analyze the impact of climate change on natural ecosystems and socio-economical systems. Modeled key variables included climatic data, water availability, hydrological changes, agricultural productivity, increased erosion, industrial activity based on agriculture, employment, migration, mortality in sensitive groups (Koca and Svedrup, 2012). Climate change issue was a central concern for Ewers, as well, when combining hydrology and economics (Ewers, 2005) in her study of San Juan watershed. She developed a system dynamics model that could be used to quantify the economic tradeoffs between competing water uses and estimate the effects of climate change on river flows. Observing the occurring transformations on watershed sustainability, Sunaryo and colleagues (1996) conclude that natural and environmental problems are the result of impact of 4 economic factors, namely: population growth, economic growth, food production and changes in land use, mainly deforestation.

Therefore, it appears to be worthwhile to address the issues of resilience to climate change impacts in developing countries at a watershed level. Additionally, engaging stakeholders in the process can be beneficial and bears the potential to support the process in multiple ways.

1.3. Stakeholder Participation

Knowledge of experts in a certain field can compensate for data-scarcity in data-scarce environments such as the developing countries, as mentioned in Section 1.1. For this reason, in many of the studies where researchers choose to work with stakeholder groups, experts are also included. Stakeholder engagement has been found to help address other challenges, as well.

One immediate challenge comes from the (in)effectiveness to disseminate scientific knowledge to and engage with the public in general and policy- and decision-makers in particular (Phillipson et al., 2012; National Academy of Sciences, 2018). Connected to that, policymakers are challenged by the amount of information they need to process they could use and by the amount attention they need to pay to all the things for which they are responsible. Many of the problems they need to address are often complex and have cross-sectoral implications. In relation to climate change specifically, it regarded as a complicated subject. Therefore, “they need to gather information quickly and effectively, often in highly charged political atmospheres, so they develop heuristics to allow them to make what they believe to be good choices.” (Cairney and Kwiatkowski, 2017).

Other challenges include: the informed engagement of other relevant stakeholders in the implementation of climate change projects, and the need for mechanisms to help engage stakeholders, governments and at-risk communities within climate change projects in an effective manner. This would contribute to establishing sustainable climate impacts and shared responsibility (Obado-Joel, 2014). Stakeholder in climate change studies is defined by Conde and Lonsdale (2004) as referring to scientists, communities, administrators, policy makers, and managers in the economic sectors most at risk.

The involvement of stakeholder groups in research has been shown to have multiple benefits. Depending on the stage, degree of participation, and other involvement principles, it can help identify and prioritize topics for research, provide pragmatic feedback on the research, ensure that final products are readable and accessible for their lay users, close the gap between research production and research use, and promote research impact (Cottrell et al., 2014; Boaz et al., 2018).

In the specific case of projects related to climate change adaptation, Conde and Lonsdale (2004) adapt the findings of Twigg (1999) and summarize the benefits of stakeholder engagement, as presented in Figure 1.1.

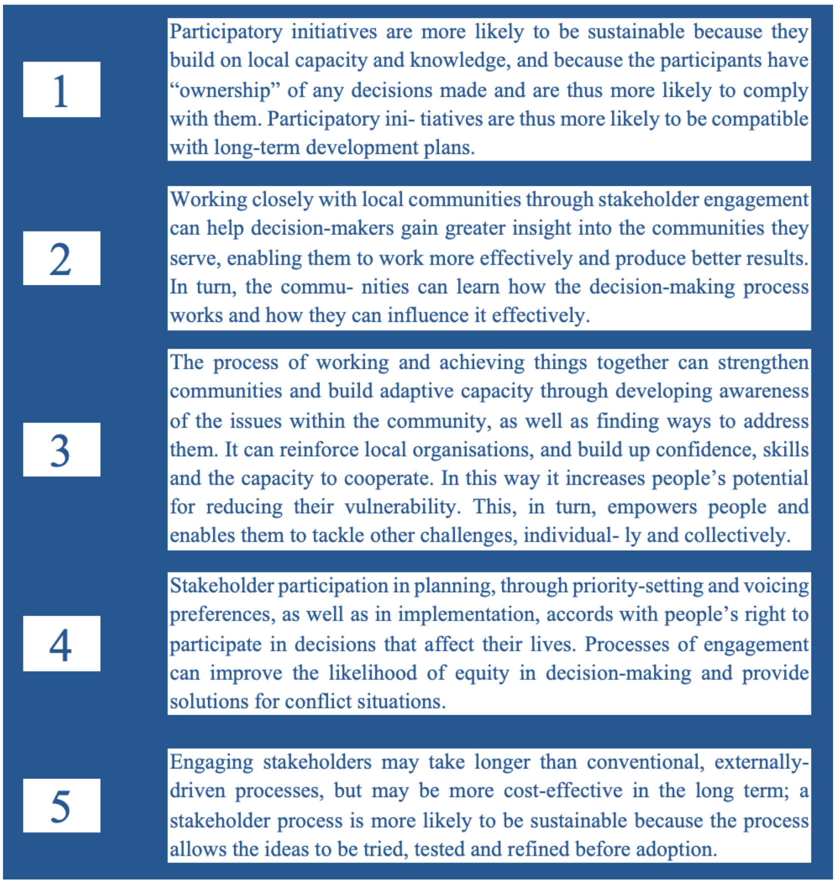


Figure 1.1. Benefits of stakeholder engagement (Conde and Lonsdale, 2004, adapted from Twigg, 1999).

Stakeholder engagement as such has become widespread since the advance of post normal science. There is no one single technique, method or scenario on how to engage stakeholders in general, and in sustainability science in particular (Mielke et al., 2017). Depending on the field of research or purpose of stakeholder engagement, approaches vary significantly (Mielke et al., 2017). Several attempts were made to categorize and conceptualize it. Conde and Lonsdale (2004) put forward a list of design guidelines for effective engagement. A summary of the list is as follows:

- **Clarity:** Clarify the objectives and goals of the engagement and evaluate the appropriateness of the techniques. Communicate clearly. Short-term interests inevitably take over when resources are scarce.
- **Understanding of related processes**: Be clear about how the engagement fits in with official decision-making processes.
- **Information management**: Explain the objectives and goals of the process in advance. Information should be provided in an accessible way, without using complex concepts and jargon.
- **Support and capacity development**: Some groups may need training or other support to educate them to the level of other stakeholders.

- **Transparency**: Stakeholder groups should be identified and invited in an open and transparent manner.
- **Trust-building**: Stakeholder processes may bring together groups with opposing views and possible with a lack of trust. Ideally, the people should feel reassured that their opinions will be heard.
- **Time for the process**: Effective stakeholder engagement will take more time than conventional processes.
- **Feedback and flexibility**: Participatory processes can be very flexible. If one technique is not working, another can be used, or the questions changed to obtain the required information. The analysis and synthesis of the outputs should be presented to stakeholders before general dissemination.

More recently, Boaz and colleagues (2018) distill a set of design principles of how to engage stakeholders in research, based on their comprehensive review of existing literature and empirical insights (Table 1.1).

Table 1.1. Design principles for stakeholder engagement (Boaz et al., 2018).

Category	Principle
Organizational	Clarify the objectives of stakeholder engagement.
	Embed stakeholder engagement in a framework or model of research use.
	Identify the necessary resources for stakeholder engagement.
	Put in place plans for rewarding effective stakeholder engagement.
	Recognize that some stakeholders have the potential to play a key role.
Values	Foster shared commitment to the values and objectives of stakeholder engagement in the project team.
	Share understanding that stakeholder engagement is often about more than individuals.
	Encourage individual stakeholders and their organizations to value engagement.
	Recognize potential tension between productivity and inclusion.
	Generate a shared commitment to sustained and continuous stakeholder engagement.
Practices	Plan stakeholder engagement activity as part of the research program of work.
	Build flexibility within the research process to accommodate engagement and the outcomes of engagement.
	Consider how input from stakeholder can be gathered systematically to meet objectives.
	Consider how input from stakeholders can be collated, analyzed and used.
	Recognizing identification and involvement of stakeholders is an iterative and ongoing process.

Stakeholder participation in building the conceptual model of the socio-ecological system with the aim to assess its resilience is also central to resilience approach. To include all stakeholder interests is regarded as being essential for the validity of the assessment, and for its eventual acceptance by society (Resilience Alliance, 2007). Similarly, in system dynamics, stakeholder involvement in model conceptualization has been extensively used through group model building activities, also known as mediated modeling (van den Belt, 2004). This approach has been shown to greatly enhance the understanding of the resource system and effects of alternative management decisions among participants in the group model building activity (Sterman, 1994; Stave, 2003; Pagano et al., 2019). It is also crucial for the success of implementation of the resulting policies from both a system dynamic and a resilience perspective. Various tools and approaches to stakeholder engagement in these two fields have been developed. Some of them will be referred to in the subsequent chapters.

2. RESEARCH SCOPE AND PURPOSE

In this research, I seek to develop an approach to policymaking for climate change adaptation. I do so by building a regional system dynamic model and analyzing it within a resilience framework. More specifically, I employ system dynamics and participatory modelling to assess the resilience of a socio-ecological system (SES) to climate change impacts. In particular, I address the case of Ikel watershed in the Republic of Moldova. I choose to look at the watershed as not only a hydrological, but a complex, dynamic socio-ecological system - a perspective considered by many scientists and practitioners as an appropriate spatial unit of study. With a formal systemic approach, I propose that we can arrive at effective policy conclusions, which can yield better performance patterns for selected environmental parameters of the Ikel watershed SES.

2.1. The Situation in the Republic of Moldova

The Republic of Moldova (R. Moldova) is a landlocked country in Eastern Europe (Figure 2.1), characterized by temperate continental climate (with warm summers and mild winters), and rich soil. These features made the country one of the most productive agricultural regions since ancient times, and a major supplier of agricultural products in south-eastern Europe. Moldova's economy relies heavily on its agriculture sector. Aside from remittances-fueled service sector, agriculture has the biggest contribution to national GDP (Gîrbu, 2011). It is a major source of income for a large part of the population of Moldova. Agricultural land covers more than 60 % of the country’s territory. More than half the population lives in rural areas and about one third (30.5 %) of the workforce is employed in agriculture. About 85 % of rural households currently own agricultural lands. Most farms (about 400 thousand) are small-sized (1.6-1.8 hectares) (Ministry of Environment, 2015).

Figure 2.1. Location of the Republic of Moldova in Europe (WorldAtlas).

The fall of the Soviet Union and the proclamation of R. Moldova as an independent state in 1991 has brought about major changes in governance and in people's everyday lives both at national and local levels. Moldova's transition from socialist to capitalist system, and from state directed economy to free market economy has posed major challenges. Such challenges include deep and protracted recession and a decade of continuous economic decline (Figure 2.2) (Fidrmuc, 2003; Hamm et al., 2012, UNEP, 2018).

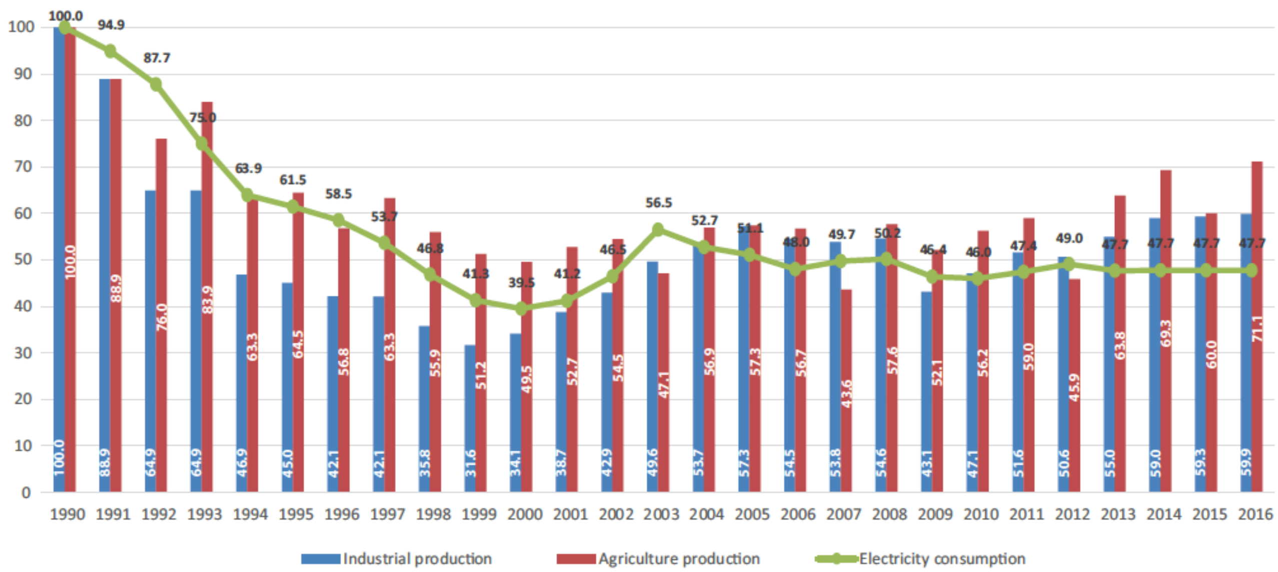


Figure 2.2. The main economic indicators of the Republic of Moldova for the 1990-2016 years, in % compared to 1990 (UN, 2018).

This, in turn has led to a series of dramatic consequences outlined by Abbott (2007), Sârbu (2013), Clark and McArthur (2014), and others, such as increased economic inequalities, an increase in poverty and unemployment, human trafficking, migration of the population from rural to urban areas, or altogether mass out-migration that started at the end of the 1990s and reached its highpoint in 2005. The main reason people emigrate is the low average monthly income in the Republic of Moldova (Stemmer, 2011). Moldova is currently one of the poorest (GDP per capita) and lowest ranked (HDI) countries in Europe.

Nevertheless, in the past decade Moldova has seen some improvement, which culminated in 2014 with signing the Moldova–European Union Association Agreement. This has led to improvements in local development, partly by resorting to participatory models of development. Using such models was possible due to (though not only) support from development partners, community involvement and local approaches to development (UNDP, 2016). An example of such model was the establishment of multiple watershed committees for smaller river such as Ikel. These watershed committees act as a network governance bodies to tackle issues related to integrated water resource management (NEC, 2015). These informal bodies are being established by local actors in an effort to prepare for the implementation of EU's water framework directive.

2.1.1. Climate Change Projections

R. Moldova is one of the countries that is slowly but steadily being affected by consequences of climate change, including the increase in the annual average temperature. From 1887 to 1980 it has witnessed an increase in annual temperature by an average of 0.05°C every 10 years, which over a period of 100 years constitutes an increase of 0.5°C. Between 1981 and 2010, the annual average temperature increased with 0.63°C for each decade. Recalculated for 100 years, this constitutes 6.3°C. Concomitantly, the frequency of droughts and floods has been increasing particularly in the past three decades. Big floods on small rivers are of particular concern. Both draughts and floods are regarded as having the biggest socio-economic impact (Ministry of Environment, 2015).

In the Fourth National Communication of R. Moldova under the United Nations Framework Convention on Climate Change (UNEP, 2018) three different Representative Concentration Pathway (RCP) scenarios were drawn, depending on different levels of GHG emissions: high GHG emissions scenarios RCP 4.5 and RCP 8.5, and low GHG emissions scenario RCP 2.6. All three RCP scenarios (Figure 2.3) estimate an increase in temperature with an annual average of 1.2-6°C by 2100 compared to that of the baseline period (1986-2005), which was 9.6°C (10.1 in the central region).

Conversely, scenarios regarding precipitation are more divergent, with some indicating decrease, and some indicating their increase in certain regions of the country by 2100. RCP 8.5 and RCP 2.6 scenarios project a slight increase in precipitation around 0.6-2 % for the 2016-2035 period, while RCP 4.5 scenario envisages a slight decrease (-1.5-2 %) for the same period. Changes in precipitation become more differentiated across the country by 2100 compared to the baseline period (Figure 2.4).

The volume of available water resources in the country is currently estimated at about 500 m^3/per capita/year, which places Moldova in the category of countries with severe water scarcity with a high risk to climate change impacts (Dniester Watershed Management Plan, 2017).

It is anticipated that water scarcity in the future will be the main problem in some regions of R. Moldova, especially in the Central and Southern regions. The most important impacts are expected to be on agricultural productivity and human health. Being one of the most underdeveloped countries in Europe and Central Asia, Moldova has a high degree of vulnerability to such changes. National Report on Human Development (UNDP, 2016) foresees that in the upcoming decades the economic, social and environmental impacts of climate change will intensify. Water-based social-ecological systems are known to be particularly vulnerable to climate change (Cosens and Fremier, 2014).

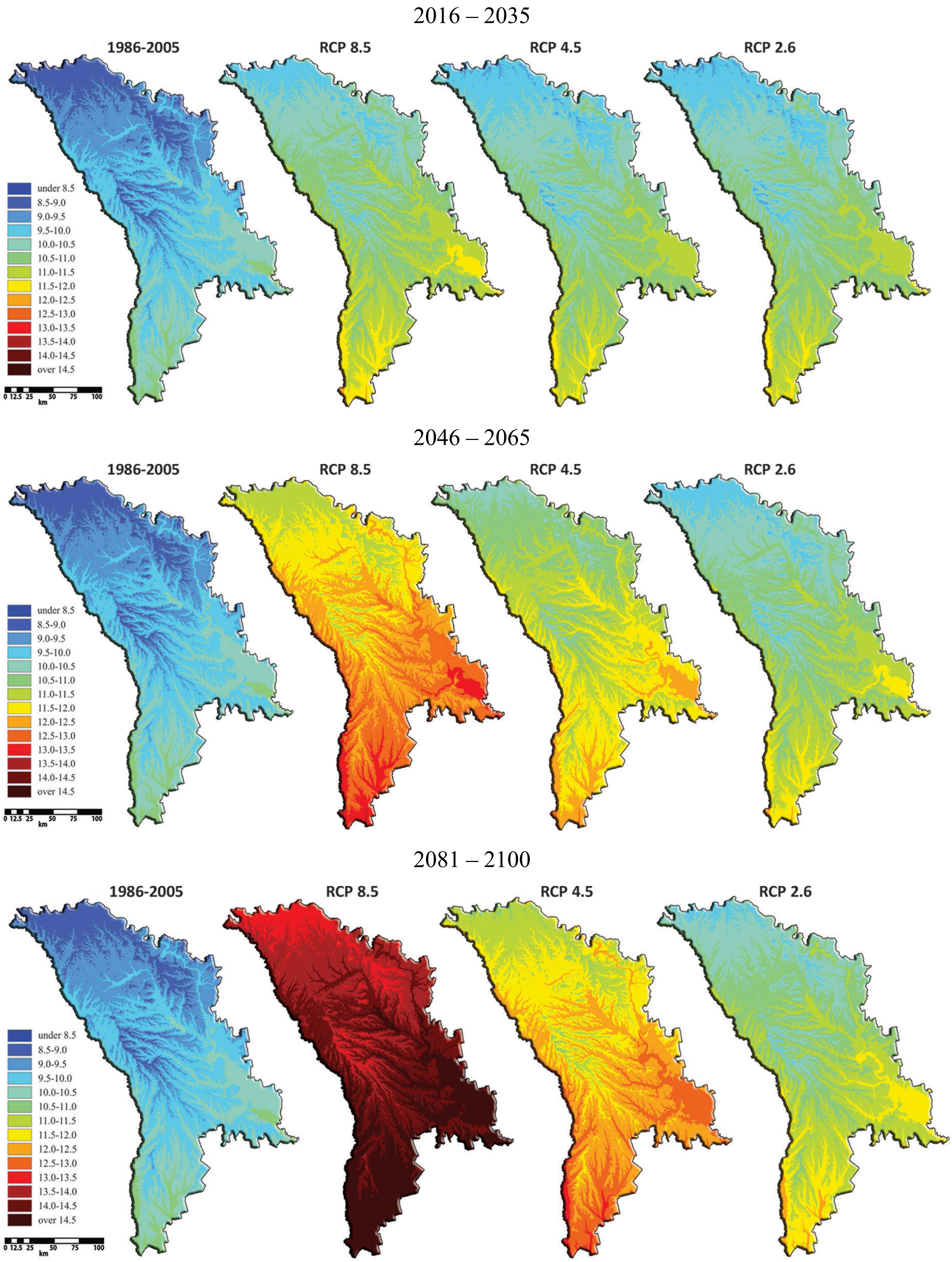


Figure 2.3. Projected annual mean air temperature in °C throughout the Republic of Moldova for the three different RCPs relative to the 1986-2005 climatological baseline period (UNEP, 2018).

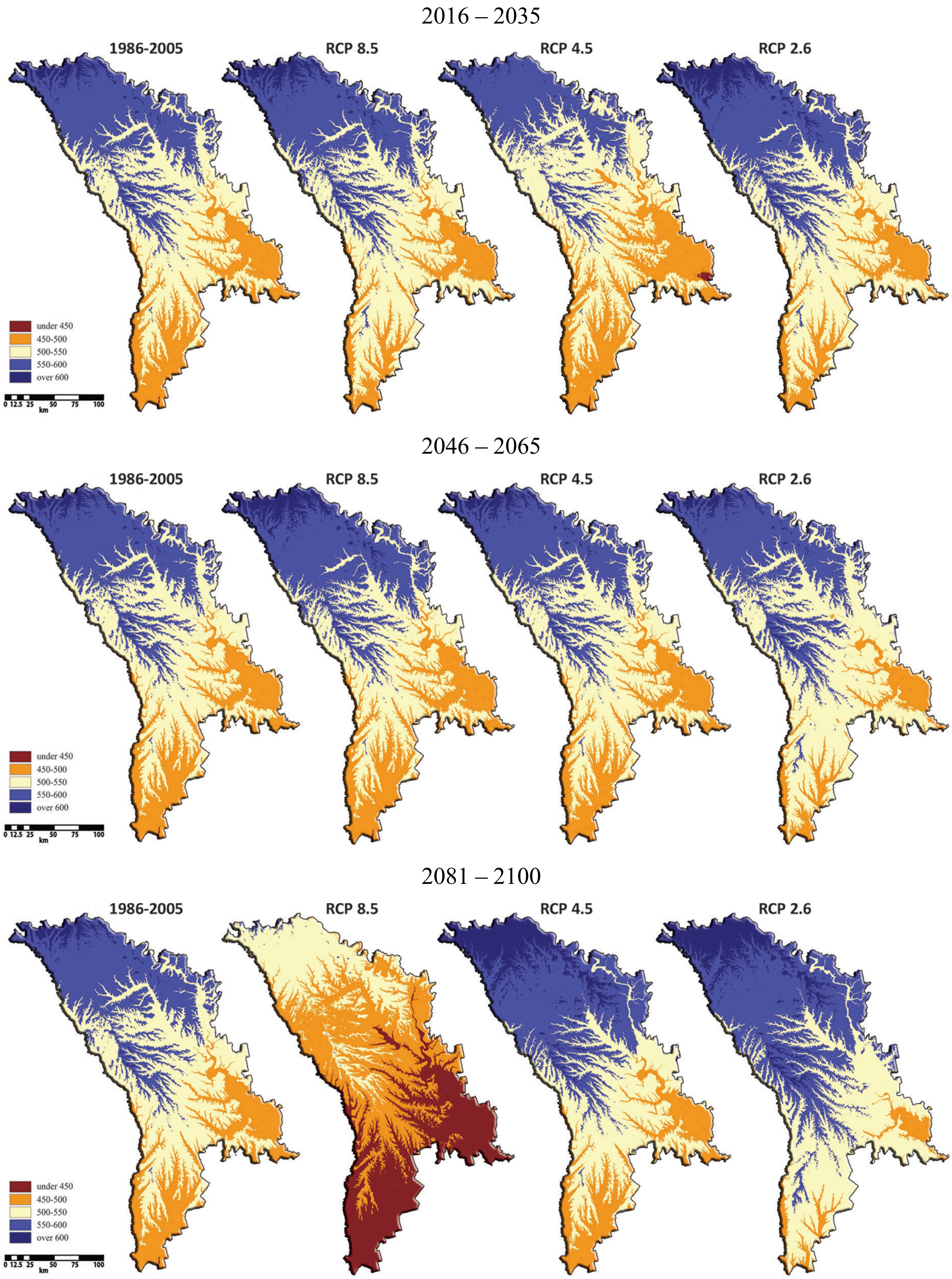


Figure 2.4. Projected annual precipitation (mm) throughout the Republic of Moldova for RCP 8.5, RCP 4.5 and RCP 2.6 scenarios compared to the 1986-2005 average baseline values (555.13 nationally, 613.8 in northern, 550.4 in central and 501.2 in southern regions) (UNEP, 2018).

Of special concern is the direct impact of climate change on agriculture, due to both its role in R. Moldova's economy (over 50 % of exports, second most important contributor to country's GDP, price fluctuation), as well as its impact on social welfare (nutrition, employment, subsistence). If no adaptation measures are taken, the estimated decrease in agricultural productivity by 2080s' (2070-2099) compared to the recent period (1981-2010) is expected to record a significant decrease in, for example, maize grain (varying between 49 % and 74 %), winter wheat (38-71 %), as well as a relatively moderate decrease in sunflower (11-33 %), sugar beet (10-20 %), tobacco (9-19 %) (Ministry of Environment, 2015).

Moreover, most soils are represented by chernozyom - a type of soil with a high content of organic matter, which is formed typically under a forest cover. The decay of organic matter may increase with higher temperatures. Although in a short-term perspective this will increase soil fertility (by releasing nutrients), on a long-term soil fertility will most probably decrease. The results of a long-term research conducted at national level show that in the past century the content of organic matter in Moldova's arable soil has decreased, while at the same time the average annual temperatures have increased. The combined effect of water regime change could lead to shortage of water for irrigation and high competition for water. This would ultimately result in higher prices and regulatory pressure. Increased soil salinity resulted from intensive irrigation on the other hand may lead to land abandonment, as lands become unsuitable for cultivation.

It is anticipated that water scarcity in the future will be the main problem in some regions of R. Moldova. The most vulnerable regions in the Republic of Moldova will be the south of Moldova (Southern Moldova Plain, Lower Dniester and Prut River terraces) and partly its central region (Subarea 2 "Central Moldavian Plateau" and Subarea 2 "Terraces of Dniester river and those of Prut, Raut Prut, Bic, Botna"). One of the units located in the Central region is Ikel watershed, where the research has been conducted. National Strategy on Climate Change Adaptation (Ministry of Environment, 2015) has concluded with a high probability that most of the risks in these areas are related to climate change. The provision of safe water for all water users will be threatened by changes in the availability of sufficient and good quality water resources associated with climate change already in 2020. Once water scarcity worsens, water-related diseases and malnutrition are expected to increase especially among rural and low-income population.

Non-climatic factors may worsen or mitigate the effects of climate change on water demand, availability and quality, agricultural productivity and public health. Increasing pollution and economic development (and thus, changes in lifestyles and consumption) will play a dominant role.

Impacts of non-climatic factors can stem from several factors such as policies and legislation, technologies and infrastructure, and land use patterns and farming / irrigation.

National Climate Change Adaptation Strategy identifies the following risks for agriculture as having a high priority:

- drought and water scarcity.
- increased irrigation needs.
- erosion, soil salinization, desertification.
- pests, diseases, and weeds.
- reduced production of basic cereals (wheat and maize). Three of these risks include the potential consequences of change in precipitation regime, heavy precipitation in winter and low water availability in summer.

Prioritized risks concerning water resources are:

- drought and water scarcity.
- increased irrigation needs.
- increased frequency and intensity of floods.
- reducing water availability in both surface and groundwater resources.
- changes in water demand.
- changes in water quality (e.g.: mineralization, hardness, dissolved oxygen), which will be affected by higher water temperatures and variations in average annual drainage layer.
- increased water pollution by pesticides and fertilizers, due to increased soil washout.
- changes in average annual drainage layer of rivers.

Even though climate change is recognized as having a global importance, the Moldovan national strategic framework does not include integrated measures to mitigate climate change or adapt to its effects. Most strategies, action plans and sectorial programs already approved by the Government, rarely include activities associated with adaptation to climate change.

Multidisciplinary nature of climate change research and incoherent interventions based on sectorial approaches, make the drafting of climate change adaptation strategies and action plans at sectorial level difficult. Ministries implement various activities at the sectorial level, which are considered as having higher priority than climate change adaptation. This in turn leads to a competition over the limited state budget (highly dependent on remittances and agricultural production), and often a conflict of between different policies and measures of different sectors. Competition over water resources for ecosystem preservation and for agricultural / household use is but one of such conflicts.

There is also a persistent lack of mechanisms for the use of climate change-related information aimed at sensitizing policymakers and influencing decision-making process. Concomitantly, low level of awareness of policymakers and civil society on issues related to climate change and adaptation at the sectorial level, makes the integrated climate change adaptation difficult and expenditures on climate change adaptation incoherent and not effective.

Although experienced at national scale, numerous researchers suggest that such risks posed by climate change need to be addressed at watershed scale (Cosens and Fremier, 2014). This is particularly important for water scarce regions where agro-ecosystems are dominant and agriculture is predominantly rainfed (Rockström et al., 2004; Gordon and Enfors, 2008; Enfors, 2012).

2.1.2. Challenges With Data Availability

The situation of data availability in R. Moldova is similar to that in other developing countries. In a report on data ecosystems for sustainable development in developing countries including R. Moldova, UNDP (2017) summarizes a number of gaps in critical areas, which makes it is extremely difficult for decisionmakers to develop evidence-based policies, monitor implementation, and evaluate their impact. Some of the identified gaps refer to: low level of data coordination and information sharing within national statistical systems; outdated data-related processes; lack of incentives for different communities of data stakeholders to share information; legislative gaps regarding rules around the collection of data by non-traditional sources, sharing of data amongst data stakeholders and compliance; deep-rooted bureaucratic resistance to change, hindering the operating procedures related to use and sharing of data; unresolved issues concerning data openness and interoperability, and others.

The main source of official information in the country is the National Bureau of Statistics, which has been criticized for weak coordination role. The data ecosystem includes various other actors engaged in data collection, processing, exchange, analysis and usage (Figure 2.5). The above-mentioned report notes that “under the law on official statistics there is currently no clear procedure for conferring non-traditional agencies and authorities involved in data production with the status of *producer of official statistics*" (UNDP, 2017), and that the country is yet to resolve multiple issues around data openness and interoperability.

Figure 2.5. Data ecosystem model in R. Moldova (UNDP, 2017).

The report has also found that data system in R. Moldova faces such challenges as weak capacity of data providers and users, inconsistent methodology, and multiplicity of data sources. Geographically, many indicators are not disaggregated to a resolution that would allow to address issues at regional or local scale. At the same time, measuring environment and governance is hindered because of lack of indicators. Even when available, collection of information on relevant indicators can be very time and resource intensive, because digital services and interactive tools are lacking in many data collecting and processing institutions.

This reality makes access to necessary and reliable data very challenging, if not virtually impossible. Withal, it also impels researchers, including the author, to resort to approaches and methods that can maximize the use of available data, and to those that can compensate for existing data-scarcity.

2.2. The Case of Ikel Watershed

Ikel watershed is a small watershed, which is part of the larger transboundary Dniester River basin (Figure 2.6). The former is located in the Central part of R. Moldova (Figure 2.7).

Figure 2.6. Location of the transboundary Dniester River basin (ENVSEC, 2015). Location of Ikel river is highlighted with red color.

Figure 2.7. Location of Ikel river (dark blue color) and Ikel watershed (light blue color).

Geographically, Ikel watershed has an area of 767.87 km^2 that makes up 2.27 % of country's territory (Ursu, 2014). Administratively, it also includes the adjacent smaller watersheds of interconnected rivers in the proximity of its flowing into the Dniester. The additional territory increases the watershed area to 878.1 km^2 (SHS, 2020).

The relief of Ikel watershed has a dominant west – east inclination. Therefore, one part of surface water resources flows out from Ikel watershed into Dniester river, the main receptor located to the east of Ikel watershed, at 7 m MSL. The volume of annual Ikel water runoff is 20.5 million m^3, with an average flow of 0.7 m^3/s. Dniester further flows south into the Black Sea (Figure 2.8). Another part percolates to the confined groundwater aquifer. The remaining part of the surface water evaporates back into the atmosphere either through direct evaporation or through evapotranspiration (ET) of the vegetation cover.

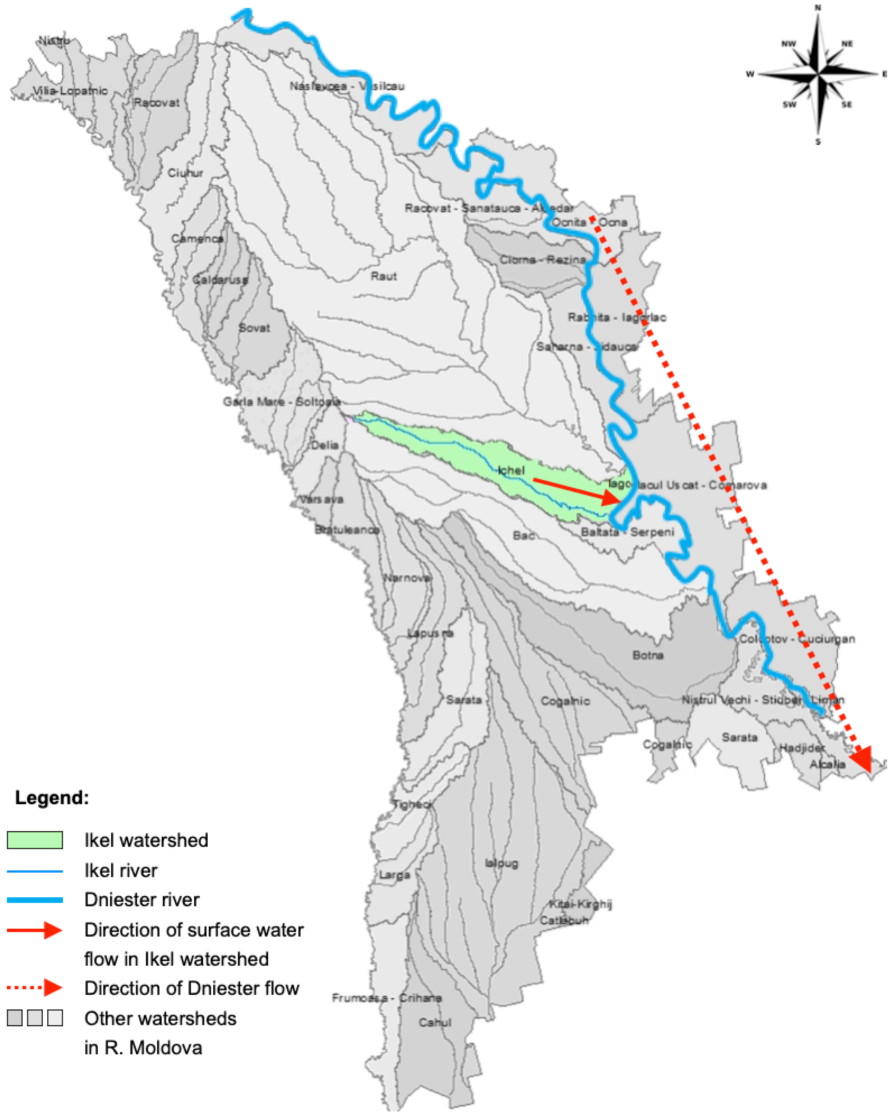


Figure 2.8. Overview of the predominant direction of surface water flow in Ikel watershed (NW-SE) and Dniester River (N-S).

The exact population in the watershed is unknown. Most reports present statistics at the level of state districts. Yet, a rough estimation based on official data of R. Moldova's National Bureau of Statistics suggests a population of 116,000 – 120,000 people (Table 2.1). For future scenarios, the UN Department of Economic and Social Affairs (2019) makes several probabilistic projections for the population of R. Moldova, according to which the trend in declining population is expected to continue in the years to come, with current projections stating that by the year 2050 the population will be changing at -0.87 % annually (Figure 2.9).

Table 2.1. Estimated population of Ikel watershed SES between 2004 and 2019, based on data provided by NBS for the population present in the constituent counties between 2004 and 2019.

Year	Ikel SES Population
2004	121816
2005	115360
2006	115166
2007	116810
2008	116716
2009	116582
2010	116635
2011	116680
2012	117037
2013	117852
2014	118221
2015	117965
2016	117629
2017	117346
2018	116857
2019	116514

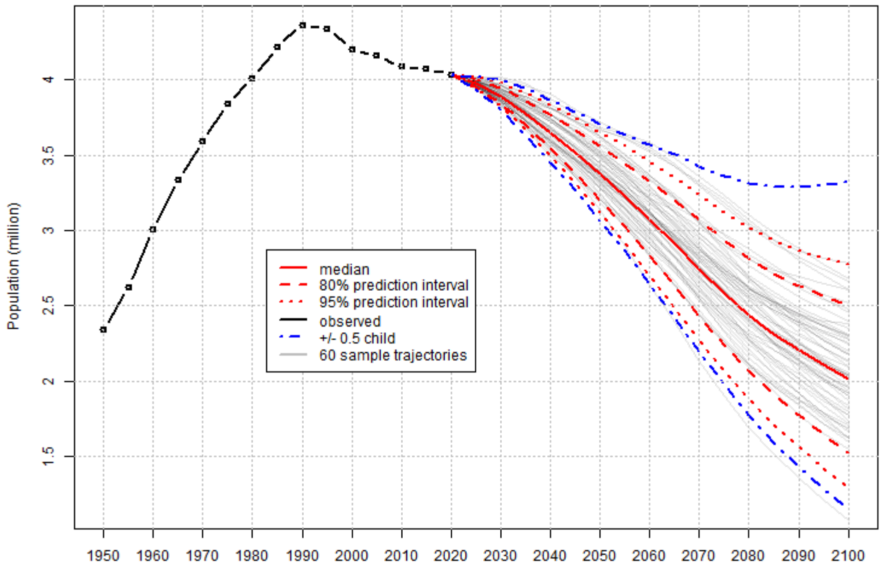


Figure 2.9. Estimates and probabilistic projections for the population of R. Moldova (UN Department of Economic and Social Affairs, 2019).

The watershed is shared by 6 different administrative divisions (Table 2.2), known in R. Moldova as rayons, to which I will refer as counties (Figure 2.10). 64 administrative units (villages, communes and towns) are located with the watershed.

Table 2.2. Share of Ikel watershed area under the administration of each of the 6 counties.

County	County's share of watershed area
Criuleni	29 %
Strășeni	28 %
Călărași	25 %
Orhei	10 %
Ungheni	4 %
Chișinău municipality	4 %

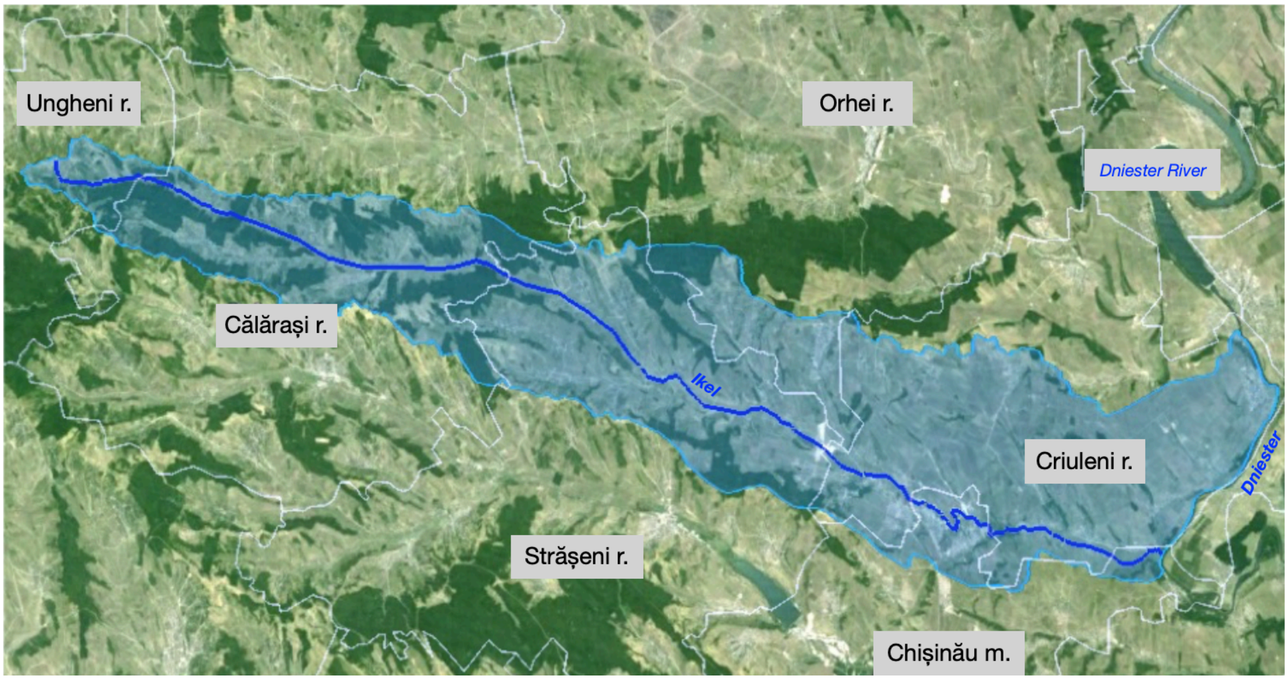


Figure 2.10. Counties sharing Ikel watershed area (Ciobanu, 2016).

As in the case of most of Moldovan small towns and villages, the main occupation of people living in Ikel watershed for many years has been agriculture – either subsistence or commercial farming. This has changed after 1990, and the area has since been characterized by strong demographic changes, low economic production, a drain of the workforce (Stemmer, 2011), population aging, and high rates of unemployment and migration among economically active population. About 25 % of the rural population is estimated to have migrated abroad. Among those who live in rural areas, agricultural activities remain the main occupation, whereas remittances from abroad remain the prevalent income source (Ministry of Agriculture, 2013; National Bank, 2019).

Major crop categories currently cultivated in this region include maize, cereals, legumes, grapes, vegetables and fodder crops. Data on cultivated area for these crops in Ikel watershed is not readily available. However, based on national data, maize is the most commonly cultivated crop in the counties with the biggest share of Ikel watershed area. Table 2.3 below shows cultivated crops in each of these counties for the year 2019.

Table 2.3. Area for cultivation of various crops in each of the counties that share the Ikel watershed area (NBS).

County	**Share of Ikel watershed area**	**Cultivated area (hectares)**						
		Maize	**Cereals**	**Legumes**	**Sunflower**	**Rapeseed**	**Potatoes**	**Vegetables**
Criuleni	29 %	4149	2289	401	5093	1041	49	501
Strășeni	28 %	834	621	80	783	0	10	33
Călărași	25 %	294	326	24	191	0	0	24
Orhei	10 %	6266	9296	283	7298	492	26	191
Ungheni	4 %	7539	7678	155	7918	554	0	57
Chișinău mun.	4 %	506	1473	23	1017	13	2	21

Previous studies suggest that there has been a very high human pressure on the landscape in the watershed (Ursu, 2014; Dniester Watershed Management Plan, 2017), leading to a decrease in biological diversity and an increase in its vulnerability to various risks. Ursu (2014) reveals that extensive agricultural land use at the expense of meadows and forests threatens what the author refers to as ecological equilibrium. Currently, most of the land in Ikel watershed (~80 %) is attributed to agricultural use (arable land and orchards), while ~1 % is covered by built area (Table 2.4).

Table 2.4. Land use shares in Ikel watershed (after Ursu, 2014).

Land use	**Share in Ikel watershed**
Arable land	~80 %
Forested area	~7 %
Meadows (incl. Degraded land)	~2-3 %
Water bodies	~9 %
Built area	~1 %

Water is a key resource in agriculture, because its availability affects the evapotranspiration and hence the growth of plants. Evapotranspiration depends on both available soil water, and on the potential evapotranspiration (PET) specific to each type of vegetation, while soil water is directly dependent on precipitation.

In Ikel watershed, there are two main sources of water: surface water (including the subsurface water flows), which is directly dependent on precipitation, and the groundwater in the confined aquifer. The latter is only partly replenished by local precipitation through percolation, while being mostly recharged by the underground inflow. This deep, confined groundwater aquifer within the limits of Ikel watershed, is located in the Baden-Sarmatian bedrock layer at an average depth of 100-

200 m below surface (Teleuta et al., 2004), and is replenished by groundwater inflows from upstream. This aquifer consists of three groundwater bodies (Figure 2.11).

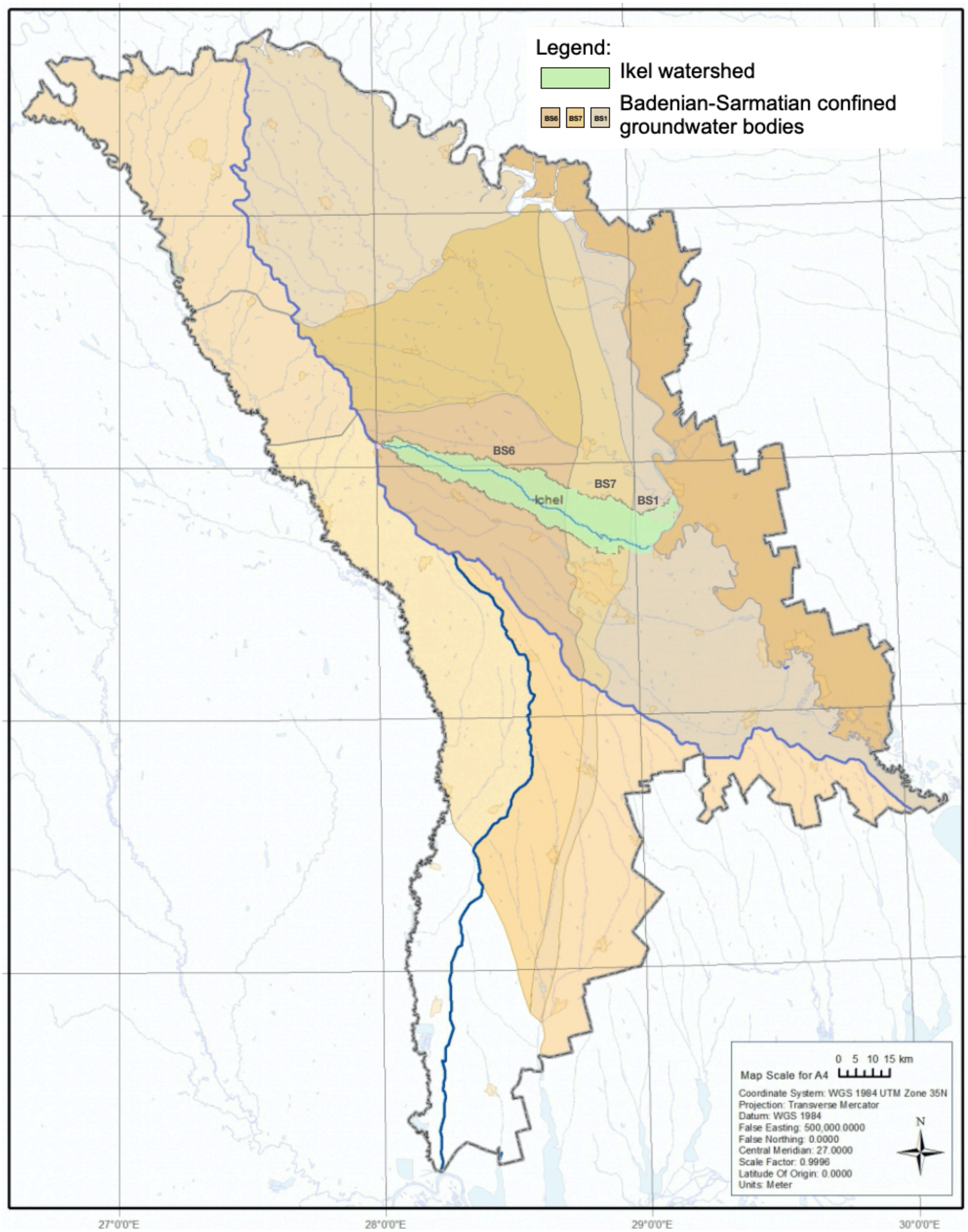


Figure 2.11. Groundwater bodies in the Baden-Sarmatian confined aquifer layer under Ikel watershed (SIRA, 2020).

Unlike the surface relief, the bedrock of Ikel watershed has a slight northeast-southwest inclination, becoming deeper towards the southern region of the country (Figure 2.12).

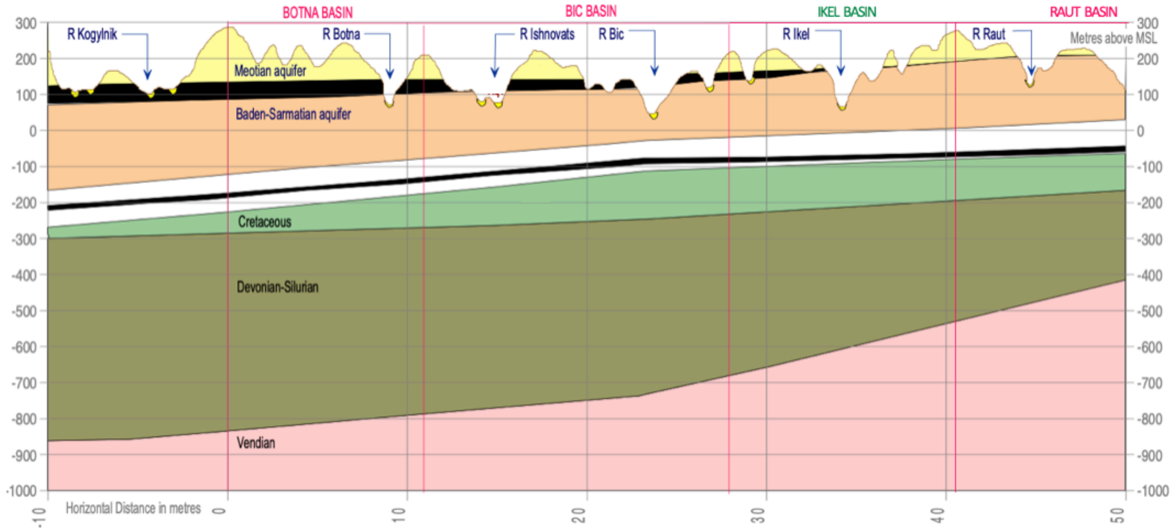


Figure 2.12. North-South geological section through the watersheds/basins of Răut, Ikel, and Bîc rivers (Euroconsult Mott MacDonald, 2012). The layers colored in black are the two aquitards confining the Baden-Sarmatian groundwater stock.

As a consequence, the deep groundwaters typically flow from the north to the south of the country and of the Ikel watershed. Hence the confined groundwater under the latter is replenished by inflows from the deep groundwater stocks under Răut watershed to the north and drained by outflows into the deep groundwater stocks of the Bîc watershed to the south (Figure 2.13).

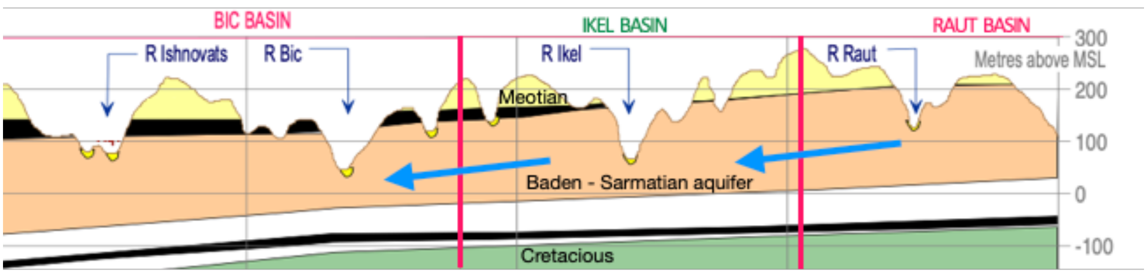


Figure 2.13. A closer view of the deep groundwater flows in Ikel watershed. Blue arrows indicate the direction of inflow (from deep groundwater aquifer under Răut watershed to the north of Ikel) and outflow (to the deep groundwater aquifer under Bîc watershed located to the south of Ikel).

Average annual precipitation in the central region of R. Moldova between 1960 and 2019 was 551 mm (UNEP, 2018; NBS, 2020), while for the period 2000 to 2019 it was 542.2 mm (Table 2.5).

Table 2.5. Annual precipitation in the central region of R. Moldova for the period 1990 – 2020. Data for 1990-2001 are sourced from the Fourth National Communication of the Republic of Moldova under UNFCCC (UNEP, 2018), while data for the 2002-2020 period - from NBS.

Year	Annual precipitation in the central region of R. Moldova (mm)
1990	360
1991	673
1992	417
1993	533
1994	403
1995	702
1996	711
1997	607
1998	666
1999	484
2000	437
2001	618
2000	437
2001	618
2002	604
2003	459
2004	591
2005	638
2006	564
2007	480
2008	466
2009	446
2010	734
2011	428
2012	522
2013	531
2014	604
2015	431
2016	644
2017	635
2018	609
2019	403

According State Hydrometeorological Service (2014), the minimum required Ikel river flow is 0.72 m^3/s. However, average annual Ikel river flow has been decreasing from 1.08 m^3/s in 1988 to 0.36 m^3/s in 2018 (Figure 2.14).

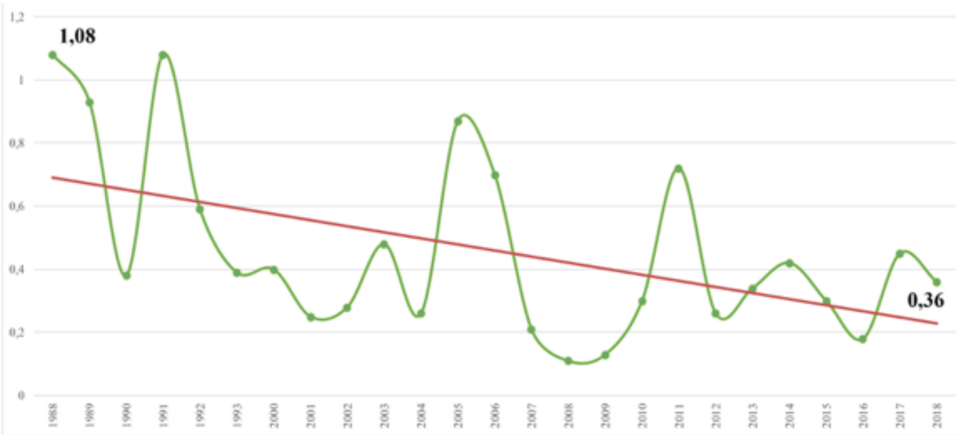


Figure 2.14. Average Ikel flow from 1988 to 2018 at hydrological station Goian. The green line shows the annual average values. The trendline is shown in red (SHS, 2020).

Decline in and degradation of land and water resources are expected to have implications on agricultural productivity, ecosystem services, income of local people, on local and national budget and on public health (Ministry of Environment, 2015). To strengthen the climate change adaptation efforts, the Moldovan Government adopted a National Climate Change Adaptation Strategy 2014 – 2020. No specific scientific projections of future climate risks have been developed for this specific watershed. However, scenarios can be derived from projections developed for the Central region of R. Moldova. The watershed is at high risk of droughts, loss in agricultural productivity, water scarcity, water and water scarcity-related diseases (Ministry of Environment, 2013).

Analyzed individually, the impacts of climate change on various components of the Ikel watershed system are relatively easy to anticipate. But when it comes to complex interactions between a number of variables changing at different rates, implications for the sustainability of Ikel watershed as socio-ecological system are hard to grasp. The thresholds, the possible future behavior of the system, the leverage points where interventions can be made to prevent the system from switching to an undesired state, and the possible policy and management options to prevent it from doing so are even harder to grasp in the absence of a suitable mechanism to analyze such complex interactions and systemic feedback.

2.3. Research Purpose

By building Ikel CliRes – a regional system dynamics model for Ikel watershed as a socio-ecological system, and by analyzing it within a resilience framework, my aim is to provide decision- and policymakers with a decision support tool that will help build the resilience of this SES to climate change impacts. Making use of the results of this research will help them arrive at effective policy conclusions, which can yield better performance patterns for several issues of major regional concern.

The ultimate purpose of the research is to support the development and effective implementation of policies for climate change adaptation in developing countries through a formal systemic approach, which could:

- Help policymakers, decisionmakers and other stakeholders better understand the socio-ecological system under focus, and what builds or erodes its resilience to climate-change impacts.
- Give policy- and decisionmakers a reliable and user-friendly tool to experiment long-term impact decisions in a consequence-free environment.
- Foster the commitment of stakeholders to the implementation of policies aimed at building the system's resilience to climate change impacts.

3. METHODOLOGICAL APPROACH

To build and analyze the model, I have resorted to several methods, techniques and tools from two related fields: system dynamics and resilience of socio-ecological systems. The two have many things in common but have not been combined much in the literature prior to this research. I combined them in ways that are expected to yield better results than any of them used separately.

First, I resorted to two sequential processes: social ecological inventory (SEI) proposed by the resilience assessment practitioners and group model building (GMB) used extensively by system dynamicists. I employed them to identify climate change vulnerabilities in the network governance setting of Ikel watershed, and to define the dynamic hypothesis – an important step in system dynamics modeling.

Secondly, I visualized the dynamic hypothesis as a conceptual model, and used it as a basis for developing a computer simulation model using established procedures of system dynamics modeling. I refer to it as Ikel Climate Resilience or *Ikel CliRes* model.

Following the finalization of the dynamic simulation model, a set of resilience concepts were used to assess Ikel watershed's resilience to a series of climate change threats. In addition to Ikel watershed being a well-defined geographical and hydrological unit, it is viewed in this research as a social-ecological system, a perspective that is widely used by resilience assessment practitioners.

Finally, I have conducted an analysis of various policies with relative contribution of GMB participants to identify those policies and interventions that could contribute best to increasing Ikel watershed's resilience to a defined set of climate change impacts.

3.1. Social Ecological Systems and Resilience Framework

Social-ecological systems concept has been put forward in an effort to advocate for integration as "socio-ecological systems" of what had been often considered separately as "human" and "natural" systems (Redman et al., 2004). This concept reflects a highly interconnected relationship between society and ecosystems and can be applied virtually to all natural and social systems, since there are "no natural systems without people, nor social systems without nature" (Stockholm Resilience Centre, 2015). A prior definition of SES as complex adaptive systems demarcated by either spatial or functional boundaries of certain ecosystems and/or their linked problems (Glaser et al., 2008) opened the path to non-linear modeling and analysis. SES research generally focuses on both understanding the many dimensions of the way in which a SES functions, as well as on developing and implementing normative societal goals (Partelow, 2018).

SES framework is a comprehensive conceptual framework that allows for diagnosing interactions and outcomes in socio-ecological systems and helps analyze the sustainability of a SES. The framework has been historically related to commons and collective action research, and despite some methodological challenges, it has been commended for its suitability in multiple contexts and purposes of research, "bringing a welcomed pluralism of methods, data, and associated concepts" (Partelow, 2018).

Comparatively, the general SES framework, proposed by Ostrom (2009) for the study of such linked socio-ecological systems, facilitates the integrated use of data from various disciplines, and allows for an inquiry about the environmental problems that originate from the complex interactions between a system's ecological and social components. It does not present a specific step-by-step guidance on its application. Instead, it proposes a set of multi-layered indicators, which account for multiple subsystems and their internal variables that make up a specific SES in focus. The so-called first-tier variables which stand for the subsystems of a SES in this framework (Ostrom, 2009; McGinnis and Ostrom, 2014) are structured into: *Resource Units*, *Resource System*, *Governance System*, *Actors*, *Interactions, Outcomes, External Ecosystems,* and *Social, Economic and Political Settings*. Together with the multiple and evolving number of second- and third-tier variables (Partelow, 2018), they are used as diagnostic tools by scholars or practitioners who seek to understand the determinants of sustainability in complex SESs. Additionally, these structured indicators are expected to help organize and compare SES studies across geographies and methodologies (Ostrom, 2009).

The framework has been used in multiple empirical contexts, the majority of which are focused on sustainability issues in common pool resources. Some examples are included in Partelow's review of SES applications (2018), and highlight the SES framework applicability in irrigation systems, forestry, food production systems, terrestrial conservation, watershed management, pollution management, and others.

While the framework faces several methodological challenges in its use, including the choice of variables used to diagnose the sustainability of a SES, its general character makes it applicable to a wide variety of cases, and renders it a suitable framework to facilitate multidisciplinary efforts for the dissection and better understanding of a SES's complexity.

Hence, the SES framework informs my research in a number of ways. First, it provides a widely accepted understanding of the SES concept. Secondly, it provides a vocabulary that can link this research to similar efforts across the globe, and thus make it accessible to a wider community of climate adaptation research and practice. And last, but not least, as Partelow (2018) has concluded, "integrating this framework with other conceptual and theoretical frameworks may expand its usefulness for contributing to other theories and frameworks in associated fields such as sustainability science and resilience theory".

Resilience is a concept that has been given many interpretations in various disciplines, including healthcare, psychology, economy, and others. In the context of social-ecological systems, it has a more specific meaning, which has been defined in resembling terms, yet with various degrees of detail (Barnett, 2001; Korhonen and Seager, 2008; Folke et al., 2010). Walker and Salt (2006), for example, define it as the capacity of a SES to absorb disruptive disturbances (such as prolonged droughts, flash floods, etc.) in a way that allow the system to essentially maintain its structure, functions, and feedback dominance. Often, resilience is defined in terms of its attributes. These include, but are not limited to: the elasticity of a system, i.e. the range in which a SES can be perturbed without losing the ability to return to its original form; its resistance, defined by the force required to change a particular unit in the system (Boyd et al., 2008); recover rapidity, i.e. the time it takes for a system to return to its state initial state (Fraser and Stringer, 2009; Herrera, 2017). Thus, not only does resilience thinking mean viewing the social and ecological systems as interlinked and continuously generating unexpected behaviors, but it also calls for a different approach to managing the interaction between humans and the use of natural resources (Sellberg et al., 2018).

In the context of climate change, a resilience perspective either allows for undesirable states to be transformed into desirable ones in ways that don't threaten the integrity of the atmosphere and of the ecological systems essential to humans or help buffer disturbance and generate adaptive capacity (Boyd et al., 2008). The Stockholm Resilience Centre, too, underlines the increasing importance of strengthening resilience in society and nature in order to cope with the stresses caused by climate change impacts.

The resilience framework has been proposed by Walker, Salt, Folke and other colleagues (Folke et al., 2002; Walker and Salt, 2006) as an alternative framework to the management of natural resources in SES in a way that treats environmental and social aspects as integrated entities interacting in a constantly changing world. It offers a number of approaches, ways, tools and practical guidance to strengthen resilience. Some of these focus on fostering participation and understanding the complex interactions within the SES, while others are aimed to help assess, plan and build its resilience, and support adaptive management and adaptive governance (Sellberg et al., 2018).

3.2. Resilience Assessment

Resilience assessment is an approach developed by the Resilience Alliance (2010) to improve the understanding of what makes a specific SES more resilient or less so. It helps resilience practitioners look at how systems can adapt and transform to build resilience and persistence. The goal of conducting a resilience assessment is to identify measures or actions that can build/increase/maintain the resilience. It typically uses a participatory process, and the predominantly seeks to create a common understanding among stakeholders about the structures and processes that influence the resilience rather than on measuring the resilience of the SES in focus (Sellberg et al., 2018).

The community of practice is still exploring appropriate methods (e.g., Ostadtaghizadeh et al., 2015; Boyd et al., 2015; Tenza et al., 2017; Sellberg et al., 2017; Maru et al., 2017; Enfors-Kautsky et al., 2018) to include in the resilience assessment toolbox. Many researchers undertaking a resilience assessment, besides collecting background data, resort to interviews, questionnaires (e.g., Gordon and Enfors, 2008; Sellberg et al., 2017), focus groups, and facilitated workshops (UNU-IAS, 2014) with the participation of key stakeholders to identify main issues, define and understand the system. Resilience Alliance is leading the work, and one of its proposals is a four-step process described in the "Resilience Assessment for Scientists" (Resilience Alliance, 2007):

1. *Defining and understanding the system*, or otherwise answer such questions as: *Resilience of what?* (Defining the social-ecological boundaries of the system, that is spatial and temporal scale, actors involved) and *Resilience to what?* (Identifying system drivers and disturbances, developing a historical profile of the system).
2. *Assessing resilience*:
    a. Developing the conceptual model.
    b. Identifying alternate system regimes, controlling variables, thresholds and possible future scenarios.
    c. Exploring likely interactions among thresholds.

   d. Cross-examination of the conceptual model(s) with known resilience and adaptability attributes.
   e. Identifying the cycles of change and cross-scale interactions.
3. *Understanding implications for management interventions*.
4. *Synthesizing resilience understanding*.

So far, many practitioners have based their studies mostly on qualitative and quantitative assessments of past evolution of the system. When it comes to analyzing changes over time and to identifying leverage points for intervention towards resilience building, the developed models have been predominantly qualitative or conceptual (Sharifi, 2016).

Despite extensive work on transformations towards sustainability, resilience theory has been criticized for lacking the analytical power to study such shifts (Jerneck and Olsson, 2008). More recently, multiple attempts have been made to formalize resilience assessment in ways that can help measure its attributes (Sharifi, 2016). Among these attempts are the work of Herrera and Kopainsky (Herrera, 2017; Herrera de Leon and Kopainsky, 2019; Herrera and Kopainsky, 2020) that uses system dynamics modeling to operationalize and support resilience assessment, which will be referred to in more detail in the following chapters.

3.2.1. Social Ecological Inventory

Resilience Alliance suggests defining and understanding the system as a first step in the resilience assessment process, or otherwise to answer the question of “resilience of what to what?”. “Resilience of what?” refers to defining the social-ecological boundaries of the system at the spatial and temporal scale, and defining the actors involved. “Resilience to what?” means developing a historical profile or development of the system and identifying system drivers and disturbances (Resilience Alliance, 2007; Resilience Alliance, 2010). Social-Ecological Inventory (SEI) is one of the tools that has been employed for that (Schultz et al., 2007, Schultz et al., 2011).

SEI is a community-based step-by-step technique used by some practitioners of resilience assessment as a starting point to identify existing knowledge and activities already underway in a region (Schultz et al. 2007, Schultz et al. 2011; Baird et al., 2014; Bahauddin et al., 2016; Baird et al., 2018). It also contributes to mapping key actors involved in the focus area with regards to a particular issue (Schultz et al., 2011), preparing the ground for stakeholder participation. It is seen by its proponents and users as a means to connect conventional stakeholder analysis and biological inventories, and to integrate local knowledge as a specific component of the assessment (Baird et al., 2014). The tool is generally applied in six phases, illustrated in Figure 3.1. Although depicted as a linear process, it is usually rather iterative.

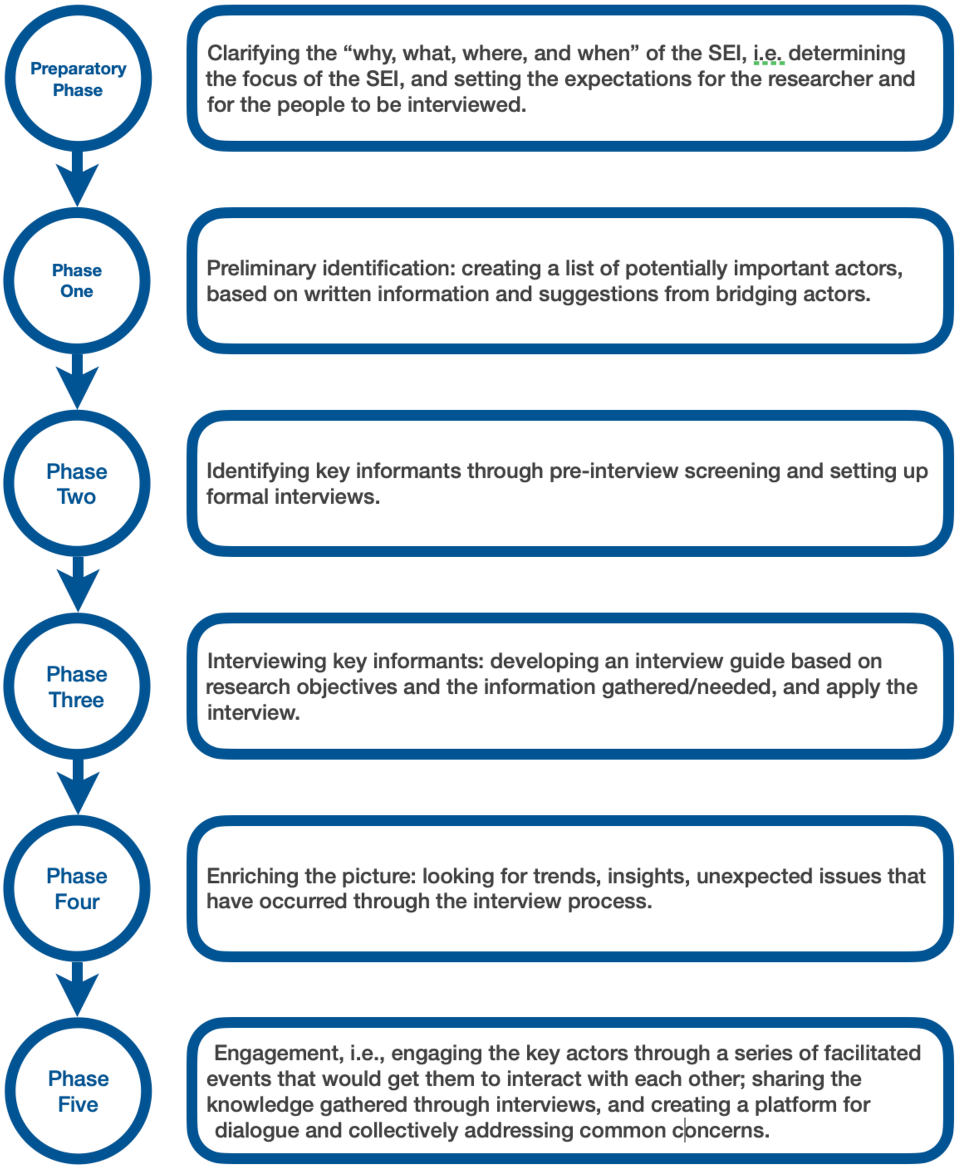


Figure 3.1. The general phases of applying a socio-ecological inventory (redrawn after Schultz et al., 2011). The last step might constitute the potential beginning of a renewed SEI process.

Based on a participatory process, conducting a SEI helps identify the current social and environmental issues and major impacts that climate change is expected to have on a SES. Schultz and colleagues (2007) illustrated a first example of the SEI implementation process in Kristianstads Vattenrike Biosphere Reserve. It has since been applied in diverse contexts, including to document the drivers, pathways, and mechanisms of resilience following an earthquake in a community in New Zealand (Cradock-Henry et al., 2019), to identify and start characterizing the permaculture landscape ecological design movement in Portugal (Oliveira and Penha-Lopes, 2020), as well as to bring together and facilitate a regional governance group to support climate change adaptation in Canada (Baird et al., 2014).

3.2.2. Network Governance in a Watershed

Virtually all natural and social systems can be considered social-ecological systems once they are looked at through such an integrated SES lens. In some cases, a SES is defined on the basis of a community that interacts with a given ecological system, or on the basis of an ecological system that provides for multiple communities and/or is governed by multiple institutions. An example of the latter is a river basin or watershed (Cabello et al., 2015). In fact, Rockström and his colleagues (2009) argue that the watershed scale "offers the best opportunities for water investments to build resilience in small-scale agricultural systems and to address trade-offs between water for food and other ecosystem functions and services".

Multiple SES studies and resilience assessments have been conducted at watershed scale (Andersson et al., 2011; Cosens and Fremier, 2014; Bhangaonkar and Fennell, 2021). In at least some watershed SESs, there is no one single formal governance institution. Instead, the governance of the SES is polycentric, making it a network governance setting. The same is the case for Ikel watershed in this research.

Network governance bodies are co-management entities in which a variety of different state and non-state actors participate, structured by different institutional arrangements (Carlsson and Sandström, 2008; Pittman and Armitage, 2017), without necessarily having a very clear set of rules or norms by which actors abide.

In the recent decades, to cope with issues and settings that grow in complexity, network governance (Jones et al., 1997) and polycentric governance (Ostrom, 2010) formats have become increasingly frequent. Both network governance and polycentric governance are network-based governance systems defined by informal cooperative arrangements, higher levels of actor diversity and opportunities for repeated interaction between these actors (Duit and Galaz, 2008; Pittman and Armitage, 2017).

Network governance is a form of inter-organizational coordination characterized by organic or informal social systems. This contrasts with bureaucratic structures within these entities and formal contractual relationships between them (Jones et al., 1997). After its introduction by Jones and collaborators in relation to the way in which firms from different industries perform their transactions, the concept was used in such contexts as governance of commons (Carlsson and Sandström, 2008; Giest and Howlett, 2014), urban ecosystem services (Ernstson et al., 2010), landscape conservation (Scarlett and McKinney, 2016), and adaptation to climate change (Juhola and Westerhoff, 2011.

3.3. System Dynamics Modeling

System Dynamics (SD) modeling primarily helps analyze complex interdisciplinary problems with a high degree of uncertainty rather than help resolve operational problems. More specifically, model building, and analysis helps understand the structure of the system that gives rise to a particular problem considered as being of interest or concern.

SD models are representations of a complex reality, a theory of how a real system operates over time. They are used to test theories in artificial settings, to explore the implications of various scenarios and policy interventions. Model analysis and experimentation by computer simulations contribute to easy and inexpensive evaluation of system behavior under various intervention options in a consequence-free environment. While some models are *ex post* forecasting ones (e.g., statistical forecasting), the SD models are causal, *ex ante* projecting mathematical models (Winz et al., 2009), which can address the fundamental structural causes of the long-term dynamic problems that require an interdisciplinary approach (Barlas, 2002).

A SD model embodies a theory about the way in which a system works with regards to some of its aspects (Barlas and Carpenter, 1990). Its main advantage is not the precision, but the provision of valuable tools for analysis, building foresight and guiding decision-making. It is also the modelling approach that is considered by decision makers generally relevant for simulating interconnected systems into the future (European Commission, 2015).

The modeling process takes place according to a well-defined procedure and steps (Sterman, 2000; Barlas, 2002), and can conclude with qualitative, conceptual models known as causal-loop diagrams (CLDs), or with formal simulation models, that support both a qualitative and a quantitative analysis. The established modeling process includes the following major steps (Sterman, 2000):

1. *Problem articulation*: defining the model purpose, the real problem that the modeler is trying to address.
2. *Formulating a dynamic hypothesis*: developing a working theory that could provide an explanation of the observed and anticipated behavior of the system and dynamic of the problem under study. At this point the modeler tries to identify the underlying feedback and stock and flow structure of the system that gives rise to the problem.
3. *Formulating a simulation model:* calibrating model parameters with data, defining and refining mathematical and logical definitions of relations between stocks, variables and parameters.
4. *Model testing and validation*: applying various structure and behavior validation tests to ensure that the model is adequately representing the real system being modeled.
5. *Policy design and evaluation*: testing and analyzing various policy options, creation of new strategies, structures or decision rules, and identifying leverage policies when necessary.

Many practitioners praise its usefulness for learning in and about complex SESs. It has been used extensively for educational and decision-making purposes, to develop a learning tool for managers and consumers to reduce water consumption (Stave, 2003), educate and engage the public in water planning process (Tidwell et al., 2004; Clifford-Holmes et al., 2017), evaluate consequences of various policy alternatives for agricultural sustainable development (Saysel et al., 2002) and flood management (Ahmad and Simonovic, 2000), and other purposes. Yeh and colleagues (2006) took a step further in developing such learning and decision-making tools by integrating ArcView, Excel and Vensim programs to make an interactive computational model to simulate soil erosion, sediment yield and resulting nutrient pollution together with related economic factors.

More recent work of some system dynamicists (Kopainsky et al., 2013; Schülter et al., 2019, Herrera and Kopainsky, 2020) has highlighted several synergies between SES framework and system dynamics approach. They showcased how SD can contribute to the representation of the complexity of interactions and of feedback effects within the SES, to the identification of trade-offs between different sets of SES services, to providing participatory approaches and social learning, exploring new pathways for adaptation and transformation, and providing management strategies for the SES in focus modeling. This renders system dynamics models capable of representing multi-scale and multi-level processes central to social-ecological systems frameworks, and further supports the resilience assessment inquiry set forth in this research.

3.3.1. Group Model Building

A SD model can be developed in several ways: it can be an endeavor of a single modeler, it can be done by a group of system dynamicists that build a model for a client group, or it can engage stakeholders in the process. Stakeholder engagement can happen at different stages with varying degrees of involvement in the model development (van Bruggen et al., 2019).

Group model building (GMB), sometimes also referred to as mediated modeling (van den Belt, 2004) is a technique or sometimes a group of techniques employed for participatory modeling. Among SD modeling practitioners, it is a common practice that involves stakeholders in the model conceptualization and/or development process, where "team members exchange their perceptions of a problem and explore such questions as: what exactly is the problem we face? How did the problematic situation originate? What might be its underlying causes? How can the problem be tackled?" (Vennix, 1996). Due to the "policy formation and analysis" character of SD models, the purpose of GMB is often to foster model buy-in, build consensus in decision-making, and heighten the motivation to turn insight from model analysis into concrete action (van Bruggen et al., 2019). Therefore, the model is usually created in close interaction with the client group, such as policymakers or managers.

System dynamicists have extensively used GMB for consensus building, decision-making, and gaining support for the implementation of the resulting policies (Rouwette et al., 2002; Scott et al., 2016; Herrera and Kopainsky, 2020). GMB has been shown to be beneficial at individual and collective levels, including: participants' learning about the problem, the credibility and acceptance of modeling results (Rouwette et al., 2002); changing participants' attitudes, intentions and subjective norms, albeit sometimes participants might not directly realize them (Rouwette et al., 2011); enhancing the understanding of the resource systems and the effects of alternative management decisions (Sterman, 1994; Stave, 2003; Turner et al., 2016); changing the perceptions of stakeholders about the mechanisms that drive the system's behavior and supporting participants' learning about the system, as well as supporting evidence-based decision-making (Herrera and Kopainsky, 2020).

An important remark however is that the benefits of GMB largely depend on case characteristics, such as size of groups, complexity of models, time investment, the way in which the scripts for the model building process are made and implemented, correspondence of the levels of aggregation between the resulted model and mental models of GMB participants, whether the analyzed model was conceptual (CLD) or a formal simulation model, and others (Rouwette et al., 2002). To ensure that more effective outcomes result from the GMB process, some recommendations made by its proponents and seasoned practitioners are that the outcomes are discussed among the GMB participants (Rouwette et al., 2002), that modeling project results in actionable insights for GMB participants (Rouwette et al., 2011), or that additional or alternative tools are used to link SD insights and implementation (Herrera and Kopainsky, 2020).

As mentioned, in GMB practitioners usually build specific types of models, i.e., SD models, by mapping variables and the relation between these into a web of relations that would include at least one internal feedback, i.e., CLDs. The process of GMB includes several steps, summarized by Andersen et al (1997) and shown in Figure 3.2.

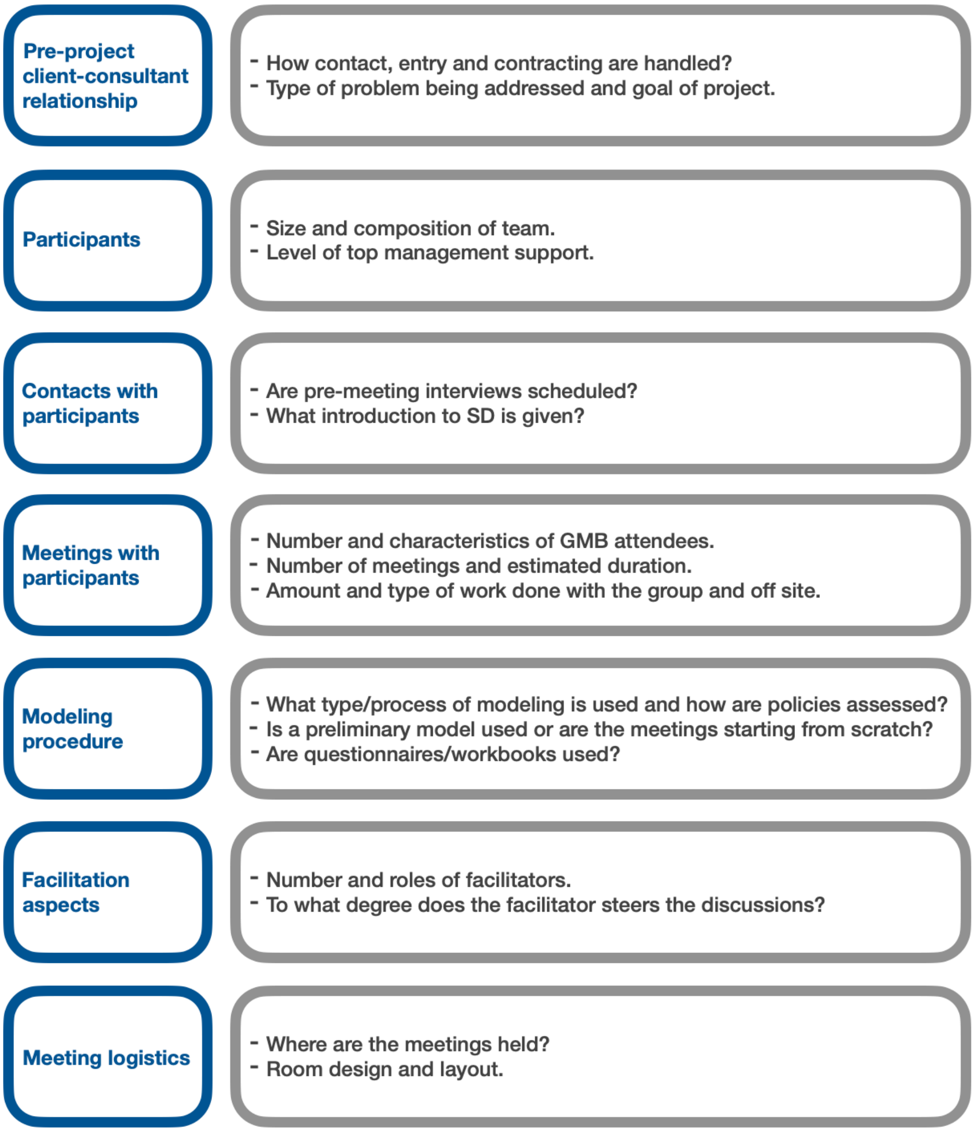


Figure 3.2. Components of group model building (adapted from Andersen et al., 1997)

The characteristic of GMB that objective facts are separated from individual values held by participants allows the GMB process to focus primarily on the description and diagnostic of a system's structure that gives rise to the problem (Vennix, 1996; Neuwirth et al., 2015). Depending on the desired outcome of the modeling process, the GMB activity can either conclude with the analysis of the resulting causal loop diagram or with a more in-depth analysis of the system behavior based on a dynamic feedback simulation.

Although GMB is most frequently used in SD modeling and is therefore uniquely associated with this field, it can be used with other modeling paradigms (van Bruggen et al., 2019). Recently, Herrera and Kopainsky (2020) successfully undertook the endeavor to integrate GMB and SD modeling in the process of planning the resilience of food systems in Guatemala to climate change impacts. In the last stages of my research, I have built on their experience to conduct resilience assessment as part of policy analysis and design stages of SD modeling with relative contribution of GMB participants.

4. RESEARCH DESIGN

4.1. Combining System Dynamics Approach and Resilience Assessment within SES Framework

As described in the previous chapter on methodological approach, I undertake a case study to conduct resilience assessment by combining the SES framework and system dynamics approach. Thus, system dynamics modeling methodology is used to conduct a participatory resilience assessment of Ikel watershed viewed as a socio-ecological system. The resilience approach informs the initial stages of the research where the main vulnerabilities to climate change are identified. Then, system dynamics methodology is applied in two steps: for building the conceptual model through a group model building activity, and then for building a formal simulation model. Social-ecological inventory and group model building are employed in a coupled manner to engage stakeholders in this process (Figure 4.1).

The model is then used to assess the resilience of Ikel watershed to specific climate change impacts, as well as the effectiveness of various resilience-building policies. The step-by-step research process detailed in Section 4.2 *Detailed Research Steps*.

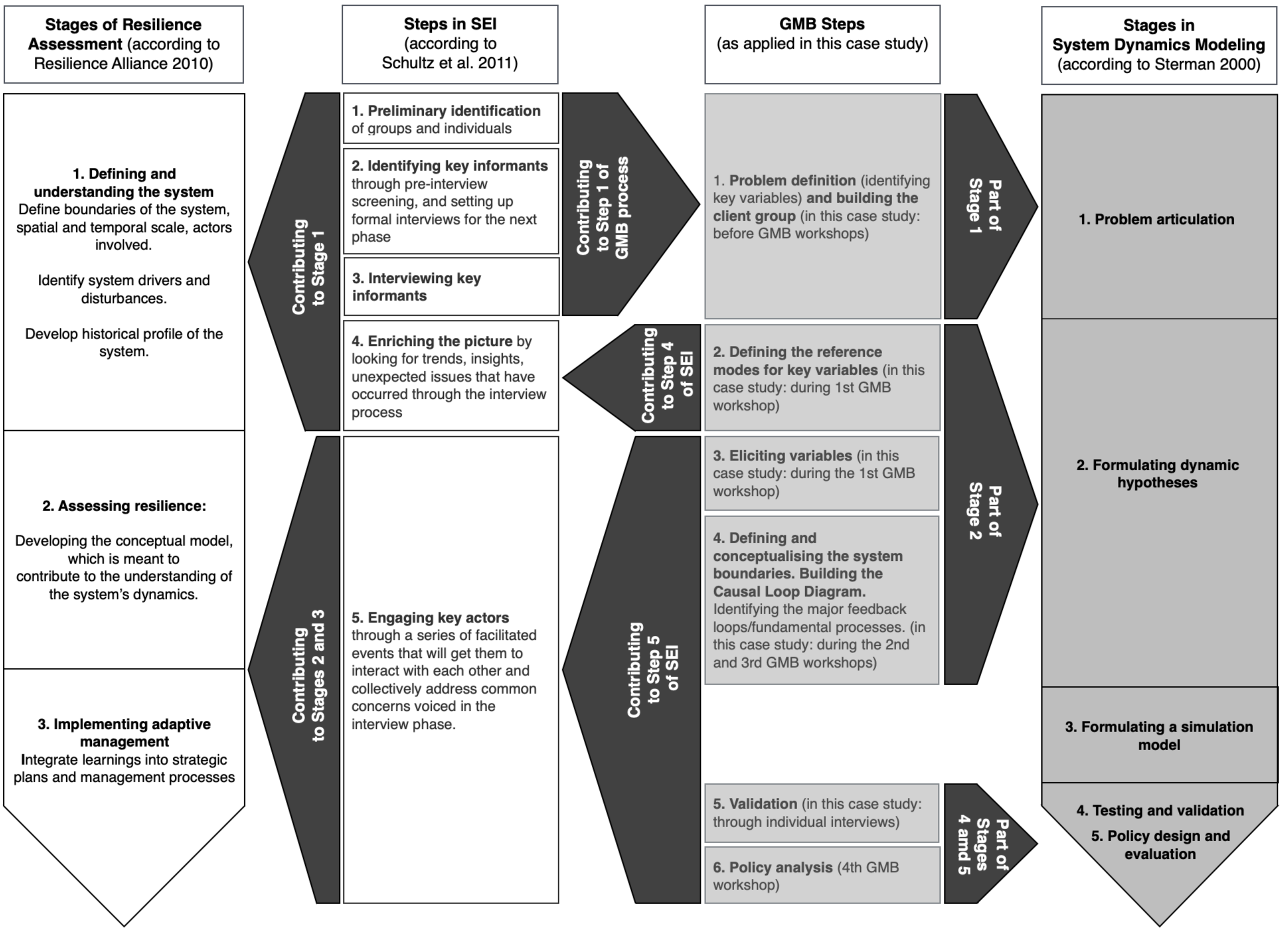


Figure 4.1. Flowchart representing the coupled use of SEI and GMB processes, and their places and roles in their respective approaches.

4.2. Detailed Research Steps

The step-by-step research process is summarized in Table 4.1 below. As shown in Figure 4.1 and mentioned in the previous section, it starts with a coupled use of SEI and GMB techniques. This is meant to contribute both to defining and understanding the system, as proposed by the resilience framework, and to the definition of the dynamic problem, as required by the SD approach. A detailed description of each research step is presented below.

In the 1st step of the research, SEI in a network governance setting is applied. I start form the Ikel watershed committee and its secretarial organization, the National Environmental Centre (NEC), a local NGO, as the bridging actors. Having an experience of more than 15 years in the field, NEC has helped identify a number of 55 potential key informants. I then individually interview 25 out of 55 potential local stakeholders from different organizations to identify perceived vulnerabilities to climate change impacts in the Ikel watershed. The interviewed stakeholders come from public institutions, local and national public authorities, non-governmental organizations, farmers, academia and international organizations (Appendix C). The resulting information was processed and analyzed. This provided a list of over 50 issues that interviewees have seen as potentially important local impacts of climate change. The issues were ranked in order of frequency and importance, with the top three most important impacts selected for validation at the research step. Additionally, based on the interviews, a group of 20 participants was set up for the first GMB workshop (Appendix C).

The 2nd step of the research is the first GMB workshop (Figure 4.2). For this, detailed scripts have been developed in advance, based on a context-based adaptation of elicitation techniques proposed by Andersen and Richardson (1997). During this workshop, I validate the results of interviews, introduce the modelling process, system dynamics thinking and modelling vocabulary and tools. I proceed with eliciting reference modes for the 3 key variables identifies through the interviews, and further elicit additional model variables.

In the 3rd step, a draft causal loop diagram is prepared by us based on the outcomes of the GMB workshop. This draft CLD depicts the fundamental processes at work in the Ikel watershed, and is intended for feedback, validation and strengthening of ownership during one-to-one discussions with each GMB participant, which happens during the 4th research step. The individual meetings result in a series of inputs for the conceptual model, which I then integrate into a more refined version of the CLD.

Table 4.1. Overview of the research design.

Research step	Resilience approach within SES framework	System dynamics modeling	Resilience assessment in system dynamics modeling
Step 1	**Defining and understanding the system** Defining the social-ecological boundaries of the system, that is spatial and temporal scale, actors involved. Identifying system drivers and disturbances, developing a historical profile of the system	**Definition of the dynamic problem:** Defining key variables and reference modes	System dynamics methodology provides the tools to identify the key variables of concern for a group, to define and conceptualize the system boundaries and identify the "system drivers". Group Model Building activities help identify the current social and environmental issues and major impacts that climate change is expected to have on the watershed.
Step 2		**Definition of the dynamic problem:** Eliciting variables.	
Step 3		**Definition of the dynamic problem:** Defining and conceptualizing the system boundaries; identifying the "system drivers", i.e., the major feedback loops.	
Step 4	**Assessing resilience:** Developing the conceptual model, which is meant to contribute to our understanding of the system's dynamics	**Model conceptualization** describes the dynamic hypothesis in a qualitative manner. This step is the concrete basis for formal model construction.	Developing the conceptual model is a step in the resilience assessment where system dynamics modelling has already somehow started to be employed.
Step 5			
Step 6	-	**Formal model construction** is the numerical step. At this stage the stock-flow diagram is built, numerical values of parameters and initial values of stocks are estimated, and mathematical formulations that describe cause-effect relations for all variables are defined.	SDM methodology requires the transition from a conceptual to a formal model at an earlier stage. This has the potential to facilitate the completion of a later stage in resilience assessment (*Synthesis of resilience understanding*), where I identify the components of resilience and adaptability.
Step 7			
Step 8			
Step 9		**Model validation** or validity testing	This is an important step for developers and users to gain confidence in the developed formal model, that is currently absent in the Resilience Assessment framework mostly because of the absence of formal, quantitative models.
Step 10			
Step 11	**Assessing resilience:** Identifying possible alternate system regimes, controlling variables, thresholds and possible future scenarios	**Policy analysis: sensitivity analysis** Simulation experiments are done to assess how much the output behavior of one (or more) variables of interest changes as a result of changes in selected parameters, inputs, initial conditions, or other structural changes.	What resilience assessment practitioners refer to as "alternate system regimes" is what in system dynamics modelling can be defined as a change in dominance of different feedback loops. Naturally this cannot be accurately done without a formal/numerical simulation model. This, I argue, is where the system dynamics methodology can prove particularly useful through the development of a quantitative model.
Step 12	**Assessing resilience:** Exploring likely interactions among thresholds. Cross-examination of the conceptual model(s) with known resilience and adaptability attributes.	**Policy analysis:** Model analysis. Alternative policies are designed, and interaction of policies is considered.	Exploring likely interactions among thresholds is something that has been identified as "technically challenging and an active area of research" in resilience assessment literature. Having developed a formal model this, I propose, is a task performed during the model analysis step of the system dynamics methodology.
-	*Identifying the cycles of change and cross-scale interactions*	*This step is not a matter of modelling at this point in time, and thus does not constitute the focus of this research*	
Step 13	**Understanding implications for management interventions** aims at identifying the implications for policy and management without specifically recommending anything.	**Policy analysis** including formal simulations.	Having a SDM based formal simulation model is likely to make it possible for the modeler and beneficiaries to test and experiment the different scenarios and implications for management interventions in different "sectors" of the model.
Step 14			
Step 15	**Synthesizing resilience understanding** This stage is aimed to help identify the points of intervention in the system for managing resilience.	**Communication and implementation**	Here, I propose, the system dynamics modelling with its methodology has the potential to help identify the leverage points where interventions for resilience building can yield best results with minimum relative effort and will provide the needed support for adaptive management/ governance.
Step 16			

Figure 4.2. Images from the working process during the 1st Group Model Building workshop.

For the 5th research step, I organize the second GMB workshop (Figure 4.3). Here I do a walk through with workshop participants to validate the last version of the causal loop diagram, to discuss and build a common understanding among GMB participants of the system under study. At this point, I also elicit a set of initial policy options for building resilience to climate change and build consensus around how certain policies might influence the system overall. Further, we start the process of building the formal simulation model: buildup of stocks, flows, auxiliary variables, and information connectors. This workshop features six participants, less than half of those at the first GMB workshop.

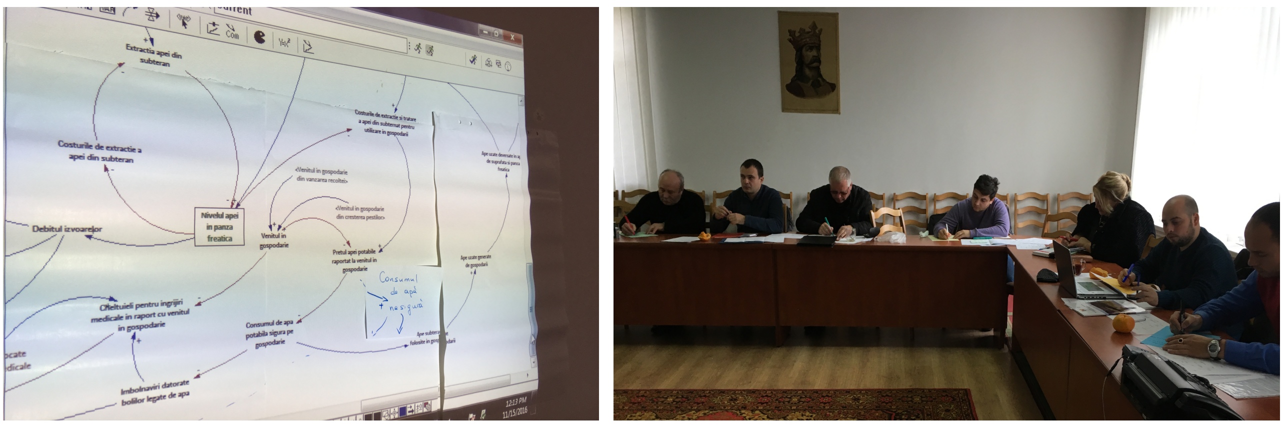


Figure 4.3. Images from the working process during the 2nd Group Model Building workshop.

With the conclusion of the 5th research step, I have a conceptual model of the system that is the basis of resilience assessment in many previous resilience studies. Similarly, many SD practitioners consider it a tool good enough for the description of the dynamic hypothesis and qualitative analysis of the system under study. Yet, a CLD is also the concrete basis for formal model construction. The process of transition from a conceptual, qualitative model to a formal simulation one, is not explicitly covered by the resilience framework. However, the SDM methodology requires precise interventions for the transition from a conceptual to a formal model. These interventions make up steps 6 to 10 in my research.

During the 6th research step, I proceed with the construction formal simulation model. This takes place between the second and the third GMB workshops. Here I draft the initial version of the stock-flow diagrams for each model sector. I then conduct the third GMB workshop as part of the 7th research step, where, together with the GMB participants, I do a first set of direct structural validation tests for the developed stock-flow diagrams (Figure 4.4).

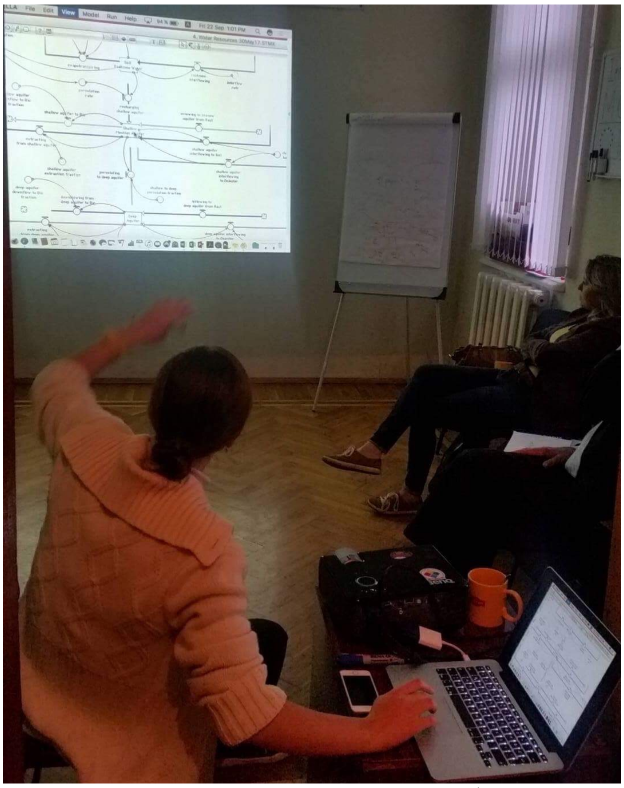


Figure 4.4. Image from the working process during the 3rd Group Model Building workshop.

The 8th research step consists of individual work of the researcher. At this stage, I continue the refinement and further direct structural validation of the stock-flow with stakeholders through individual interviews (Appendix C). Once a satisfactory structure is developed, I proceed with writing down mathematical formulations that describe the cause-effect relations for all variables. I then compile a list of data requirements containing most of the parameters in the model and proceed with estimating the numerical values of parameters and initial values of stocks. Further, I develop and test the formal computer model.

The 9th research step starts the process focused exclusively on model validation. At this stage, I check dimensional consistency with realistic parameter definitions; robustness of each equation under extreme conditions; extreme condition simulations. I then proceed to the 10th research step, which consists of conducting individual interviews for further structural validation with GMB participants and other stakeholders - mainly experts in relevant fields of study.

Step 10 of the research concludes the main efforts of structural validation of the formal model and continues with behavior validation. Both sets of validity testing are described in detail in chapter 8. "Validation".

After model validation, the research continues with step 11, where, from an SD perspective I run simulations to do sensitivity analysis, while from a resilience perspective - to identify controlling variables and thresholds. In SD terms, I also do simulation experiments to assess how much the output behavior of one (or more) variables of interest changes as a result of changes in selected parameters, inputs, initial conditions, or other structural changes. In resilience terms, this process contributes to the identification of possible future scenarios.

Then, in the 12th step, I run simulations to do policy analysis, in SD terms, or else to design alternative policies and consider their interaction. From a resilience standpoint, this step is defined as exploring likely interactions among thresholds and cross-examination with known resilience and adaptability attributes.

According to the resilience study framework, this step would be followed by efforts to identify the cycles of change and cross-scale interactions. However, this step is not a matter of modelling at this point in time, and thus does not constitute the focus of this research.

The 13th research step includes mainly individual work, where I simulate various management options, including those proposed earlier by the GMB participants and other stakeholders. This is part of policy analysis in the SD framework, but it is also part of the stage in the resilience study (step 14), where I try to understand the implications for management interventions. This understanding aims at identifying the implications for policy and management without specifically recommending anything.

In the 15th research step, I continue to work individually to identify the components of resilience and adaptability, and thus the points of intervention in the system for managing resilience. Then, during step 16, I organize a concluding seminar to communicate the outcomes to decision makers and interested stakeholders. Both steps are equally part of communication and implementation stages of the SD framework, and of synthesizing resilience understanding within the resilience framework.

4.3. Addressing Data Scarcity

In Section 2.1.2 *Challenges With Data Availability*, I have shown that data scarcity is one of the expected challenges in this research. To address this challenge, I adopt an approach whereby I seek to first ensure that I make use of most reliable and accurate data possible, and when that is not possible - the best possible estimate for the required data.

As indicated in the UNDP report on data ecosystems for sustainable development in developing countries including R. Moldova (2017), the main source of official information in the country is the National Bureau of Statistics (NBS). Therefore, I have used it as the first data source. Furthermore, the report confirms what the majority of stakeholders in this research have indicated, which is that institutions of public administration are the most likely places of data collection, processing, analysis and access. For this reason, I consider it as the second source of data for my research. However, it has been confirmed in multiple sources, including the cited report, that multiple gaps related to ensuring data exchange and sharing (see Section 2.1.2), makes it difficult to access the necessary data from these institutions. That is why, I resort to additional information sources, such as: national reports, legislation and other official documents, datasets and reports published by international organizations, studies and reports of national and international academia, articles and reports published by civil society organizations, and press articles.

Additionally, I resort to practices previously employed by the scientific community to address similar challenges, such as combining expert knowledge with local data and Bayesian approaches. Multiple studies found that expert knowledge can improve estimation under scarce data and compensate for data scarcity (Scholten et al., 2013; Shen et al., 2015). For some data points where none of these resources provide satisfactory and reliable information, I resort to estimations based on fundamental textbooks and comparable cases from elsewhere in the world. I present the data source hierarchy in Figure 4.5.

In the specific case of Ikel watershed, it is important to note that none of the social, economic, environmental or climatic data has been collected by the Moldovan authorities at watershed level. In the best of cases, the highest data resolution available from the NBS is provided at county levels, towns, and summed values for all villages in a county. This makes it difficult to make us of the official data to calculate various indicators at watershed level. To infer data for Ikel watershed, I proceed in one of the following ways:

- When data is available at national level only, I make us of the average national value or values given for the central region of Moldova (e.g., precipitation, temperature).

- When data is available at county level, I calculate a weighted average of the counties based on the share of the counties that make up Ikel watershed. For example, 26 % of Călărași county is within the boundaries of Ikel watershed. 71.1 thousand people were living in Călărași county in 2019. I infer that 71.1 thousand x 26 % = 18.49 thousand people from Călărași county lived in Ikel watershed that year. I calculate the values from other counties in a similar way, and then assume that the sums of these represents the number of people who were living in Ikel watershed in 2019.

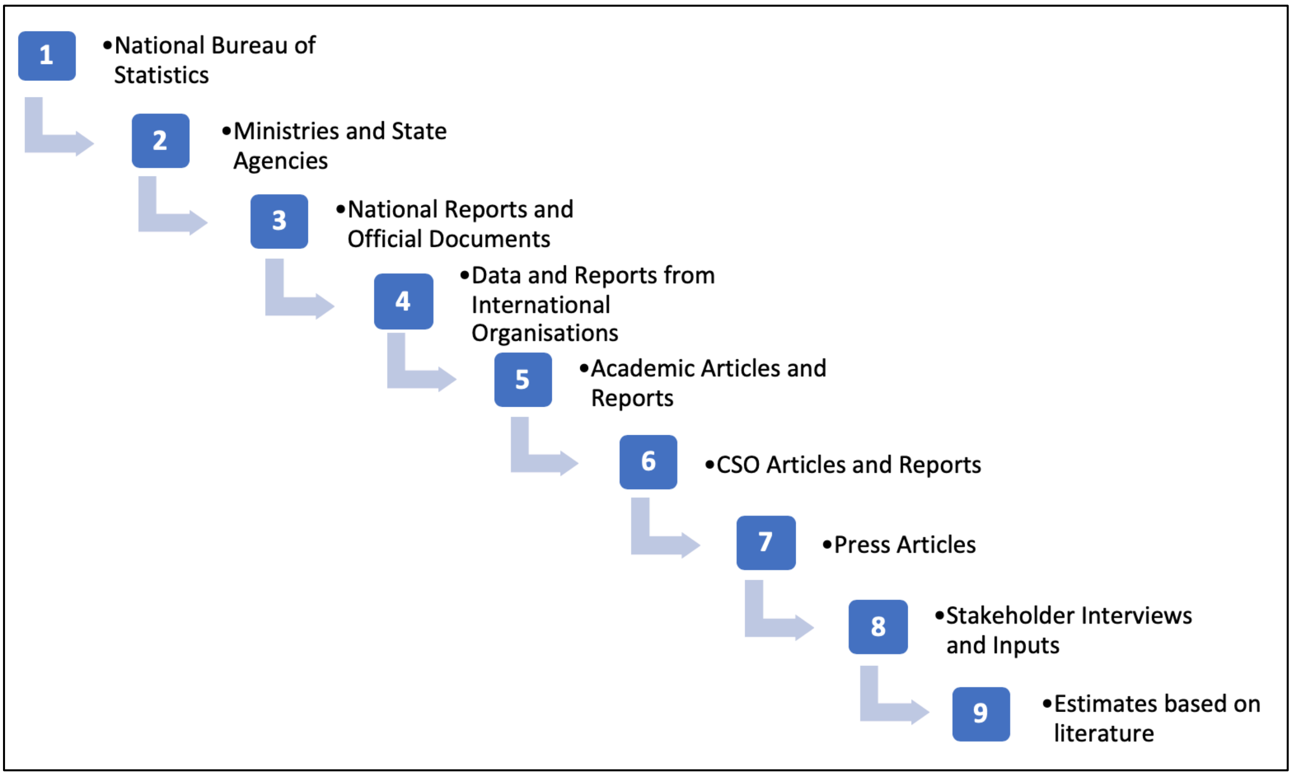


Figure 4.5. Hierarchy of data sources utilized in this research, in order of their priority.

5. PROBLEM IDENTIFICATION PROCESS

In this chapter, I introduce the problem as defined by the stakeholders through the sequential use of SEI and GMB, illustrated Figure 4.1 and detailed in Chapter 4 above. I first present the insights from applying the SEI. Then, I define the problem development over time in system dynamics terms. The latter is helpful and necessary in order to proceed with building the conceptual and formal simulation models described in chapters 6 and 7 respectively.

5.1. Insights from Applying the Social Ecological Inventory

Individual interviews carried out with the 25 stakeholders before the first GMB workshop, revealed that anticipated local impacts of climate change include, among others, concerns related to: declining quality of environmental factors, ecosystem health, reduced ability of communities to maintain or improve their access to water supply and sanitation, threats to food security, financial inability to compensate for losses incurred due to extreme weather events, declining public health, reduced local income diversity, growing out-migration, dependency on foreign aid. Interviewees perceived the situation in much of the impact areas as declining, with moderate hope for improvement, should no additional efforts be taken.

The results of individual interviews were discussed, and there was a consensus among first GMB workshop participants that the main concerns were (Figure 5.1):

1. Agricultural productivity, or crop yield per area of land.
2. Groundwater availability, or the amount of water in the shallow and deep aquifer that can be used.
3. Biodiversity, or richness of local species of land and water flora and fauna.

We define these as key variables central to the dynamic problem to be analyzed in system dynamics terms (Sterman, 2000).

Looking at ongoing actions related to climate change adaptation in the area that aim to reduce the vulnerability of key variables, and looking at the role of stakeholders, participants mentioned a few grass-root activities. The National Climate Change Adaptation Strategy was mentioned as one of the most important processes happening at the national level. Participants underlined the need for an adaptation of the latter at the watershed level. However, given the limited budget available, they emphasized the need for a prioritization of adaptation policies and activities based on a better understanding of optimal intervention points.

Despite the perceived importance of local action, there was a general disbelief in the willingness and capacity of the local communities to take voluntary action to increase resilience. The interviewees placed great value on the role of the Central Government to take measures, while at the same time noting that since R. Moldova’s independence from USSR (in 1991), the Government had failed consistently to do so. Nonetheless, activities carried out by civil society organizations, local public-private partnerships, and local governance networks, such as the Ikel Watershed Committee, were highlighted as potential contributors to some level of successful intervention locally. A key role in supporting climate change adaptation efforts was generally attributed to external aid and development programs from international institutions, such as the United Nations, European Union, Swiss Agency for Development and Cooperation, Austrian Development Agency, and others.

5.2. Defining the Problem Development Over Time

System dynamics modeling is generally employed to understand the structure of the system that gives rise to a problem (elaborated in more detail in Section 2.3). To define the problem and thus start the modeling process, the questions that SD practitioners commonly ask are along the lines of “What is the problem development over time?”, “Why and how does the problem occur?” or “What are the processes within the system that create or worsen the problem?”. Consistent with this, I can formulate the concerns identified through SEI as follows:

- Why does or might the agricultural productivity, groundwater availability and local biodiversity decrease? How does that happen? What are the internal feedbacks in the Ikel watershed SES that are responsible for these dynamics?

- How can the stakeholders improve the resilience of these key variables to climate change impacts, such as prolonged draughts, increase in average temperature, increase in rainfall intensity, and increase or decrease in average precipitation?

The past and future time horizon for the problem, as well as the reference modes were also defined during the first GMB, which took place in 2016. At that time, participants considered that the roots of the problems lie about 30 years back in the past. It was also suggested that we consider a similar time frame into the future.

Reference modes are tools commonly used in SD modeling as graphs over time to visualize problematic behavior and preferred behavior and conduct behavior validation of the model (Andresen and Richardson, 1997; Sterman, 2000; Schwaninger and Groesser, 2018). During the first group model building workshop, we revisited the historical profile of the system and expressed the changes in key variables as graphs/reference modes (Figure 5.1).

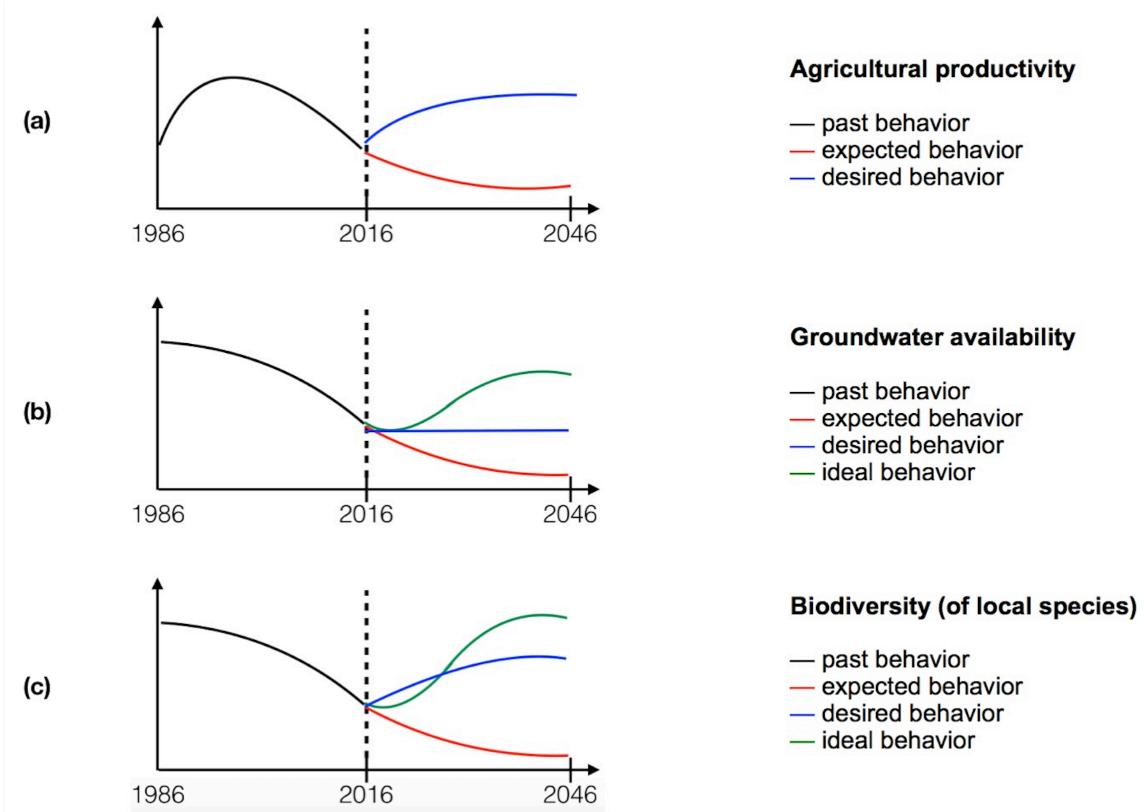


Figure 5.1. Reference modes of key variables, as elicited from participants in GMB workshops. *Agricultural productivity* (a), *Level of water table in wells and groundwater* (b), *Biodiversity of local species* (c). The reference modes depict the behavior of variables in the past 30 years (in black), the behavior that GMB participants expect to see in the next 30 years under current conditions (in red), the behavior that GMB participants desire to see in the next 30 years (in blue). For the key variables "Levels of water table in wells and groundwater", and "Biodiversity" participants also expressed a more optimistic (ideal) scenario for the next 30 years (in green).

Firstly, we considered how each of the key variables has changed in the past 30 years. Thus, according to workshop participants: agricultural productivity has seen a steady increase until mid-1990's, followed by a decrease; groundwater availability has been slowly declining both in terms of quantity and quality; and biodiversity of local species has been slowly declining.

Secondly, participants discussed and agreed on the expected behaviors of key variables in the following 30 years. Participants reconfirmed during the workshop that, should no additional efforts be put into climate change adaptation, the three key variables would continue to decline.

Thirdly, we considered the desired behavior of variables under focus in the future. In this case, participants expressed two types of desired scenarios: the desirable scenario, and the ideal scenario. For the desirable scenario: agricultural productivity would increase and reach the level experienced in the early 1990s; groundwater availability would remain at its current level without further decline; and biodiversity would slightly increase compared to its current situation. For the ideal scenario: groundwater availability would go back to the levels registered at the beginning of 1990s, whereas the biodiversity would increase to a level exceeding the one at the beginning of 1990s.

Having defined the problematic behavior of the key variables, the reference modes, and the desired alternatives, which equally mark the beginning of a drafting process for the system's boundary, I then proceed to defining the dynamics hypothesis.

6. CONCEPTUAL MODEL

In system dynamics, the formulation of dynamic hypothesis is a gradual process. Initially, a set of possible theories are identified that could explain the problematic behavior. These are commonly represented as cause-and-effect relation. For example, less crop yield might be caused by smaller amounts of precipitation; it might also be caused by decreasing soil quality. The set of possible causes may be rather large. However, it constitutes the basis of identifying endogenous causalities of the feedback structure. Starting from this endogenous feedback structure, we develop maps of causal structures which are richer in variables. This SD modeling step is in line with what the resilience practitioners would call “identifying system drivers and disturbances”, which also precedes the development of a conceptual model.

6.1. Endogenous Feedbacks Emerged from Group Model Building

During the 1st GMB workshop, causes and results of change in the key variables were elicited from GMB participants during the first GMB workshop (Figure 6.1).

Figure 6.1. Images from the 1st Group Model Building workshop depicting the process of eliciting model variables.

The elicitation process started to reveal interconnections between the key variables. For example, one such example is the availability of water for irrigation. One participant mentioned it as a cause for change in agricultural productivity, while another participant suggested it as an effect of change in availability of groundwater, i.e., if there is less groundwater available in the aquifer, less of it can be used to irrigate crops, leading to a decreasing agricultural productivity in water intensive crops. Similarly, an effect of reduced agricultural productivity would affect the environment due to growing demand for additional land. This in turn would lead to converting natural land into arable land, negatively affecting its biodiversity. Because of the difficulties posed by measuring biodiversity (Duelli, 2003; Lyashevska and Farnsworth, 2012), participants agreed to use the area of natural and forested land as proxies for management and policy (Moser et al., 2002; Stephens et al., 2015).

In-between workshops, I reformulated and integrated the proposed variables into a comprehensive causal loop diagram (Appendix A) and distilled the main processes within Ikel SES depicting the dynamic hypothesis. These processes are described by four reinforcing causal loops in Figure 6.2, Figure 6.3, Figure 6.4, and Figure 6.5. They include key variables and climate change threats and provide a first conceptual insight into what could contribute to eroding or increasing the resilience of key variables as identified by the GMB participants. The dynamic hypothesis and the comprehensive causal loop diagram were validated during individual meetings with GMB participants and during the second workshop.

In the causal loops, key variables of interest are marked with green color. Relationships with positive polarities (i.e., change in one variable causes the connected variable to change in the same direction) are depicted with blue arrows, while negative ones (i.e., change in one variable causes the connected variable to change in the opposite direction) – with red. Processes which happen much slower compared to the other processes are illustrated with a delay mark on the causal arrow (||).

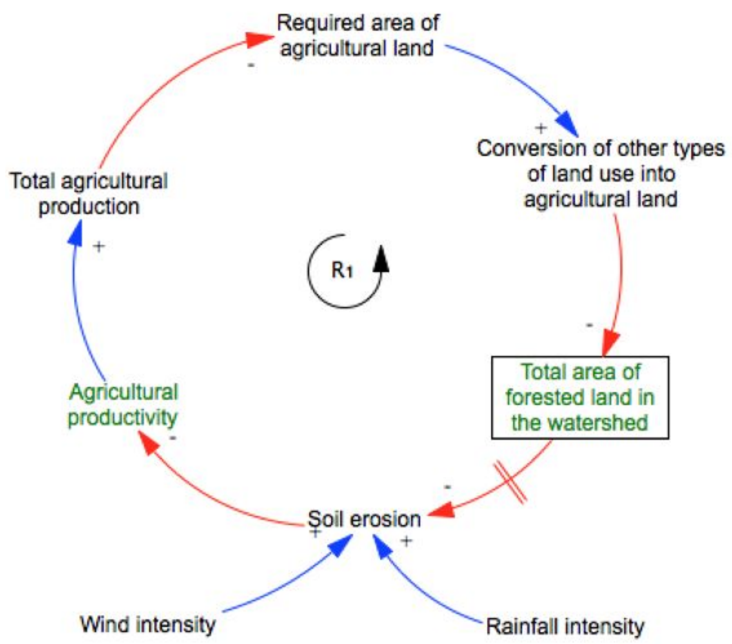


Figure 6.2. Reinforcing loop R1 shows how the attempts to increase total agricultural production requires other types of land use to be converted into arable land. This determines a decrease in other types of non-arable land use, included forested or bioproductive areas. After a longer period, through exposing the land to erosion factors, soil erosion increases, which in turn leads to lower levels of productivity of the exposed arable lands, and thus, to smaller amounts of total crop production.

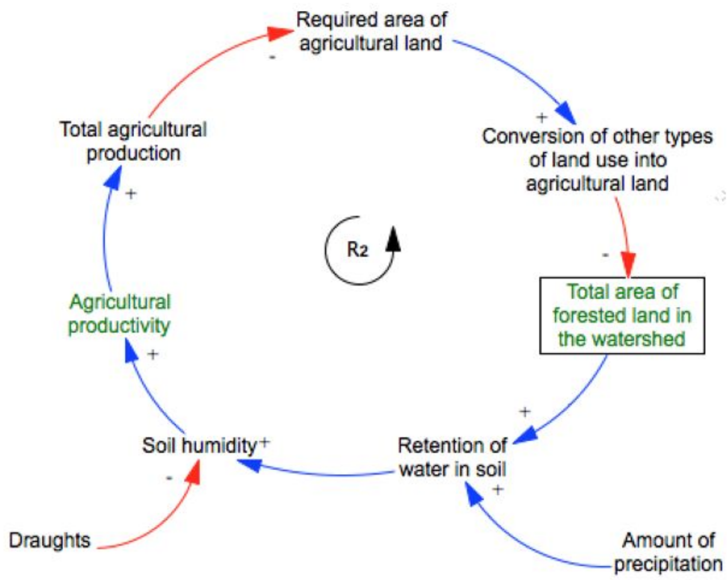


Figure 6.3. Reinforcing loop R2 shows how, similarly to the process described for R1, conversion of forests and other bioproductive lands into arable land to increase total agricultural production triggers a decrease in soil humidity. Deprived of sufficient water, agricultural productivity and consequently total crop production decrease.

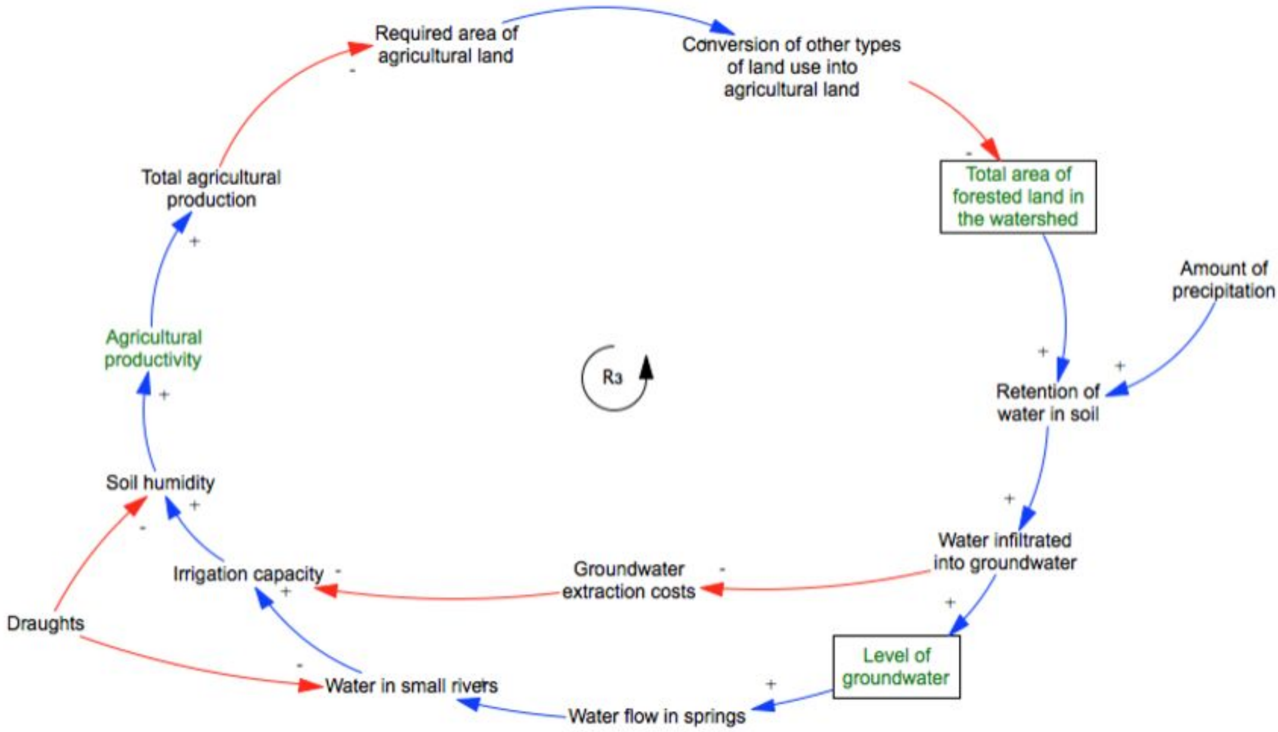


Figure 6.4. Reinforcing loop R3 shows how conversion of forests and other bioproductive lands into arable land is done to increase the total agricultural production. This, however, triggers a decrease in soil water retention capacity and in infiltration and percolation of water, which determines a decrease in groundwater stock. With less and deeper water, the extraction costs increase, and the irrigation capacity decreases. Soil humidity decreases and eventually the agricultural productivity and total production decrease, as well.

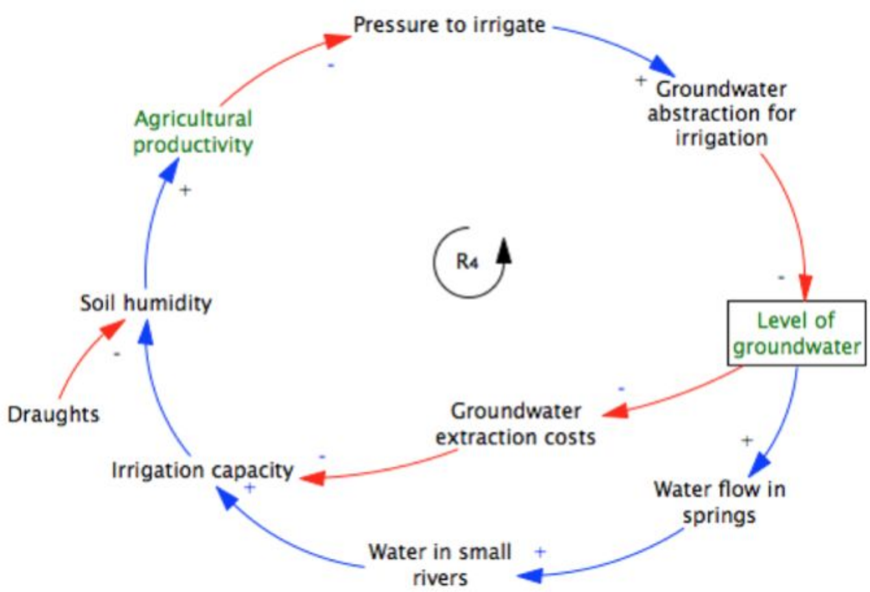


Figure 6.5. Reinforcing loop R4 shows how, with the decrease in agricultural productivity of arable land due to insufficient soil humidity, the pressure to irrigate increases. This leads to an increase in abstraction of water for irrigation, further reducing the level of groundwater. With less and deeper groundwater available, the water in small rivers decreases, limiting the irrigation capacity due to lack of surface water, while the extraction costs increase, limiting irrigation capacity due to high extraction costs of groundwater. A decrease in irrigation capacity further contributes to a decrease in soil humidity on arable land.

6.2. Model Boundary

The comprehensive CLD encompassing all variables proposed by GMB participants has proven to be extremely broad. Although helpful in understanding the complexity of the system, it included a high volume of information that did not fit the purpose of Ikel CliRes model and elaborated excessively on the main processes. In addition, its complexity breached the basic principle in SD of modeling a problem, not a system. Consequently, the variables from the comprehensive CLD were classified into endogenous, exogenous and excluded ones (Sterman, 2000). Endogenous factors are linked through causal relations to several causal loops. Exogenous factors are those who influence the dynamic of the system but are not influenced by it in turn. Excluded factors are those not taken into account in developing the simulation model. The model boundary diagram that summarizes the list of endogenous, exogenous and excluded variables is presented in Figure 6.6 below.

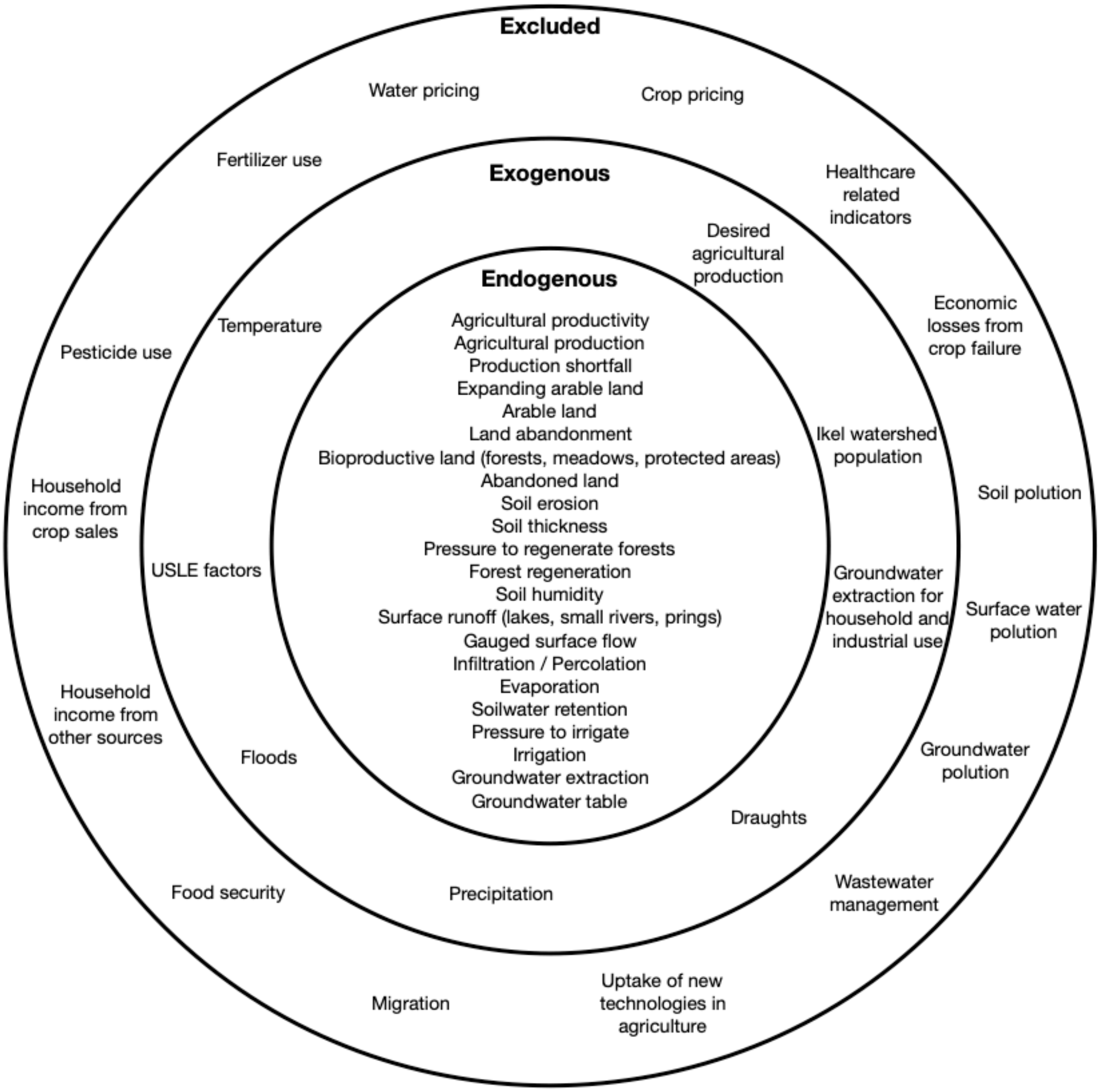


Figure 6.6. Model boundary diagram listing which of the variables elicited from GMB participants were considered as endogenous, exogenous and excluded for formal model building.

6.3. Conceptual Model

Based on the inputs from GMB participants, on distilling variables by focusing on the main processes and on the endogenous consequences of the feedback structure, a more refined version of the causal loop diagram has been produced (Figure 6.7). The resulted conceptual model includes endogenous and exogenous variables and has been validated through individual interviews with GMB participants.

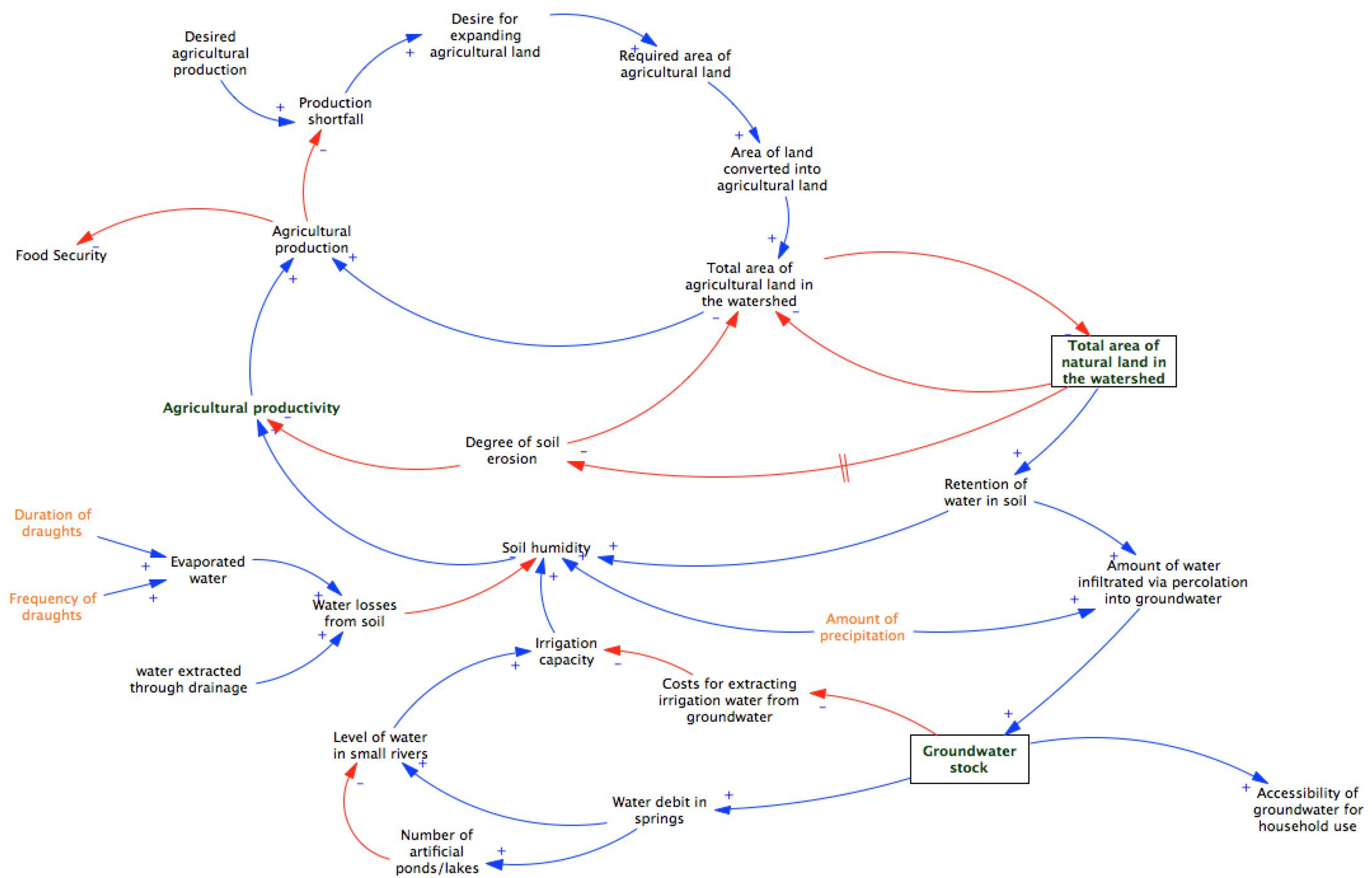


Figure 6.7. Conceptual model depicting the major loops that connect the key variables, as identified by the GMB participants. Red arrows indicate a negative polarity, blue arrows indicate a positive polarity. Key variables are highlighted in green color. Climatic variables are highlighted in orange color.

The conceptual model combines the four main processes described above and illustrates the interplay between them. The validation process for this CLD implied a walk-through of the GMB participants during the individual interview. Additionally, another round of walk-through was conducted during the 2nd GMB workshop with all the participating stakeholders, followed by a generic discussion about the implications of change in certain variables of choice. After this discussion, participants generated a list of preliminary policy options (Table 6.1).

Table 6.1. Policy options proposed by stakeholders following the analysis of the conceptual model.

1	Increasing of forested area and involving citizens in reforestation
2	Increasing the access to water supply systems
3	Reducing land abandonment of productive arable land and support its reintroduction into the production circuit
4	Increasing/rehabilitation of forest strips (for the protection of arable land) with walnut/fruit/melliferous tree species
5	Improving environmental law enforcement to reduce illegal logging and breaching of existing environmental legislation
6	Reforestation on degraded, unproductive or agriculturally inaccessible lands
7	Increasing the length and surface of forested area in sanitary protection areas of rivers and lakes
8	Rehabilitation of natural wetlands

The possibility to have group discussions on the conceptual model depicting the main processes prompted the participants to prioritize climate change actions at watershed level. This resulted in a five-year Local Watershed Climate Change Adaptation Plan that was adopted by the watershed committee (Ikel Watershed Committee, 2016). Some of the actions proposed there started to be implemented before the dynamic feedback simulation had been developed (Biotica, 2017).

From a resilience assessment perspective, eliciting policies for resilience building from participants, and integrating them into strategic plans completes the stage of resilience assessment (Resilience Alliance, 2010). When putting forward policies for resilience building, stakeholders base their proposals on a conceptual model, since the potential of proposed policies/measures to increase resilience can be analyzed descriptively. A conceptual model can take many forms. A SD model is but one of possible alternatives for this purpose.

From a SD perspective, the developed conceptual model is a suitable tool for learning about the system and for putting forward some possible policy options, as well. However, to test such proposed policies, the SD modeling process requires that a formal simulation is built, validated and analyzed.

7. FORMAL MODEL DESCRIPTION

The formal model, built on the basis of the conceptual model with relative contribution of the GMB participants, consists of about 160 variables and four main sectors representing different environmental, social and agricultural components. In the next subsections, I illustrate the sector overview of the model, and describe the major input-output relations between the sectors. Then, a more in-detail description of each sector is provided, including stock-flow structures, variables, equations and assumptions. The formal simulation model is built using the STELLA software and submitted on an external USB device (memory stick).

7.1. Ikel CliRes Model Overview

Ikel CliRes model consists of four major inter-connected model components, which we refer to as sectors: *Water resources, Irrigation, Erosion,* and *Drivers of change in land use* (Figure 7.1). The dynamic described in model sectors do not reflect the dynamic within an economic sector with the same name. An additional, smaller sub-sector is connected to the latter by providing information on *agricultural workforce availability* in Ikel watershed. The key variables are concentrated in two of the sectors: *Water resources* and *Land use.* All sectors exchange information and material, which are depicted as arrows. A short description is attached to the arrows. Each sector in the diagram contains the major variables in that sector. Additionally, the diagram highlights specific climatic variables that affect each of the model's sectors.

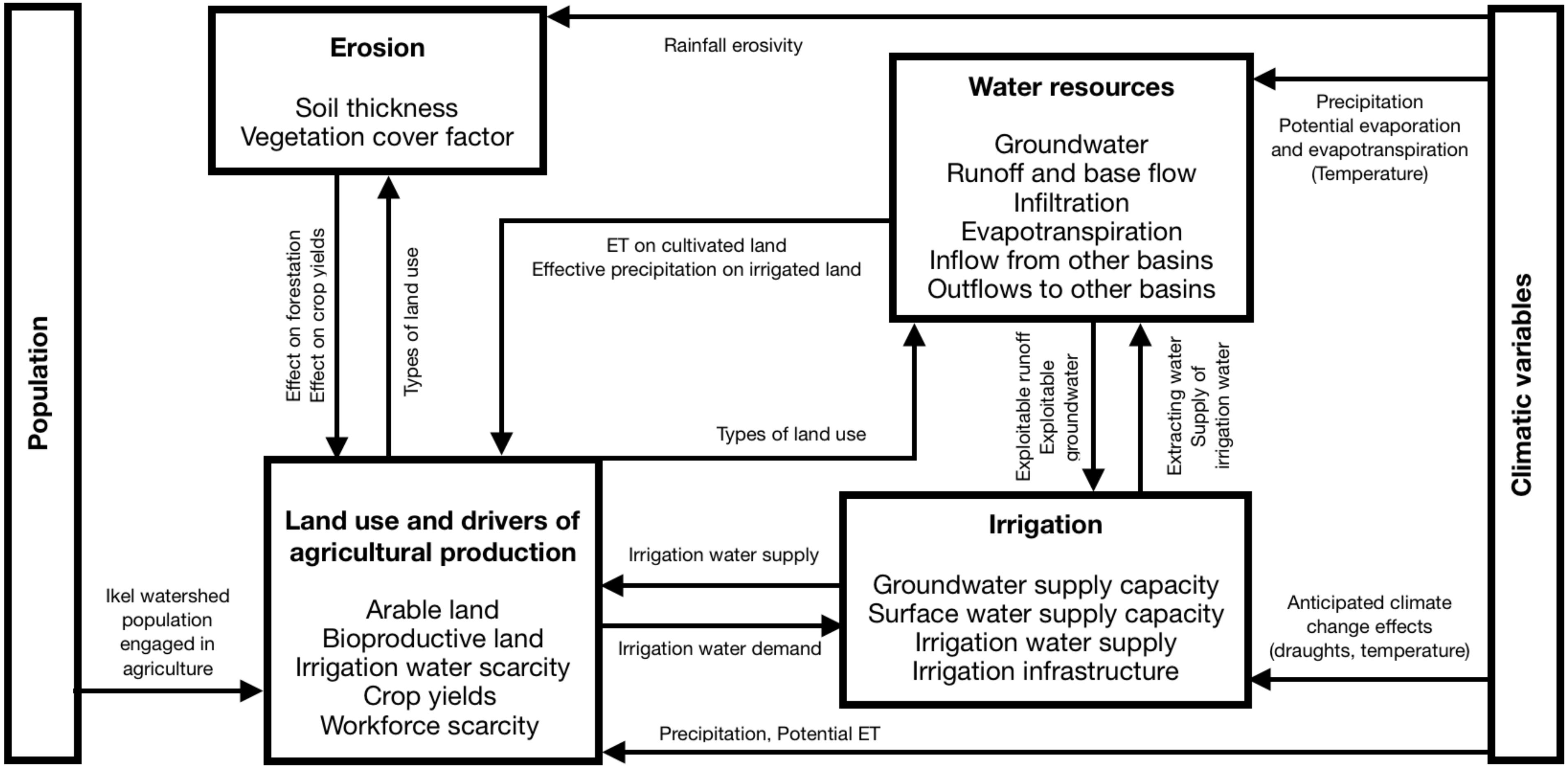


Figure 7.1. Overview of the formal simulation model.

Ikel CliRes receives external information on rainfall erosivity (in the erosion sector), precipitation, temperature-related effects on evaporation and evapotranspiration (in the water resources sector), information for climate related forecasts (in the irrigation infrastructure sector), and precipitation and information on potential evapotranspiration (in the drivers of change in land use sector).

7.1.1. Water Resources

This sector builds the water budget of the watershed. It also provides evapotranspiration on arable lands and effective precipitation on irrigated arable land to the land use sector. It receives information on types of land use from the land use sector, supplies the irrigation infrastructure sector with information on exploitable runoff and on exploitable groundwater, and receives from this sector supply of water from irrigation.

7.1.2. Irrigation Infrastructure

The irrigation infrastructure sector receives information on irrigation water demand from land use sector. At the same time, it supplies irrigation water to the land use sector. It also receives information on exploitable runoff and exploitable groundwater from water resources sector, as well as runoff and groundwater for irrigation. This sector provides the water resource sector with information on the amount of groundwater extracted and supplies it with water from irrigation.

7.1.3. Erosion

Erosion sector receives information on types of land use from land use sector and provides it with information on the effects of soil erosion on forestation and on crop yields.

7.1.4. Drivers of Change in Land Use

This sector supplies the water resources and erosion sectors with information on types of land use. It also supplies the irrigation infrastructure sector with information on irrigation water demand. It receives water supply from the irrigation infrastructure sector, ET on cultivated land and effective precipitation from water resources sector, and information on the effect of soil erosion on forestation and on crop yields from the erosion sector. Furthermore, it also receives information on Ikel watershed workforce engaged in agriculture.

7.2. Model Sector Descriptions

7.2.1. Water Resources

This sector builds the watershed water budget, looks at the dynamics of water availability in surface and groundwater resources depending on climatic variables, land use and demands for human consumption. It also generates the exploitable water resources and determines the water available for crops, which in turn inform other sectors of the model.

To inform this sector, build the structure, calibrate parameters, and define variables, three main data sources were used: governmental institutions (including NBS, the Agency for Geology and Mineral Resources - AGMR, and the Ministry of Environment and Agriculture), scientific literature (including studies and reports), and stakeholder inputs (including participants of GMB process and external stakeholders: local experts, researchers, decision-makers, reporters). Wherever data was not available, assumptions were made based on textbooks on the subject and existing international scientific literature. Sources for each variable are presented in Table 7.6 below.

Generally, R. Moldova is highly dependent on surface water resources. The main sources for surface water supply are Diester and Prut rivers. Moldova's Environmental Agency estimates that approximately 85 % of water is abstracted from surface waters nationally, which means 15 % of all abstracted water comes from groundwaters. The total volume of water resources that are available from an economic point of view is 5.6 km^3. This includes 4.3 km^3 of surface water and 1.3 km^3 of groundwater (FAO ECA, 2012).

Within the scope of this research, water resources in Ikel watershed are conventionally divided in two: surface water resources (including Ikel river, lakes, subsurface flows and shallow groundwater) and deep groundwater. In this sector all surface water resources including unconfined aquifers located above the first aquitard (a thick layer of clays) are aggregated into single variables that build up the runoff.

Surface waters are replenished from precipitations (Table 2.5) and, to a certain extent, from deep groundwater that is extracted, used and then discharged from households, industrial settlements or irrigation surplus into surface water bodies. Water from the Dniester River itself is used in parts of the watershed for irrigation and other technical uses. The infiltration and surface-runoff fractions vary greatly depending on specific conditions such as the type of land-use, types of soils, saturation, slope:

sandy soils, bioproductive lands and flat areas have, on average, a lower runoff and higher infiltration coefficient values.

The deep groundwater aquifer located in the Baden-Sarmatian bedrock layer at an average depth of 100-200 m below surface (Teleuta et al., 2004) is confined between the upper aquitard and lower aquitard. It is replenished by groundwater inflows from upstream. This aquifer consists of three groundwater bodies (Figures 2.10 – 2.12), which are aggregated in Ikel CliRes model as a single deep groundwater stock *GW* (Figure 7.5).

As shown in Chapter 2.2, the bedrock of Ikel watershed has a slight northeast-southwest inclination, becoming deeper towards the southern region of the country. As a consequence, the deep groundwaters typically flow from the north to the south of the country and of the Ikel watershed. GW stock under Ikel watershed and subsequent upstream aquifers are recharged mostly from precipitations falling in the upper region of the Dniester Basin, which flow downstream due to inherently interconnected nature of all aquifers in Dniester Basin (OSCE/UNECE, 2005). Hence the confined groundwater under Ikel is replenished by inflows from the deep groundwater stocks under Răut watershed to the north and drained by outflows into the deep groundwater stocks of the Bîc watershed to the south (Figure 2.13). In addition to inflows from groundwater aquifers located upstream, the confined groundwater also receives a certain amount of water through percolation from the surface water bodies. Due to the very low permeability of the aquitard separating the latter from the deep groundwater stock and due to the depth of the aquifer, the percolation process is rather slow.

There is currently no limitation on the amount of water that can be abstracted from confined aquifers. The legislation in place currently requires that water bodies be identified, and protection areas designated if more that 10 m^3/day are being abstracted from them, or if it supplies water for more than 50 people (Law 272/2011 and Law 249/2018). Although country-level data on abstracted water from surface and underground sources is available, the Environmental Agency and the law do not make a clear distinction between the abstraction of shallow and deep groundwater.

Overall, water abstraction has decreased by 75 % nationally between 1990 and 2000 (Figure 7.2). Since then, water extraction is considered to be relatively constant, with an annual average of 725 million m^3 (MEA, 2020). Table 7.1 details the data on water abstraction by source at national level. Approximately 84 % of the underground waters are estimated to be abstracted from Dniester watershed. This figure, however, is believed to be highly uncertain, and the amounts of water abstracted from underground aquifers are, in fact, much larger (MEA, 2020).

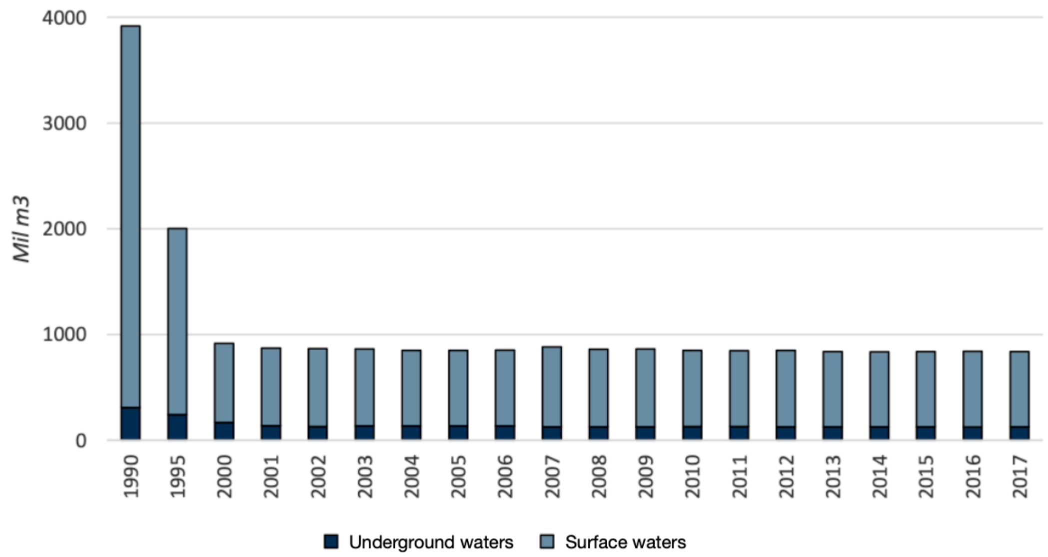


Figure 7.2. Evolution of water abstraction from 1990 to 2017 in R. Moldova (MEA, 2020). Actual data is likely to vary.

Table 7.1. Water abstraction from underground and surface resources between 1990 and 2017 at national level. Official data is likely to vary from actual data (MEA, 2020).

Year	Underground water abstraction (million m^3)	Surface water abstraction (million m^3)
1990	311	3607
1995	244	1761
2000	168	750
2001	138	736
2002	132	734
2003	135	729
2004	135	717
2005	136	716
2006	136	718
2007	129	756
2008	127	734
2009	129	736
2010	130	721
2011	130	718
2012	129	721
2013	128	711
2014	127	710
2015	128	712
2016	126	717
2017	127	713
2018	128	709

At municipal and county level, NBS provides the values of abstracted water from subsurface and confined aquifers combined, and only for years 2008 – 2018 (Table 7.2). In Ikel CliRes, this value is estimated based on weighted average of county-level data.

Table 7.2. Water abstraction from aquifers per administrative region in Ikel watershed (counties and Chișinău municipality) between 2008-2018, in millions m^3 (NBS).

	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
m. Chisinau	90,1	88,3	84,4	79,9	80,1	76,9	76,2	75,6	78,4	74	71
r. Calarasi	1,2	1,5	1,4	1,4	1,4	1,4	1,5	1,5	1,4	1,4	1,5
r. Criuleni	2,8	2,1	2	2	2	1,8	2,2	2,5	2,1	2,1	2,3
r. Orhei	3,7	4,4	4	4	3,9	3,6	3,5	3,4	3,6	3,8	3,9
r. Straseni	1,3	1,3	1,3	1,5	1,5	1,6	1,8	1,8	1,8	2,2	2,4
r. Ungheni	3,1	3,6	3,3	3,6	4,1	3,5	3,1	3,4	2,9	3,2	3,1

Figure 7.3 below illustrates the share of water abstraction by sector, according to official records, and Table 7.3 details the figures of water abstraction in the agriculture forestry and fishing sector.

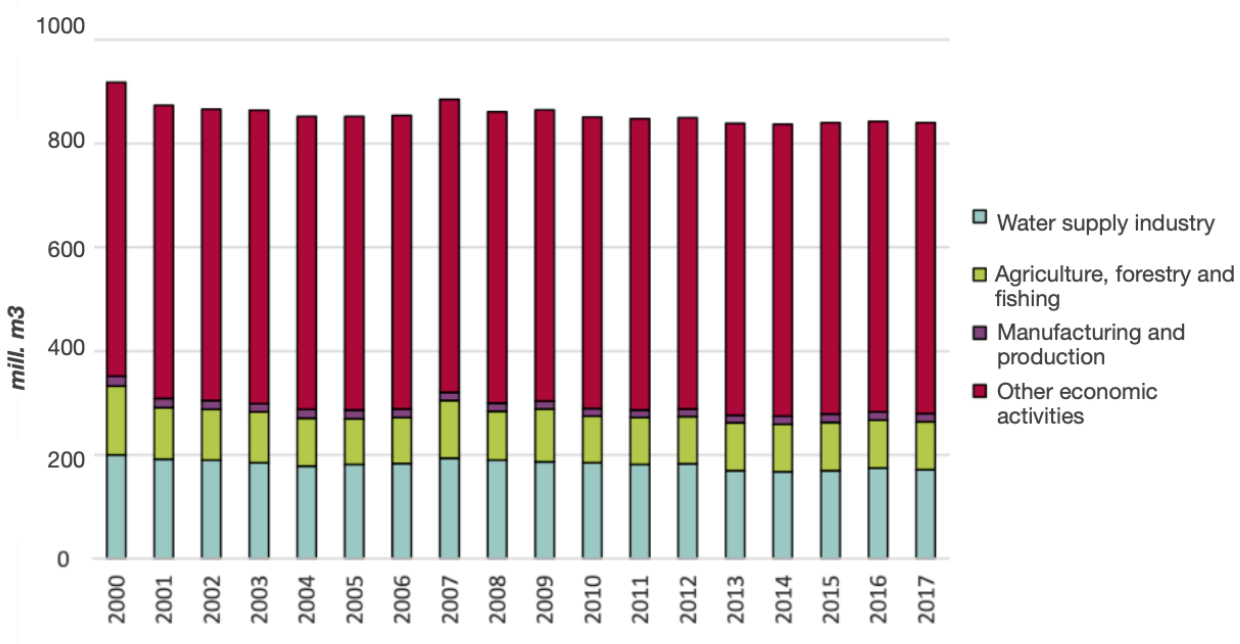


Figure 7.3. Evolution of water abstraction in R. Moldova between 2000-2017, by sector (MEA, 2020). Actual data likely to vary.

Table 7.3. Annual water abstraction in R. Moldova between 2000-2017, by sector, in million m^3 (MEA, 2020). Actual data likely to vary.

Year	Agriculture, forestry and fishing	Municipal water supply	Manufacturing and production	Other economic activities
2000	121	200	19	566
2001	87	192	18	565
2002	91	190	17	561
2003	85	185	16	565
2004	80	179	17	564
2005	76	88	17	565
2006	76	88	17	565
2007	95	111	16	564
2008	80	94	16	561
2009	89	102	15	561
2010	76	185	15	561
2011	76	182	15	561
2012	76	183	15	561
2013	83	170	15	562
2014	83	168	16	562
2015	81	170	16	561
2016	82	175	16	560
2017	81	172	16	560

It should be noted, however, that governmental institutions caution on data uncertainty, which is very high, especially with regards to individual abstraction of groundwater and surface water (MEA, 2020). There is no control over how people use the supplied tap-grade water, with many farmers and local consultants confirming that part of municipal waters supplied to small hold farmers is used for irrigation. Moreover, due to weak institutions, many wells are being drilled by farmers to use underground water either illegally or under the "special use" pretense (i.e., manufacturing, other economic activities). They remain operating under the radar due the lack of monitoring and law enforcement, which steam from the weakness of state institutions.

Figure 7.4 below illustrates the simplified, single-stock diagram of the *water resources* sector, while in Table 7.6 I provide the list and description of parameters used to calibrate this sector. This sector does not feature notable feedback looks, but rather influences and is influenced by processes in other sectors.

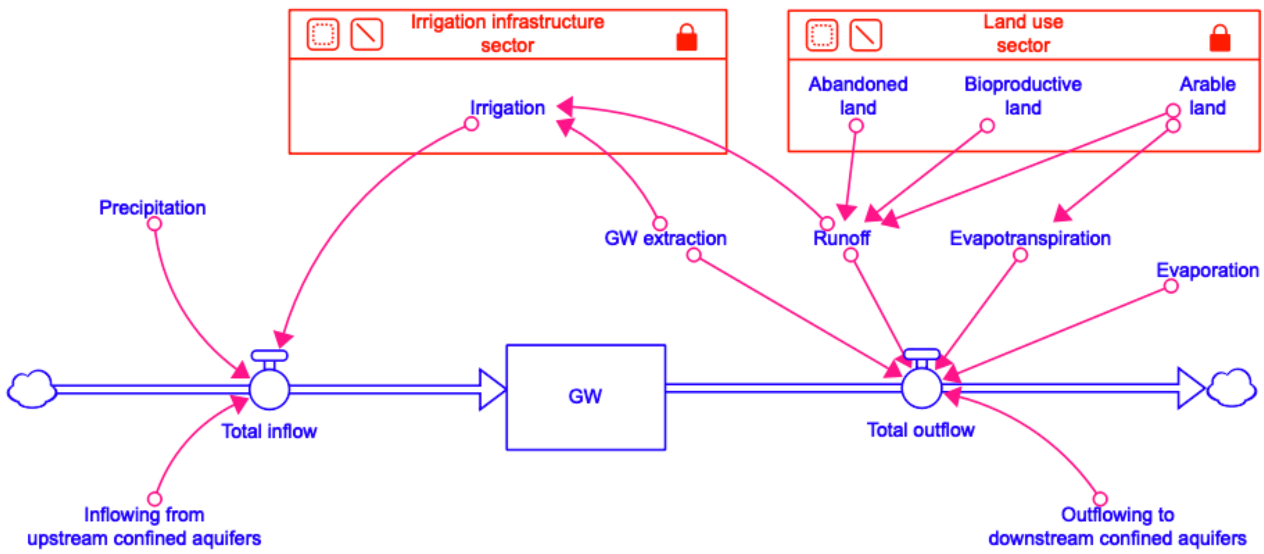


Figure 7.4. Overview of the *water resources* sector, which builds the Ikel watershed budget. The stock-flow diagram illustrates the total inflows and outflows that determine the groundwater stock.

Groundwater stock is replenished through inflow from upstream aquifers, precipitation and irrigation water that percolates through the upper aquitard. It is decreased directly with outflows to downstream aquifers and with extraction for household and industrial use, as well as for irrigation purposes (Figure 7.5).

$Groundwater_t = Groundwater_{t-1} + (Percolation\ from\ non\text{-}irrigated\ land + Percolation\ from\ irrigated\ land + inflowing) - (outflowing + extracting)$ {m^3}.

In this model, the inflow and outflow equations are defined as shown below.

*Percolation_from_non-irrigated_land = infiltration_on_non-irrigated_land * Percolation_fraction* {m^3/year}.

*Percolation_from_Irrigated_Arable = infiltration_on_Irrigated_Arrable * Percolation_fraction* {m3/year}.

Figures for percolation rate in Ikel watershed are not available, therefore the corresponding parameter an assumed value (Table 7.6). I also check the sensitivity of Ikel CliRes to different values of this parameter in the designated chapter below.

inflowing = equilibrium_shortfall / Recharging_time {m^3/year}.

In line with the climate change scenarios, which foresee more intense rainfall and therefore more runoff and less infiltration and percolation in the groundwater recharging area (middle and upper Dniester Basin), this trend is reflected in the Ikel CliRes model as decreasing speed of recharge, i.e., increasing recharge time. More specifically, it is assumed that:

- between years 1990 - 2025, *rech_t = 10 years*.
- between tears 2025 - 2035, *rech_t* increases from 10 years in 2025 to 15 years in 2035.
- between years 2035 - 2050, *rech_t = 15 years.*

*outflowing = Groundwater * Outflow_fraction* {m^3/year}.

extracting = MIN (GW_supply_for_irrigation + Household_and_industrial_use; 0) {m^3/year}.

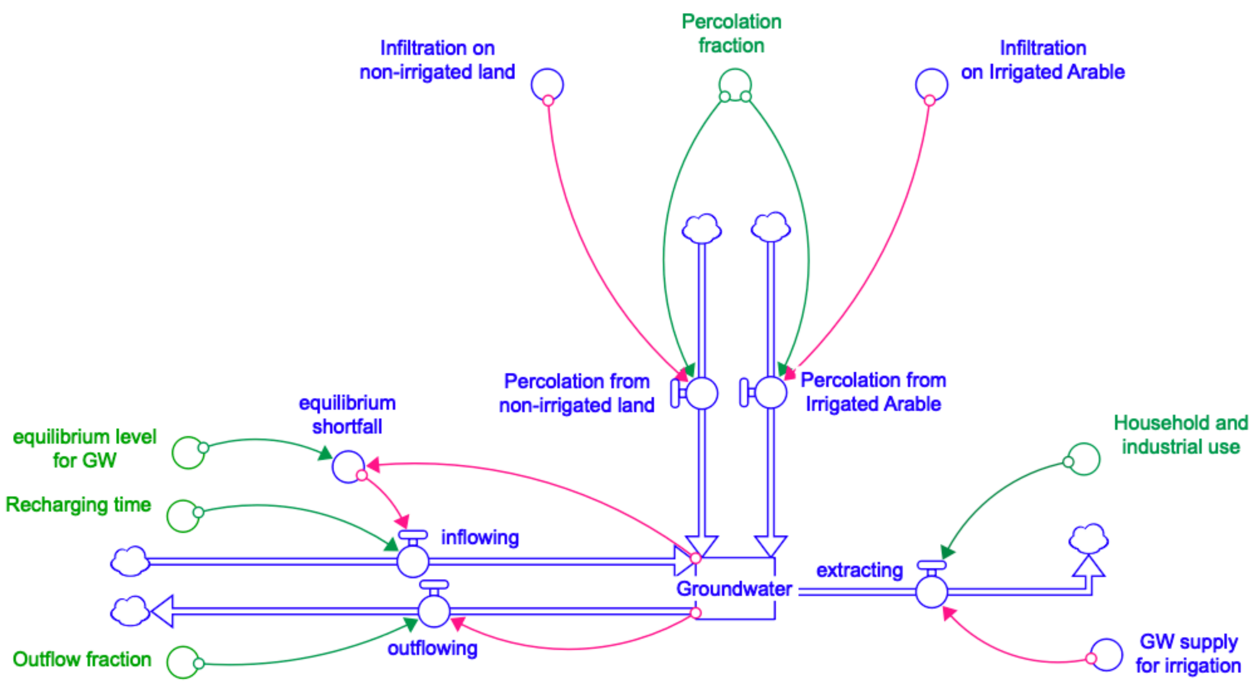


Figure 7.5. Stock-flow structure including the inflows and outflows to/from the groundwater stock. Parameters (exogenous variables) are highlighted in green color.

Inflowing rate is conceptualized as being dependent on the recharge time and on the shortfall between the existing groundwater stock at a given time and what is called an "equilibrium level" of the groundwater stock:

equilibrium_shortfall = equilibrium_level_for_GW - Groundwater {m^3}.

equilibrium_level_for_GW is a proxy that describes the maximum filling capacity of the groundwater stock during a year. In other words, it is a theoretical value that indicates what amount of water would be needed for the deep groundwater stock under Ikel watershed to be entirely filled with water, at full capacity, for a year, resulting in no more water being able to flow in from upstream. The difference between this value and the Groundwater value (*equilibrium_shortfall*) is the "empty" capacity that needs to be recharged through inflow. The recharge happens over a given recharge time *Recharging_time* defined in years.

Infiltration_on_Irrigated_Arable includes infiltration of water from precipitation fallen on irrigated arable land alongside water from irrigation, while *Infiltration_on_non-irrigated_land* is the sum of precipitation water infiltrated from three types of land use: bioproductive, abandoned and rainfed arable lands. (Figure 7.6). Equation for infiltration on bioproductive land is showcased below as an example of how infiltration on each type of land use was defined.

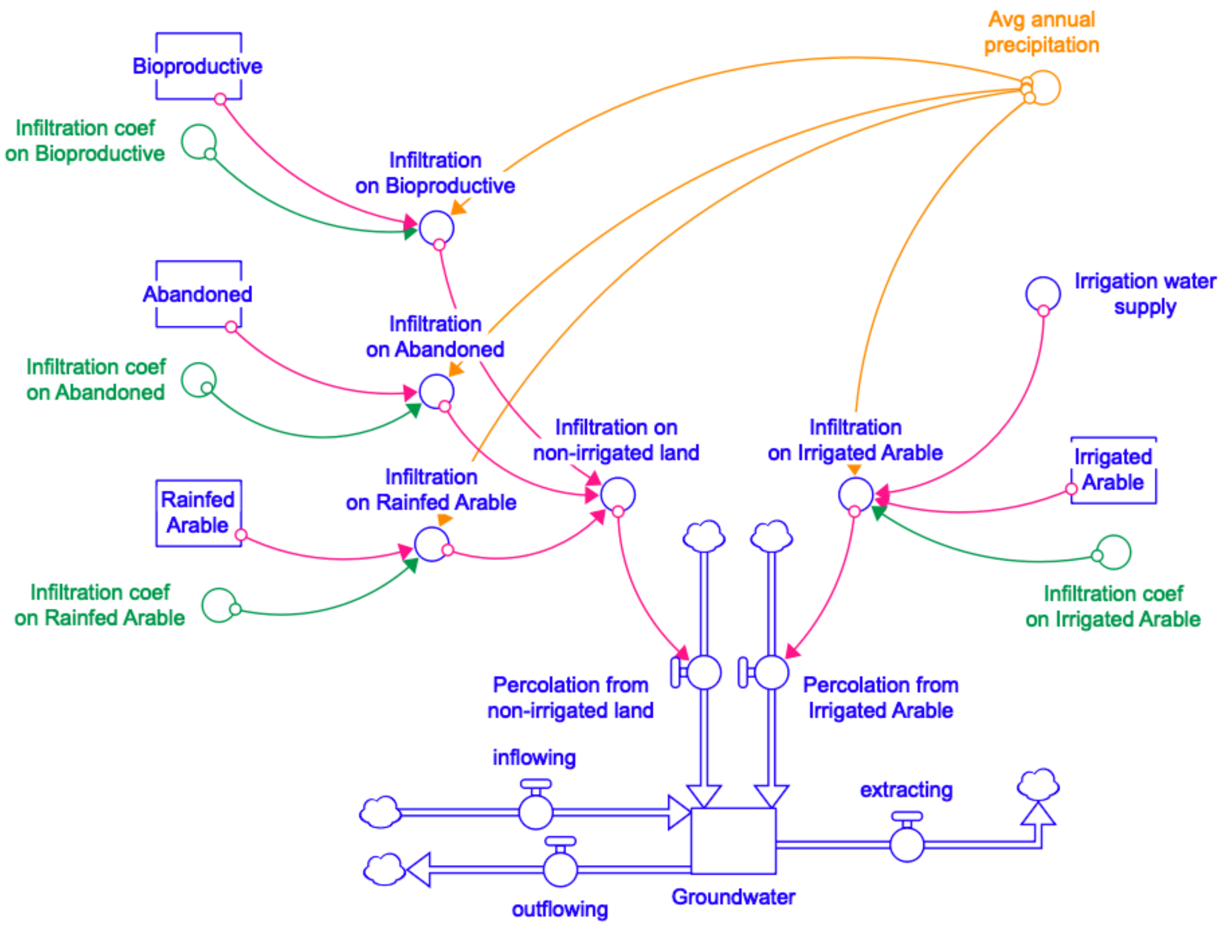


Figure 7.6. Stock-flow diagram illustrating the formation of infiltration variables from irrigated and non-irrigated land. Exogenous variables are highlighted in green color, while climatic exogenous variables – in orange.

*Infiltration_on_Irrigated_Arable = Irrigated_Arable * Avg_annual_precipitation * Infiltration_coef_on_Irrigated_Arable + Irrigation_water_supply* {m^3/year}.

Infiltration_on_non-irrigated_land = Infiltration_on_Bioproductive + Infiltration_on_Abandoned + Infiltration_on_Rainfed_Arable {m^3/year}.

*Infiltration_on_Bioproductive = Bioproductive * Avg_annual_precipitation * Infiltration_coef_on_Bioproductive* {m^3/year}.

Infiltration rates are not commonly expressed as fractions of precipitation, but as length/time, and are highly dependent on soil conditions. In this sector, the infiltration coefficient parameters are given assumed values (Table 7.6), and I further test the sensitivity of Ikel CliRes to the different coefficient values. Table 7.4 illustrates the estimated runoff coefficient based on hydrology textbooks.

Table 7.4. Runoff coefficients on different types of land cover (adapted from Fetter, 2001; Goel, 2014).

Land use type	**Runoff coefficient**
Built area	0.6 – 0.95
Farmland	0.18 – 0.3
Abandoned	0.1 – 0.4
Bioproductive	0.05 – 0.3

As shown in Figure 7.5, only a fraction of infiltrated water percolates to the groundwater stock. The remaining fraction of infiltrated precipitation water makes up the subsurface runoff or *Base flow*. Similarly, only a fraction of precipitation (and irrigation) water infiltrates, while another fraction makes up the surface runoff, and yet another either evaporates or is made available for crops and/or vegetation (and is released by these through evapotranspiration) (Figure 7.7).

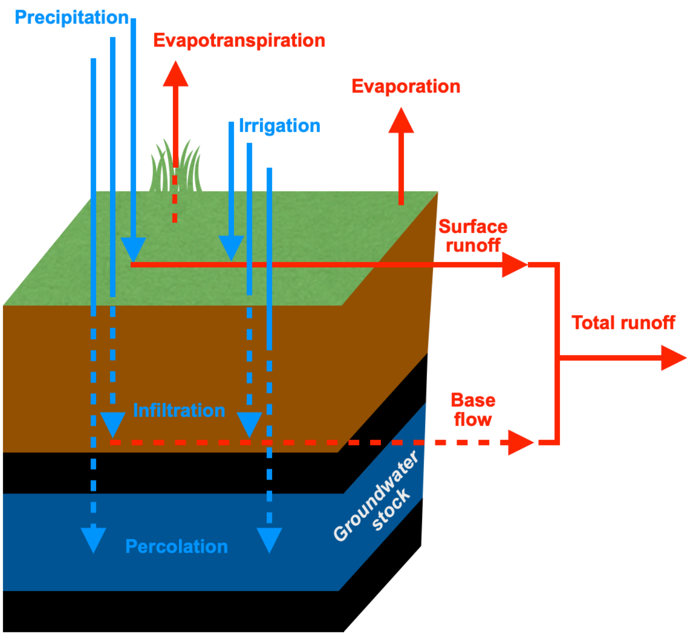


Figure 7.7. Precipitation water flows as conceptualized in the water resources sector of Ikel CliRes model. Blue arrows depict flows that contribute to increase in the groundwater stock. The red arrows are flows that withhold precipitation and irrigation water, preventing it from reaching the said stock.

In this sector, precipitation falls on four types of aggregated surfaces: blue (rivers and lakes) and grey (built) area, irrigated land, and non-irrigated land. Infiltration, runoff and evapotranspiration (ET) fractions vary for each type of land use, whereas precipitation on constructed (grey) areas and water bodies (blue area) either adds up to the total runoff or evaporates.

From total annual runoff in Ikel watershed, except for the minimum required Ikel flow, the remaining amount is considered available to be gauged for irrigation. Together with irrigation water extracted from Dniester River, this amount constitutes a theoretical exploitable surface runoff.

Similarly, of the groundwater stock, a certain amount is extracted for industrial and household use, and an amount less or equal to the fraction allowed for exploitation is considered as groundwater exploitable for irrigation purposes. Data for groundwater extracted annually (*extracting*) from the confined aquifer is not readily available. It is the main source of drinking and industrial water supply in a number of towns within Ikel watershed, and is not open for irrigation use, although this proposal is under intense debate.

Evaporation and real ET data is not readily available for Ikel watershed, and is, indeed, a challenging figure to calculate. Evapotranspiration depends on both available soil water, and on the potential evapotranspiration (PET) specific to each type of vegetation:

ET_on_Irrigated land = MIN (Water_available_for_ET_on_Irrigated_land, PET) {m/year}.

ET_on_Rainfed Arable = MIN (Pe_on_Rainfed_Arable, PET) {m/year}.

*Water_available_for_ET_on_Irrigated_land = (Avg_annual_precipitation * Irrigated_Arable + Irrigation_water_supply - Runoff_on_Irrigated_Land - Infiltration_on_Irrigated_Arable) / Irrigated_Arable* {m/year}.

Pe_on_Rainfed_Arable = (Avg_annual_precipitation * Rainfed_Arable - Runoff_on_Rainfed_Arable - Infiltration_on_Rainfed_Arable) / Rainfed_Arable {m/year}.

Evaporation rate in Ikel CliRes is defined according to the simplified Penman formula for the evaporation rate from a lake (Linacre, 1977):

$$E_0 = \frac{700\, T_m/(100-A)+15(T-T_d)}{(80-T)} \left(\frac{\text{mm}}{\text{day}}\right) \tag{7.1}$$

where:

T_m = T + 0.006 h

h = elevation (meters) (169.8 m average elevation in Ikel watershed)

T = average temperature (Table 7.5)

A = latitude (degrees) (41.11°N for Ikel watershed)

T_d = the mean dewpoint

(T-T_d) = monthly mean values of this term can be obtained from the following empirical relationship (when precipitation is at least 5 mm/month and T-Td ≥ 4°C):

$$(T - T_d) = 0.0023h + 0.37\,T + 0.53\,R + 0.35\,R_{ann} - 10.9°C \tag{7.2}$$

where:

R = mean daily range of temperature (9° for Ikel watershed (Geerts, 2002))

R_{ann} = difference between the mean temperatures of the hottest and coldest months (Table 7.5).

Table 7.5. Average values for annual temperatures, for temperatures of hottest month (July) and for temperature of coldest month (January). Annual data for 1990-2001 are sourced from the Fourth National Communication of the Republic of Moldova under UNFCCC (UNEP, 2018), while annual and monthly data for the 2002-2020 period - from NBS. Monthly values for 1990-2001 were generated randomly based on monthly data for 2002-2020 using RANDARRAY function in Excel (uniform distribution).

Year	**Average annual temperature** ($°C$)	Mean temperatures of the hottest month ($°C$)	Mean temperatures of the coldest month ($°C$)
1990	11.3	23.2	-6.6
1991	9.4	21.7	-2.2
1992	10.1	24.4	3.7
1993	9.4	22.8	-5.4
1994	11.3	23.6	-1.3
1995	10	21.4	-1.4
1996	9.1	25.6	1.9
1997	9.4	24.7	-3.6
1998	10.3	24	-3.9
1999	11	23.7	-4.6
2000	11.2	22	1.4
2001	10.3	24.6	1.3
2002	10.8	24.2	-1.9
2003	9.8	21.6	-3
2004	10.3	21.7	-3.8
2005	10.5	22.7	1.1
2006	10.2	22.1	-6.6
2007	12.1	25.8	3.9
2008	11.3	22.2	-1.5
2009	11.4	24	-1
2010	10.6	23.3	-5.2
2011	10.5	23	-1.6
2012	11.2	26	-2.6
2013	11.1	21.7	-1.9
2014	10.9	23	-1.9
2015	12	24.4	-0.5
2016	11.2	23.4	-3.3
2017	11.2	22.4	-4.2
2018	11.2	22.2	-0.8
2019	12.2	22.1	-2.6
2020	12.7	23.7	1.5

Below I present the list, description, value and source of parameters used to calibrate this sector.

Table 7.6. List and description of the parameters: *water resources* sector.

Variable	Description	Value	Units	Source
Annual_precipitation	Annual precipitation for Ikel SES	Table 2.5	m year^{-1}	NBS; UNEP, 2018
Avg_annual_T	Average annual temperature	Table 7.5	°C	NBS
delay_time	Delay time for runoff calculation	0.25	years	Assumed
Equilibrium_level_for_GW	Equilibrium level for the confined aquifer / groundwater stock	0.073	m^3	Assumed
Fraction_of_GW_allowed_for_exploitation	Exploitable groundwater fraction	0	1/year	Assumed
GB_fraction	Gray and blue area fraction of Ikel watershed	0.1	dmnl	Ursu, 2014
Household_and_industrial_use	Groundwater extracted for household and industrial use	0.003	km^3 year^{-1}	MEA and NBS national data.
Ikel_watershed_area	Ikel watershed area	878.1	km^2	SHS, 2020
Infiltration_coef_on_Abandoned	Infiltration coefficient on abandoned land	0.3	dmnl	Assumed
Infiltration_coef_on_Bioproductive	Infiltration coefficient on bioproductive land	0.5	dmnl	Assumed
Infiltration_coef_on_Irrigated_Arable	Infiltration coefficient on irrigated arable land	0.2	dmnl	Assumed
Infiltration_coef_on_Rainfed_Arable	Infiltration coefficient on rainfed arable land	0.2	dmnl	Assumed
Irrigation_from_Dniester	Exploitable water from Dniester River	1000	m^3 year^{-1}	Assumed
Mean_T_of_coldest_months	Mean temperatures of coldest month	see Table 7.5	°C	NBS; UNEP, 2018
Mean_T_of_hottest_months	Mean temperatures of hottest month	see Table 7.5	°C	NBS, UNEP, 2018
Outflow_fraction	Groundwater outflow fraction to downstream basins	0.3	dmnl	Assumed
Percolation_fraction	Percolation coefficient	0.1	dmnl	Assumed
PET	Potential evapotranspiration	0.8	m year^{-1}	FAO
Recharging_time	Recharge time of the confined aquifer / groundwater stock	10 to 15	years	Assumed
Runoff_coef_on_Abandoned	Runoff coefficient on abandoned land	0.4	dmnl	Fetter, 2001; Goel, 2014
Runoff_coef_on_Bioproductive	Runoff coefficient on bioproductive land	0.1	dmnl	Fetter, 2001; Goel, 2014
Runoff_coef_on_Irrigated_Arable	Runoff coefficient on irrigated arable land	0.3	dmnl	Fetter, 2001; Goel, 2014
Runof_coef_on_Rainfed_Arable	Runoff coefficient on rainfed arable land	0.3	dmnl	Fetter, 2001; Goel, 2014
Total_Exploitable_Runoff	Total exploitable runoff	0.189	km^3 year^{-1}	Assumed

7.2.2. Irrigation Infrastructure

This sector describes the formation of capacity for irrigation water supply. It forecasts exploitable water resources and distributes the sourcing of demanded irrigation water between surface and groundwater supply. Based on availability of water from these sources, and on the demand for irrigation coming in from *land use* sector, a decision is taken to invest or not in creating additional irrigation infrastructure. The speed of reducing the shortfall between desired and existing capacity is influenced by investment, represented by the formation time of new capacity. Existing infrastructure capacity is eroded due to limited lifetime of both surface water and groundwater supply equipment. Unless investments are being made in its maintenance, this capacity decreases over time. The sector generates the water supply for irrigation, which supplies water to the *water resources* sector through irrigation, and also informs the *land use* sector about the level of water scarcity or lack thereof.

To build the structure and define variables and parameters in this sector, three main data sources are used: governmental institutions (including NBS, Environmental Agency, the “Apele Moldovei” state agency for water resource management), studies and reports of international organizations involved in irrigation research and development projects (such as Millennium Challenge Corporation from the United States, Account for Moldova - MCA), and stakeholder input (including farmers and local consultants). Wherever data was not available, assumptions were made based on expert opinion and anecdotal evidence. Values and sources for each parameter are presented in Table 7.11 below.

4.3 km^3 of surface water and 1.3 km^3 of groundwater resources are estimated by FAO to be available for economic use in R. Moldova. The water quality of the two main rivers, Prut and Dniester, is considered adequate for consumption and irrigation. The quality of inland rivers and small watercourses generally falls into the "polluted" or even "highly polluted" classes (FAO ECA, 2012), making them unsuitable for irrigation. This prevents governmental agencies from issuing usage permits for irrigation purposes. Yet, small dams are frequently built on these watercourses, and their water used for irrigation. The specificity of the topographic structure of R. Moldova in general, and of Ikel watershed in particular, requires the pumping of water upwards from the river valleys.

Data on forecasted exploitable water reserves at Ikel watershed level is not readily available. At Dniester district level, average surface water reserves amount to 820 million m^3. 84.3 % of water abstraction is made from surface sources, while 4.9 % - from groundwater sources. According to Dniester Watershed Management Plan (2017), the total groundwater reserves in the Republic of Moldova are 3478.3 thousand m^3/day. The reserves in the lower Baden-Sarmatian layer make up

2339.4 thousand m^3/day. Table 7.7 illustrates the estimates for exploitable groundwater by category of use in the counties sharing the watershed. At the same time, Moraru (2018) lists the values of estimated exploitable groundwater nationally being between 760.3 thousand and 1566.6 thousand m^3/day.

Table 7.7. Estimated exploitable groundwater by category of use (Dniester Watershed Management Plan, 2017).

County	Estimated exploitable reserves, (thousands m^3/day)		
	Drinkable	**Technical**	**Total**
Călărași	-	8.2	8.2
Criuleni	224.2	-	224.2
Orhei	47.7	4.8	52.5
Strășeni	16.5	2	18.2
mun. Chișinău	83.8	10.9	94.7

As of June 2020, it is not legally allowed to use deep groundwater for irrigation; the amount extracted is, in principle, only used for municipal and industrial needs. Nevertheless, its use for irrigation purposes by individual farmers is very likely.

There is currently no exact data available on total functioning irrigation infrastructure capacity in R. Moldova in general, and in Ikel watershed in particular. The most recent figures show that there are over 70 irrigation systems throughout the country, which were built over 40 years ago (MCA, 2015). Much of the fixed existing irrigation infrastructure is a remnant of the Soviet period; it is both degraded and unsuitable for the post-privatization arable land property model (MCA, 2015). Hence, it is less likely that efforts will be made to restore all of them.

More recently, investments have been made in the rehabilitation of some of these systems. One such example is the Millennium Challenge Corporation of America's rehabilitation of 11 irrigation systems, one of which is located in Ikel SES. Table 7.8 shows official data from 2013 on capacities of three irrigation systems located in Ikel SES, which abstract water directly from Dniester River (ME, 2013).

Table 7.8. Capacities of Ikel SES irrigation systems abstracting water from Dniester River, as provided by the Ministry of Environment (2013).

Irrigation system	Pumping distance from abstraction point (km)	Irrigable area (ha)	Irrigated area in 2012 (ha)	Percent irrigated from irrigable	Water consumption in 2012 (thousand m^3)
Coşerniţa	6	488	10.5	2.15 %	6.6
Criuleni de Sus	30	1000	11	1.1 %	12.3
Criuleni	0.6	677	5	0.74 %	2.8

As mentioned above, irrigation is mainly done with water abstracted from surface water resources and shallow aquifers. It is also very plausible that part of the irrigation is done by individual farmers from municipal water system, which in Ikel watershed is generally supplied with water from deep, confined aquifers abstracted through artesian wells. In Figure 7.8, the difference between abstraction points and artesian wells is illustrated. Figure 7.9 illustrates the distribution of abstraction points and artesian wells from surface and groundwater resources respectively in R. Moldova, and Figure 7.10 illustrates the same for the eight abstraction points and 14 artesian wells in Ikel SES.

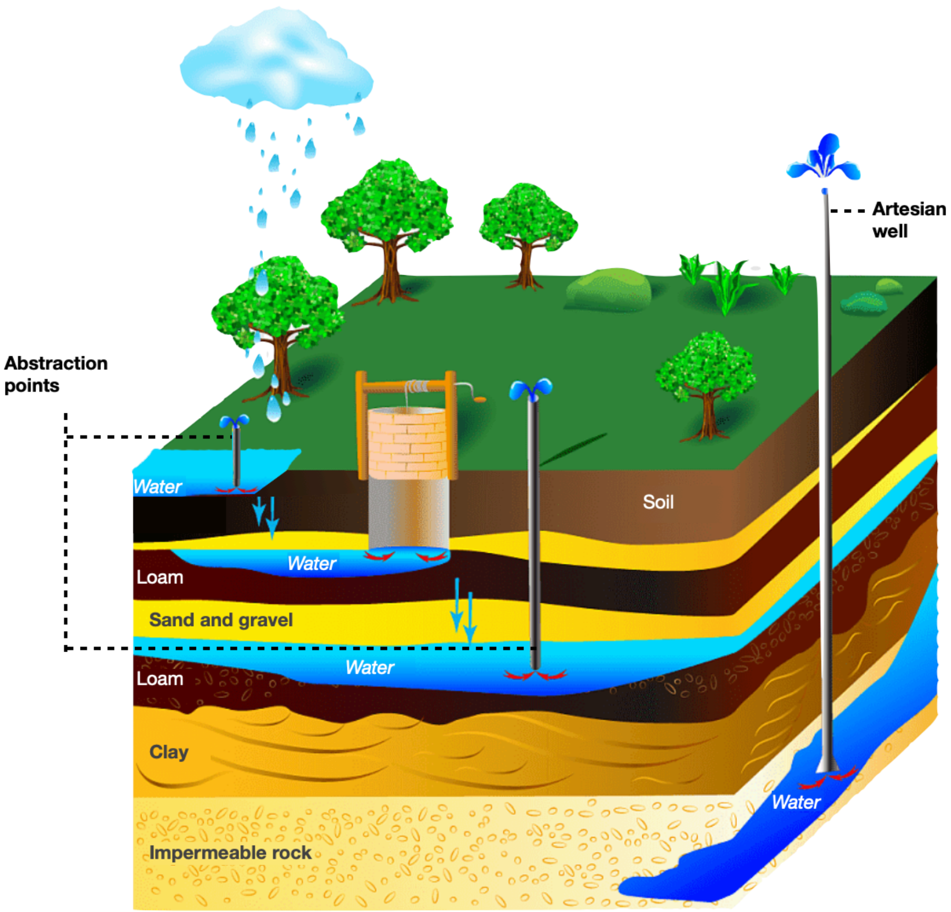


Figure 7.8. Visualization of the difference between abstraction points and artesian wells.

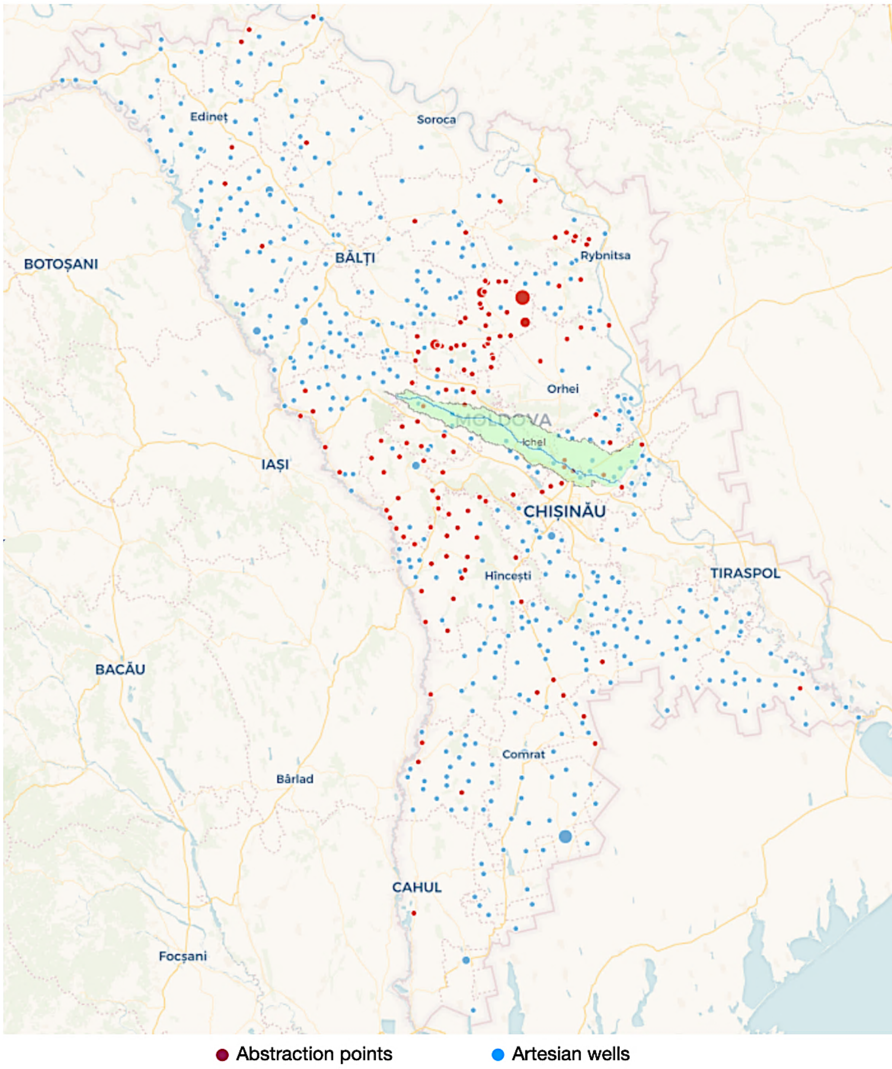


Figure 7.9. Distribution of abstraction points and artesian wells from surface and groundwater resources respectively in R. Moldova (AMA, 2020).

Figure 7.10. Abstraction points and artesian wells (AMA, 2020).

Data for irrigation water supply from all sources at Ikel watershed level is not readily available. Table 7.9 illustrates the official figures for water supply between 2008 – 2018 in the counties sharing Ikel watershed. Table 7.10 illustrates the same data at country level, by sector, including irrigation water supply, for the period 2000 – 2018.

Table 7.9. Water consumption between 2008 – 2018 in counties sharing Ikel watershed, in millions m^3 (NBS).

	2008	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**
m. Chisinau	58.5	54,8	53.0	52.0	51.1	50.4	45.2	45.6	45.6	47.6	47.3
r. Calarasi	1.0	1.3	1.1	1.0	1.1	1.2	1.2	1.2	1.2	1.2	1.3
r. Criuleni	1.6	1.8	1.8	2.1	2.2	1.9	2.3	2.3	1.9	1.9	2.0
r. Orhei	3.2	3.7	3.4	3.5	3.3	3.1	3.0	3.0	3.2	3.3	3.4
r. Straseni	1.3	1.2	1.1	1.2	1.3	1.4	1.6	1.6	1.6	1.6	1.6
r. Ungheni	2.4	2.7	2.4	2.7	2.9	2.7	2.7	2.9	2.8	2.8	2.9

Table 7.10. Water consumption and water supply for irrigation, production and total consumption in R. Moldova between 2000-2016 (State Environmental Inspectorate, 2009; State Environmental Inspectorate, 2018; NBS).

Year	**Irrigation water supply (million m^3)**	**Manufacturing, production and other economic activities (million m^3)**	**Drinking water supply (million m^3)**	**Overall water consumption (million m^3)**
2000	50	-	-	849
2001	42	587	19	797
2002	46	587	20	792
2003	54	586	20	795
2004	47	585	20	786
2005	43.3	583	18	785
2006	36	583	17	787
2007	63	581	17	809
2008	48	581	17	794
2009	38	580	17	795
2010	40	581	17	785
2011	39	580	17	785
2012	39	580	17	786
2013	38	580	17	782
2014	38	579	16	777
2015	39	579	17	777
2016	38	578	16	776
2017	38	583	20	777
2018	39	582	20	777

In Ikel CliRes *irrigation infrastructure* sector, irrigation supply capacity is an aggregated variable acting as a proxy for all infrastructure and workforce involved in the extraction, distribution, and application of irrigation. In this model, irrigation supply capacity is conceptualized as being supplied from exploitable surface runoff (*Surface_water_supply_capacity* stock) and from exploitable groundwater (*Groundwater_supply_capacity* stock), as illustrated in Figure 7.11.

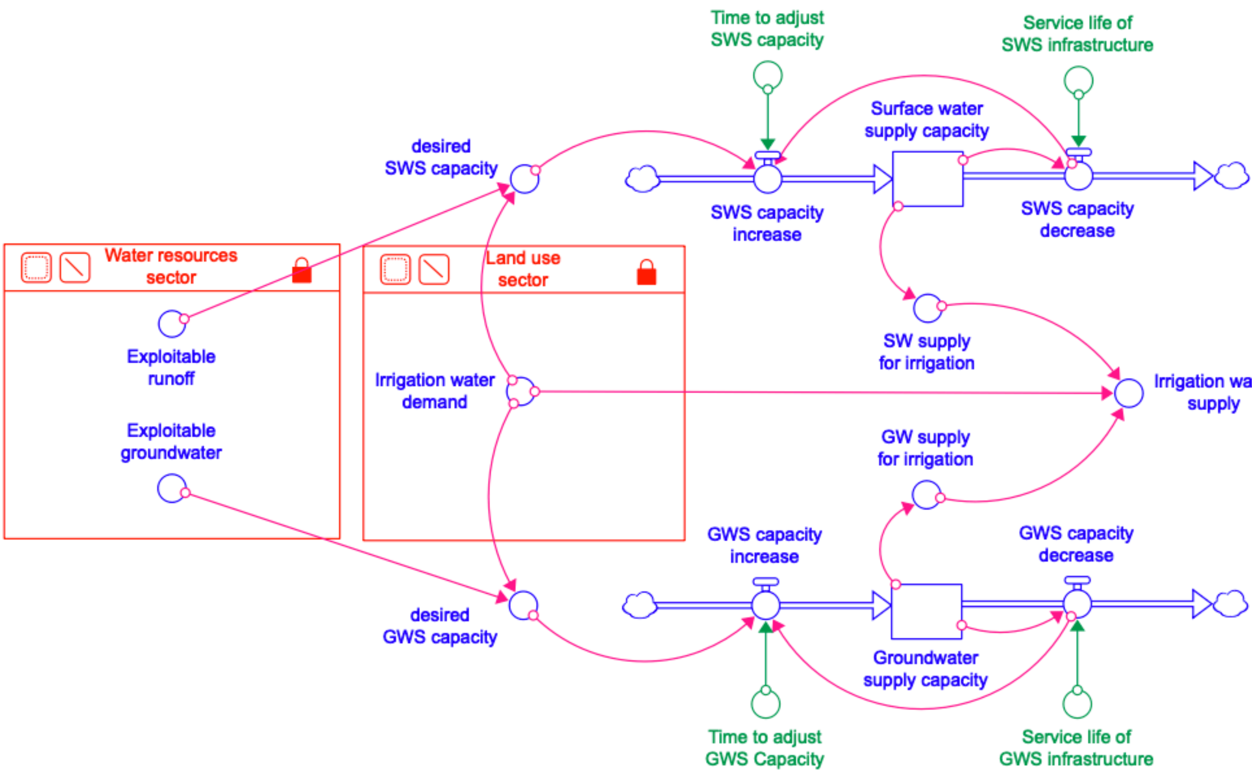


Figure 7.11. Overview of the *irrigation infrastructure* sector, which describes the formation of capacity for irrigation water supply. The stock-flow diagram illustrates the drivers of increase and decrease in the supply capacity stocks for surface water and groundwater irrigation. Exogenous variables are highlighted in green color.

Both stocks increase and decrease due to similar causes. Irrigation supply capacity increases with investments in irrigation infrastructure (*SWS_capacity_increase* and *GWS_capacity_increase*). The capacity decreases as the infrastructure wears off due to approaching or reaching the end of service life (*SWS_capacity_decrease* and *GWS_capacity_decrease*):

$$Surface\_water\_supply\_capacity_t = Surface\_water\_supply\_capacity_{t-1} + SWS\_capacity\_increase - SWS\_capacity\_decrease \ \{m^3/year\}.$$

Groundwater_supply_capacity$_t$ = *Groundwater_supply_capacity*$_{t-1}$ + *GWS_capacity_increase* - *GWS_capacity_decrease* {m^3/year}.

Irrigation supply capacity increases based on the shortfall between the existing capacity and the desired capacity, as well as on investments in the maintenance and/or replacement of existing capacity that wears off. The capacity is adjusted in a defined period, referred to as *Time_to_adjust_capacity*:

SWS_capacity_increase = MAX (0, (SWS_capacity_shortfall / Time_to_adjust_SWS_capacity) + SWS_capacity_decrease) {m^3/year^2}.

GWS_capacity_increase = MAX (0, (GWS_capacity_shortfall / Time_to_adjust_GWS_capacity) + GWS_capacity_decrease) {m^3/year^2}.

If there is no shortfall between existing and desired capacity, the only investment is in the maintenance of existing infrastructure. If there is a shortfall between desired amounts and existing infrastructure capacity, a larger investment in the capacity is being triggered, e.g:

SWS_capacity_shortfall = desired_SWS_capacity - Surface_water_supply_capacity {m^3/year}.

The speed of investment may vary depending on the capacity of the local stakeholders. In this sector, *Time_to_adjust_SWS_capacity* and *Time_to_adjust_GWS_capacity* parameters are proxies for the available budget, institutional capacity, speed of decision making, and other factors involved in infrastructure building. They aggregate these factors to illustrate how much time it takes to build the required capacity and eliminate the shortfall. The shorter the time, the faster and the more supply capacity can be built.

The desired capacity is distributed between surface water infrastructure and groundwater infrastructure depending on the availability of exploitable water resource. Therefore, the more water is desired from one source (e.g., from exploitable runoff), the less is desired from the other (e.g., exploitable groundwater). Also, the desired capacity is either the exploitable water resource or the irrigation water demand – whichever is the smallest, e.g.:

*desired_SWS_capacity = MIN (Exploitable_runoff, Forecasted_irrigation_water_demand * Forecasted_expl_runoff_ratio)* {m^3/year}.

Forecasted_expl_runoff_ratio = *Forecasted_expl_runoff* / *Total_forecasted_expl_water* {dimensionless}.

Total_forecasted_expl_water = *Forecasted_expl_GW* + *Forecasted_expl_runoff* {m^3/year}.

Forecasted variables for exploitable runoff (*Forecasted_expl_runoff*), exploitable groundwater (*Forecasted_expl_GW*), and irrigation water demand (*Forecasted_irrigation_water_demand*) are defined using forecast formulation in STELLA software *FORCST.* FORCST calculates the trend in inputs, which in our case are indicated exploitable runoff, exploitable groundwater, and irrigation water demand respectively.

FORCST (<input>, <averaging time>, <horizon>)

Where:
input = either *indicated_expl_runoff, Exploitable_GW* or *Perceived_irrigation_water_demand*
averaging time = the time over which the trend is calculated:

- 10 years for *Forecasted_expl_runoff*
- 10 years for *Forecasted_expl_GW*
- 5 years for *Forecasted_irrigation_water_demand*

horizon = the distance into the future for which FORCST extrapolates the trend:

- 5 years for *Forecasted_irrigation_water_demand*
- 5 years for *Forecasted_expl_runoff*
- 5 years for *Forecasted_expl_GW*

Decrease in irrigation infrastructure is due to aging and equipment withering. The rate of decrease is given by the average lifetime of irrigation supply infrastructure, set in this model to 20 and 30 years respectively. As mentioned above, the aging both reduces the capacity, and prompts investments in the maintenance of existing infrastructure.

SWS_capacity_decrease = *Surface_water_supply_capacity* / *Service_life_of_SWS_infrastructure* {m^3/$year^2$}.

GWS_capacity_decrease = *Groundwater_supply_capacity* / *Service_life_of_GWS_infrastructure* {m^3/$year^2$}.

The supply of irrigation water is shared between exploitable runoff and groundwater sources, depending on the demand and on the existing infrastructure capacity at the time of demand. For example, if there is more infrastructure capacity and available water resources from surface waters, more of the water for irrigation will be supplied from these sources and less from the groundwater sources. Irrigation water supply then contributes to the dynamics in the *land use* sector.

The values of *Surface_water_supply_capacity* and *Groundwater_supply_capacity* show how much water it is technically possible for the existing infrastructure to supply and meet the demand. However, the possible supply is also influenced by the factual availability of either exploitable runoff, or exploitable groundwater resources, or both. This means that the sector will supply as much water for irrigation as is either technically allowed by the irrigation infrastructure, or actually existing as exploitable water resource:

Irrigation_water_supply = SW_supply_for_irrigation + GW_supply_for_irrigation {m^3/year}.

Possible_SW_supply = MIN(Surface_water_supply_capacity, Total_Exploitable_Runoff) {m^3/year}.

Possible_GW_supply = MIN (Groundwater_supply_capacity, Exploitable_GW) {m^3/year}.

Table 7.11. List and description of parameters used to calibrate the *irrigation infrastructure* sector.

Variable	**Description**	**Value**	**Units**	**Source**
Service_life_of_GWS_infrastructure	Average lifetime of groundwater supply infrastructure	30	years	Based on interviews with farmers
Service_life_of_SWS_infrastructure	Average lifetime of surface water supply infrastructure	20	years	Based on interviews with farmers
Time_to_adjust_GWS_Capacity	Adjustment time for groundwater supply capacity increase	10	years	Assumed
Time_to_adjust_SWS_capacity	Adjustment time for surface water supply capacity increase	10	years	Assumed

7.2.3. Erosion

This sector investigates the impact of a series of factors on the soil erosion and on average soil thickness. It determines the effect of soil erosion on crop yield and influences the forestation.

To build the structure and define variables and parameters in this sector, I resorted to three main data sources: pedology textbooks and previous system dynamics work on soil erosion and conservation models, scientific work on this topic conducted by researchers in R. Moldova and press articles on soil erosion published by local and international experts. Wherever data was not available, assumptions were made based on expert opinion and similar work in other geographies. Sources for each variable are presented in Table 7.20 below.

In Ikel SES, the major soil groups are chernozems (~55 % of Ikel watershed), gray forest soils (~18 %) and alluvial soils (~17 %), and to a lesser extend other types of soils (~10 %) (Ursu, 2014). Figure 7.12 shows an overview of dominant types of soil in Ikel SES.

Figure 7.12. Spatial distribution of major soil groups in Ikel SES (Ursu, 2014).

Erosion is the main process that affects the soil average thickness. Estimates for soil erosion in Ikel watershed are not readily available. At national level, these estimates vary between 30 m^3 per hectare annually (Krupenikov, 2004; Cerbari et al., 2010; Jigău, 2015), and 50 m^3 per hectare in some parts of the country (Krupenikov and Constantinov, 2004). That is between 0.3 cm and 0.5 cm of soil depth. Due to the very slow process of soil regeneration, Krupenikov (2004) estimates that to maintain the stock of fertile soil in R. Moldova, an approximate amount of maximum 5 m^3 per hectare should be eroded annually, or 0.06 cm of soil depth. This ideal rate is 6 to 10 times slower than the current rates. In Ikel CliRes model, erosion reduces the average soil mass stock (Figure 7.13).

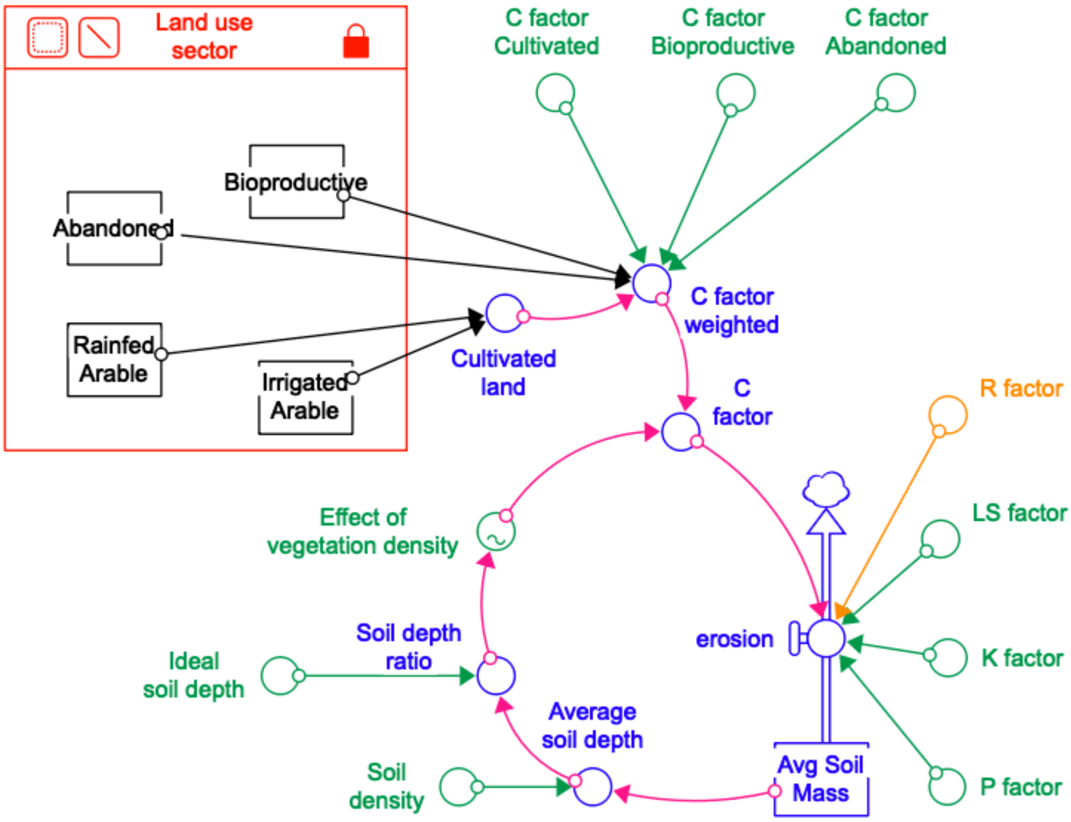


Figure 7.13. Overview of the *erosion* sector. The stock-flow diagram illustrates the drivers of decrease in average soil mass stock. Exogenous variables are highlighted in green color, while climatic exogenous variables – in orange.

Average soil mass stock in this model is a limited resource. It can only decrease with erosion but does not regenerate. This is due to pedogenesis being an extremely slow process, which is equal to nearly zero within the timeframe of this model. The stock decreases with erosion – a much faster process in this context.

$Avg\_Soil\_Mass_t = Avg\_Soil\_Mass_{t-1} - erosion$ {t/m^2}

To model *erosion*, I make use of the universal soil loss equation (USLE), as defined by Wischmeier & Smith (Morgan, 2005):

$$E = R \; x \; K \; x \; L \; x \; S \; x \; C \; x \; P \qquad (7.3)$$

where:

E = average annual soil loss, computed per unit area and expressed in the units selected for K and for the period selected for R.

R = rainfall erosivity factor

K = soil erodibility factor

L = slope length factor

S = slope steepness factor

C = crop or cover management factor

P = erosion-control or conservation practice factor

*erosion = R_factor * K_factor * LS_factor * P_factor * C_factor* {t/m^2/year}.

Rainfall erosivity factor R is a climatic variable. It measures the ability of rainfall to cause erosion on the surface of the earth. In R. Moldova, the variability in climatic conditions led to a fairly wide range of rainfall erosivity values (Figure 7.14). According to some estimates, these values range from 572.4 (in the southeast) to 1259.1 MJ mm ha^{-1} h^{-1} year^{-1} (in northwest), with an average country value of 880.4 MJ mm ha^{-1} h^{-1} year^{-1} (Castraveț, 2018). At smaller scale however, values of R differ based on the methodology used to calculate it. For example, values of R modeled by Castraveț (2018) for the same lower Prut region in R. Moldova varies between 101 and 143.73 MJ mm ha^{-1} h^{-1} year^{-1} as per Foster's equation, between 422.29 and 600.6 MJ mm ha^{-1} h^{-1} ywar^{-1} according to Roose's equation, and between 893 and 1161 resulting from the regression equation.

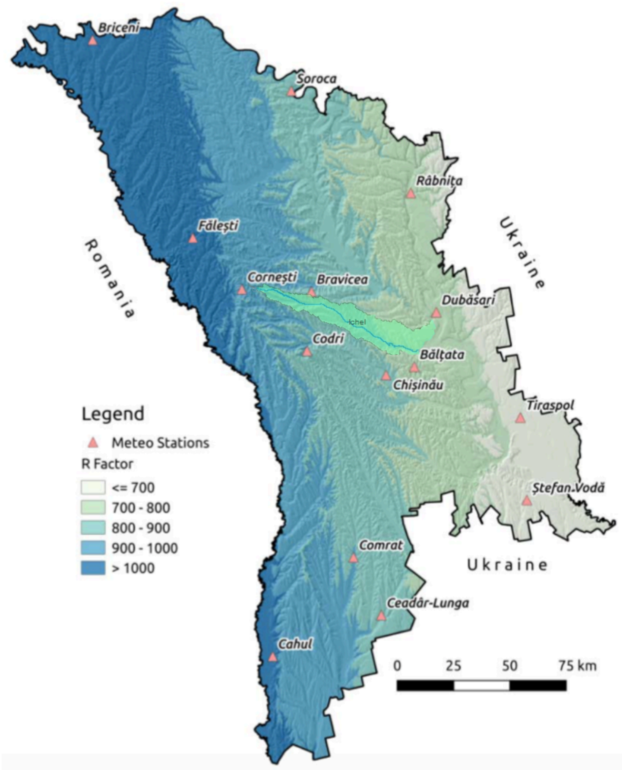


Figure 7.14. Rainfall erosivity in the Republic of Moldova, in MJ mm ha^{-1} h^{-1} year^{-1} (Castraveț, 2018). Area of Ikel watershed is highlighted in brighter green color.

As underlined by local researchers, no precise high resolution R factor data is readily available for R. Moldova. Therefore, R factor is assigned an approximated value (Table 7.20), and sensitivity tests are conducted to understand how much this variable may influence the behavior of the model.

Soil erodibility factor K is the mean annual soil loss per unit of R. It is a value that quantifies the bonding character of a soil type and defines the resistance of the soil to both detachment and transport. It varies for different types of soils by soil texture, strength, infiltration capacity, organic and chemical content, strength and stability (Morgan, 2005). Therefore, K is a variable factor that differs for various types of soil, and from region to region in a geography. For Ikel watershed, the K factor values are not readily available. consequently, I estimate them based on available proxy data.

According to Castraveț, (2012), K ranges between 0 – 0.7 tons ha h $ha^{-1}MJ^{-1}$ mm^{-1}. The higher is the value of K, the greater is soil predisposition to erosion. K values are adapted for the selected types of soil (Table 7.12) based on Aquaproiect and ICPA (2014) and Castraveț, (2012). Table 7.13 illustrates the average selected values for major selected soil groups. The resulted values are in line with Dobrovolischi's (2004) experiments in some regions of R. Moldova.

Table 7.12. Soil erodibility class for various soil types (adapted from Aquaproiect and ICPA, 2014).

Soil Type	**Erodibility class**	**K factor**
Cambic, clay-illuviated, chernozems and eutricambosoils	Low erodibility	0.0 – 0.2
Chernozems, grey-luvic phaeozems	Medium erodibility	0.3 – 0.5
Rendzines, pararendzine phaeozioms, preluvosols, typical luvosols and albico luvosols	High erodibility	0.6 – 0.7

Table 7.13. Selected soil erodibility factors (K) for chernozems, gray forest soils and alluvial soils in Ikel SES.

Soil Type	**K factor min**	**K factor max**	**K factor average**
Chernozem (Low, Medium)	0.1	0.2	0.15
Gray forest soils (Medium)	0.3	0.5	0.4
Alluvial soils (High erodibility)	0.6	0.7	0.65
Weighted average for Ikel	**0.23**	**0.35**	**0.29**

Topographic dimensionless factor LS defines the influence of slope length (L) and steepness (S) on soil erosion. Steeper slopes cause higher velocity of overland flow, while longer slopes result in runoff accumulation from larger areas, and thus also lead to higher velocity of overland flow. Therefore, erosion would be expected to increase with increases in slope steepness and slope length, albeit in a non-linear manner (Morgan, 2005).

LS factor values for Ikel watershed are not readily available. A number of regional research projects conducted by Moldovan researchers (e.g., Castraveț, 2012; Ursu, 2014; Angheluța, 2019) allows for an approximate estimation of LS values for Ikel watershed. Ursu (2015) calculates the average slope steepness value in Ikel at 5.5º, and the maximum at 21.5º (Figure 7.15).

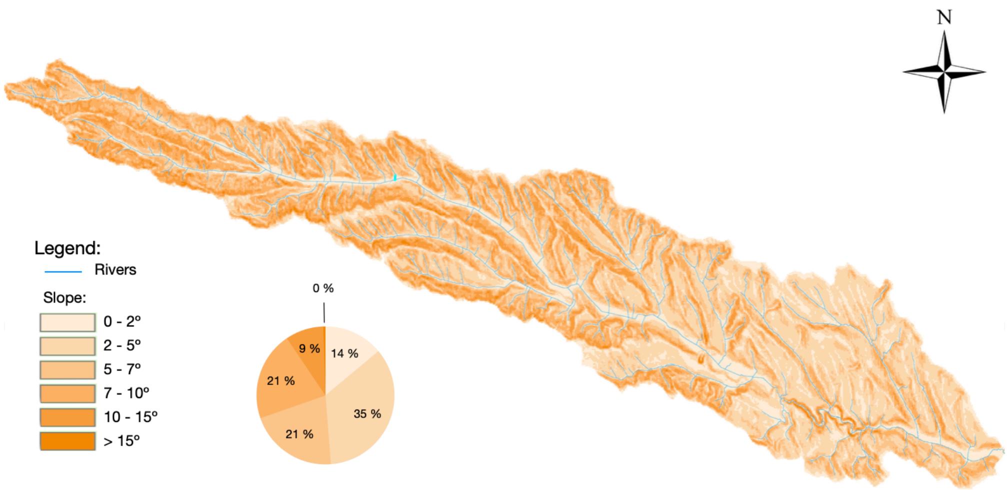


Figure 7.15. Spatial distribution and share of slope steepness in Ikel watershed (Ursu, 2014). In her research, Ursu does not include the northeastern territory of Ikel SES, which Moldovan authorities administratively included in the watershed.

Angheluța (2019) calculates the LS factor for Codrii de Nord geographic entity, where a part of the upstream section of Ikel watershed is located. The LS values for this entity under Angheluța's research is shown in Table 7.14.

Table 7.14. Share of LS values for the Codrii de Nord area (Angheluța, 2019).

LS value	LS share
0 - 2	21 %
2.01 - 3	19 %
3.01 - 5	25 %
5.01 - 10	32 %
10.01 - 24.9	3 %

Based on this information, approximate values for Ikel SES are estimated by assuming similar slope shares (e.g., I assign the dominant slope steepness share in Ikel the LS value for the dominant LS share in Codrii de Nord). Results are presented in Table 7.15 below.

Table 7.15. Estimated LS-factors for in Ikel SES.

Slope steepness share in Ikel (adapted from Ursu, 2014)	LS value for Ikel (adapted from Angheluța, 2019)	LS factor min	LS factor max	LS factor average
35 %	5.01 - 10	5.01	10	7.5
21 %	3.01 - 5	3.01	5	4
21 %	0 - 2	0	2	1
14 %	2.01 - 3	2.01	3	2.5
9 %	10.01 – 24.9	10.01	24.9	17.5
	Weighted average for Ikel	**3.57**	**7.63**	**5.5**

Soil conservation or support factor P represents the erosion control practices, such as terracing, strip cropping, ridging, etc. Areas with no conservation practices are assigned values of P=1.0 (Castraveț, 2012). Values for this factor are not readily available for Ikel watershed either. Morgan (2005) provides a list of P-factor values for various erosion-control practices (Table 7.16).

Table 7.16. USLE P-factor values for various erosion-control practices (Morgan, 2005).

Erosion-control practice	P value
Contouring (0 - 1º slope)	0.40 (0.20 for contour bunds or strip cropping)
Contouring (2 - 5º slope)	0.50* (0.25 for contour bunds or strip cropping)
Contouring (6 - 7º slope)	0.60* (0.30 for contour bunds or strip cropping)
Contouring (8 - 9º slope)	0.70* (0.35 for contour bunds or strip cropping)
Contouring (10 - 11º slope)	0.80* (0.40 for contour bunds or strip cropping)
Contouring (12 - 14º slope)	0.90* (0.45 for contour bunds or strip cropping)
Level bench terrace	0.14
Reverse-sloping bench terrace	0.05
Outward-sloping bench terrace	0.35
Level retention bench terrace	0.01
Tied ridging	0.1-0.2

Data on the percentage and effectiveness of soil erosion control practices in Ikel SES could not be identified. Values for Ikel SES are estimated based on the above table. Given the different share of land use in Ikel watershed, a similar share in land use distribution on each slope is assumed. For example: 35 % of Ikel territory has a 2-5º slope steepness; it is shared by arable land (80 %), forests (7 %), meadows (3 %), water bodies and built area (10 %); it is thus assumed that 28 % of Ikel SES area is covered by arable land located on slopes that are 2-5º steep, 2.45% of Ikel SES area is covered by meadows located on slopes that are 2-5º steep, etc. (Table 7.17).

Table 7.17. Assumed distribution of land use by slope steepness as percentage of Ikel SES.

Slope steepness share in Ikel (adapted from Ursu, 2014)	Slope steepness in Ikel (adapted from Ursu, 2014)	Arable land share in Ikel (80 % of each slope)	Forest share in Ikel (7 % of each slope)	Meadows share in Ikel (3 % of each slope)
35 %	2 - 5º	28 %	2.45 %	1.05 %
21 %	5 - 7º	16.8 %	1.47 %	0.63 %
21 %	7 - 10º	16.8 %	1.47 %	0.63 %
14 %	0 - 2º	11.2 %	0.98 %	0.42 %
9 %	10 - 15º	7.2 %	0.63 %	0.27 %
	Weighted average for Ikel	**80 %**	**7 %**	**3 %**

Based on these assumptions and the P-factor values provided by Morgan (2005) and reproduced in Table 4.17, minimum, maximum and average weighted values for P-factor in Ikel watershed are estimated and presented in Table 7.18 below. For P values on meadows, given their predominantly degraded state (Ursu, 2014), I assume similar values as those for arable land.

Table 7.18. Estimated P-factors for in Ikel SES.

Land use	Share in Ikel SES	P factor min	P factor max	P factor average
Arable (0 - 2º slope)	11.2 %	0.20	0.40	0.30
Arable (2 - 5º slope)	28 %	0.25	0.50	0.37
Arable (5 - 7º slope)	16.8 %	0.30	0.60	0.45
Arable (7 - 10º slope)	16.8 %	0.35	0.70	0.52
Arable (10 - 15º slope)	7.2 %	0.45	0.90	0.67
Forest (0 - 15º slope)	7 %	0.01	0.1	0.05
Meadows (0 - 2º slope)	0.42 %	0.20	0.40	0.30
Meadows (2 - 5º slope)	1.05 %	0.25	0.50	0.37
Meadows (5 - 7º slope)	0.63 %	0.30	0.60	0.45
Meadows (7 - 10º slope)	0.63 %	0.35	0.70	0.52
Meadows (10 - 15º slope)	0.27 %	0.45	0.90	0.67
	Weighted average for Ikel	**0.27**	**0.57**	**0.42**

Cover management factor C represents the ratio of soil loss under a given crop or cover to that from bare soil. It is highly dependent on the type of land cover or land use. In this model, a modified version of USLE is applied, making it suitable for a dynamic model. Specifically, I formulate the C factor as a dynamic variable:

*C_factor = C_factor_weighted * Effect_of_vegetation_density* {dimensionless}

Firstly, *C_factor* is defined as a weighted average of C-factors for different land uses, which change over time: *cultivated land* including both irrigated and rainfed arable land, abandoned land and bioproductive land (Figure 7.13):

*C_factor_weighted = (C_factor_Cultivated * Cultivated_land + C_factor_Bioproductive * Bioprodictive + C_factor_Avandoned * Abandoned) / (Cultivated_land + Bioproductive + Abandoned)* {dimensionless}.

Values of the C-factors for these land covers were adapted from Tozan (1998) and are presented in Table 7.19.

Table 7.19. Estimated C-factors for bioproductive, abandoned and cultivated lands in Ikel SES.

Land use	C factor min	C factor max	C factor average
Bioproductive land (forests, pastures, meadows, etc.)	0.001	0.09	**0.04**
Abandoned land (pastures, bare soil, range, etc.)	0.1	1	**0.55**
Cultivated land (cover plants, crops after fallow)	0.3	1	**0.5**

Secondly, the weighted C factor is multiplied with a factor corresponding to an effect of vegetation density, as proposed by Tozan (1998) and Saysel (1999). The rationale is that the ability of soil to support a dense vegetative cover declines over time with declining soil depth caused by erosion. Specifically, the thinner the soil cover – the sparcer the vegetation cover. Consequently, soil erosion triggers a reinforcing feedback loop that further accelerates soil erosion (Figure 7.13): the type of vegetation that proliferates on the eroding soil is less capable of preventing further erosion, and with poorer vegetation, erosion is intensified.

In Ikel CliRes, the effect of vegetation density variable is a graphic function (Figure 7.16). It is assumed that *C_factor* can increase up to two-fold if water erosion causes the loss of more than 70 % of original soil depth.

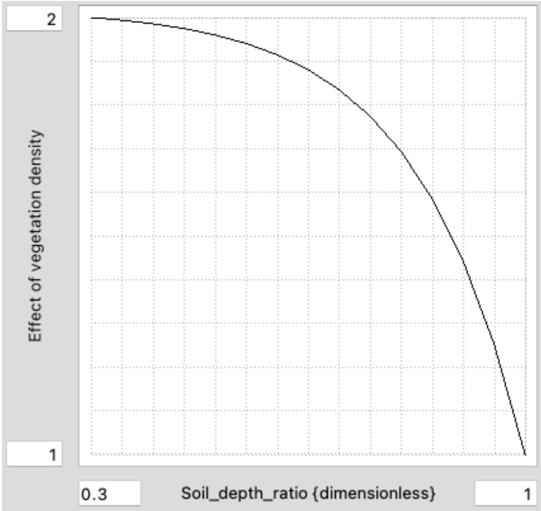


Figure 7.16. Representation of the graphic function for *Effect_of_vegetation_density* variable.

Soil depth ratio is determined dynamically, on the basis of average soil depth ratio to what is defined in this model as being an ideal soil depth:

Soil_depth_ratio = Average_soil_depth / Ideal_soil_depth {dimensionless}.

Ideal soil depth is a very aggregated variable, because the diversity of relief and variables that characterize soil quality in Ikel SES make it difficult to extract a single value. For the purposes of this model, this variable is assigned the average value of 2 m (Table 7.20).

Average soil depth is also a highly aggregated variable for all types of soils under all types of land use, except for constructed and water covered areas. It is also a proxy for soil quality in terms of organic matter. The erosion process is thus considered to affect both the thickness and the quality of soil mass. Average soil depth is calculated as follows:

Average_soil_depth = Avg_Soil_Mass / Soil_density {m}.

Soil density for Moldova is given by Krupenikov (2004) to be around 1 metric ton per square meter. Table 7.20 below shows the value and source of this and other parameters in the *erosion* sector.

The dynamics in this sector generates two variables that influence the dynamics in the *land use* sector: effect of soil depth on crop yields and effect of perceived soil erosion on pressure to build up bioproductive land by human effort. Both of these variables are graphic functions and are described in the *Land Use* Section below.

Table 7.20. List and description of parameters: *erosion* sector.

Variable	Description	Value	Units	Source
C_factor_Abandoned	Cover management factor C for abandoned/eroded land	0.55	dmnl	Estimated from literature
C_factor_Bioproductive	Cover management factor C for bioproductive land	0.04	dmnl	Estimated from literature
C_factor_cultivated	Cover management factor C for cultivated land	0.5	dmnl	Estimated from literature
Ideal_soil_depth	Ideal soil depth	2	m	Estimated from literature
K_factor	Soil erodibility factor K	0.29	tons m^2 h $m^{2-1}MJ^{-1}$ mm^{-1}	Estimated from literature
LS_factor	Topographic factor LS	5.5	dmnl	Estimated from literature
P_factor	Conservation practice factor P	0.42	dmnl	Estimated from literature
R_factor	Rainfall erosivity factor R	0.01	MJ mm m^{2-1} h^{-1} $year^{-1}$	Estimated from literature
Soil_density	Soil density	1.3	tons m^{2-1}	Krupenikov, 2004

7.2.4. Drivers of Change in Land Use

This sector determines the change in the different types of land use, and some key mechanisms that influence this change. It describes the change in yields of irrigated and rainfed crops, analyses the role of demographical and climatic factors, as well as that of water availability on the land use change dynamics. The sector generates the demand of water for irrigation, which influences the dynamics of the *irrigation infrastructure* sector. It also informs the *water resource* and *erosion* sectors about the area of various land uses.

To build the structure and define variables and parameters in this sector, I made use of the following main data sources: governmental institutions (including NBS, Environmental Agency, and others), international institutions (e.g. UN Department of Economic and Social Affairs, Millennium Challenge Corporation, and others), scientific work on this topic conducted by researchers in R. Moldova, previous system dynamics work on land use conversion, press articles published by local and international experts, and inputs from local stakeholders. Wherever data was not available, assumptions were made based on expert opinion, interviews with farmers, and similar work in other geographies. Sources for each variable are presented in Table 7.26 below.

For Ikel SES, the yearly data on change in different types of land use over the past decades is not readily available. Therefore, we estimate the values based on national data. As of 2017, total area of R. Moldova is 33,850 km^2. 12 % of the territory is covered by forests, while agricultural land use covers approximately 73 % of the national territory. Out of the latter, pastures and meadows make up less than 3 %, and uncultivated land adds up to 5 %. Nationally, land ownership is divided between state property (22 %), property of local authorities (20 %) and private property (58 %). As of 2018, 94 % of agricultural land nationally is private property (Government of R. Moldova, 2018). Table 7.21 below shows the change in areas of certain land use types between 1990 and 2020.

Table 7.21. Change in areas of agricultural lands, reserve fund and land for forestry/environmental protection in R. Moldova (Bejan, 2006; NBS). The *reserve fund* category includes the land intended for the social development of localities and for general use (public pastures, etc.).

Year	Agricultural land (thousand ha)	% of total area of R.M.	Reserve fund (thousand ha)	% of total area of R.M	Lands for forestry and environmental protection (thousand ha)	% of total area of R.M
1990	2567	76 %	-	-	416	12 %
1995	2556	74 %	-	-	425	13 %
2001	2017	60 %	621	18 %	355	10 %
2002	1947	58 %	656	19 %	356	11 %
2003	1951	58 %	604	18 %	388	11 %
2004	1951	58 %	579	17 %	406	12 %
2005	1952	58 %	554	16 %	429	13 %
2006	1953	58 %	548	16 %	432	13 %
2007	1974	58 %	509	15 %	439	13 %
2008	1979	58 %	502	15 %	444	13 %
2009	1985	59 %	497	15 %	447	13 %
2010	2008	59 %	470	14 %	450	13 %
2011	2009	59 %	467	14 %	451	13 %
2012	2009	59 %	466	14 %	451	13 %
2013	2015	60 %	461	14 %	450	13 %
2014	2024	60 %	452	13 %	450	13 %
2015	2027	60 %	449	13 %	451	13 %
2016	2028	60 %	446	13 %	452	13 %
2017	2040	60 %	436	13 %	451	13 %
2018	2042	60 %	433	13 %	452	13 %
2019	2073	61 %	399	12 %	452	13 %
2020	2092	62 %	380	11 %	452	13 %

Agricultural land category includes arable land, multiannual plantations (orchards, vine and berry plantations), pastures, meadows and uncultivated land. Table 7.22 illustrates the change in the area of these subcategories of agricultural land between 1990 and 2017 at national level.

Table 7.22. Change in areas of different subcategories of agricultural land between 1990 and 2017 in R. Moldova (Government of R. Moldova, 2018).

Year	Arable land (thousand ha)	Multiannual crop land (thousand ha)	Pastures (thousand ha)	Meadows (thousand ha)
1990	1739	471	351	5
2004	1854	298	374	3
2007	1820	302	362	2
2010	1817	301	352	2
2012	1811	299	350	2
2013	1814	295	349	2
2014	1816	295	348	2
2015	1817	292	346	2
2016	1823	289	345	2
2017	1663	289	343	2

As shown in the previous section, in Ikel watershed, as of 2014, around 56 % of the territory is covered by multiannual crop land, around 24 % arable land, 7 % - forests, 3 % - meadows. In our model, land uses that support a rich biodiversity are grouped under the *Bioproductive land* stock. Specifically, we consider this stock being made up of forested area, pastures and meadows. The *Abandoned land* stock is made up of eroded and/or uncultivated land, whereas arable land and multiannual crop land are included in the cultivated land stocks separated in *rainfed arable land* and *irrigated arable land* stocks. No historical data on abandoned land is available.

In Soviet times, more than 200,000 ha were irrigated nationally, with pumping heights of up to 400 m, in 3-4 levels. The current pumping heights are about 70 meters above river level, which limits the irrigated area to about 25,000-30,000 ha. Recent statistics show that only between 5 and 10 % (or about 10,000-20,000 hectares) of previously irrigated land (before 1990) is currently equipped for irrigation. According to FAO estimates, out of the 2,682 million ha of arable land nationally, 1,237 million ha are suitable for irrigation. Their suitability is limited by land and water characteristics, whereas degradation processes have further reduced the areas that could be irrigated (FAO ECA).

According to the Dniester Watershed Management Plan (2017), an average of 34 % of Moldva's arable lands are eroded. Out of these 10 % are highly eroded, varying from 12 % in Tighina (Southern Moldova) to 56 % in Călărași county (Central Moldova). In Ikel watershed, 1.34 % of the area (10.9

km^2) is affected by landslides. 20.26 % (17,782 ha) of the watershed is covered by forests. Most of the forested areas are located in the northeastern part of the watershed, on a rugged and high relief that is less conducive for use as arable land (Dniester Watershed Management Plan, 2017; Bejan et al, 2014). However, the quality of forest cover has been affected by illegal logging and other human interventions. In addition, the reforestation process does not instantly change the quality of the land. Instead, it takes an estimated 50 – 55 years for a forest to reach maturity (Öztürk et al., 2013) and exhibit qualities of mature bioproductive lands, such as high vegetation cover and reduced C factor, high interception and infiltration/percolation rates, highly reduced runoff rates, etc.

R. Moldova and Ikel SES's population engaged in agricultural activities is not known exactly. Official numbers are accepted to be underestimates, since many day laborers are unaccounted for, whereas subsistence agriculture is practiced by many people who are officially employed in other sectors. Official national data regarding population employed in agriculture between 2013-2019 is presented in Table 7.23. Population engaged in agricultural activities in Ikel SES is tightly connected to the size of the population in the area (Table 2.1).

Table 7.23. Moldova's population engaged in agricultural activities between 2013-2019 (NBS)

Year	Total population of R. Moldova	Population in agriculture	% of population in agriculture (official)
2013	3,559,497	35,799	0.01
2014	3,557,634	35,513	0.01
2015	3,555,159	33,018	0.01
2016	3,553,056	32,950	0.01
2017	3.550,852	33,821	0.01
2018	3,547,539	33,875	0.01
2019	3,542,708	32,821	0.01

In Ikel CliRes model, the non-constructed land within Ikel SES boundaries is divided into four main land stocks that exchange flows over time: Bioproductive, Abandoned, Rainfed Arable and Irrigated Arable lands (Figure 7.17). *Bioproductive* land is an aggregated variable acting as a proxy for forests, meadows and other forms of habitats that support local land biodiversity and help it thrive. *Abandoned* land is another aggregated variable that stands for both eroded areas and for productive arable land that has been either left fallow for a certain period or has been abandoned for other reasons than being eroded/unproductive. *Rainfed Arable* land is the sum of all cultivated lands for which no artificial irrigation is used, whereas *Irrigate Arable* land is the totality of cultivated land plots where different forms of irrigation are used. The major drivers of change are defined in this sector as being erosion, crop yield, workforce availability, irrigation water availability.

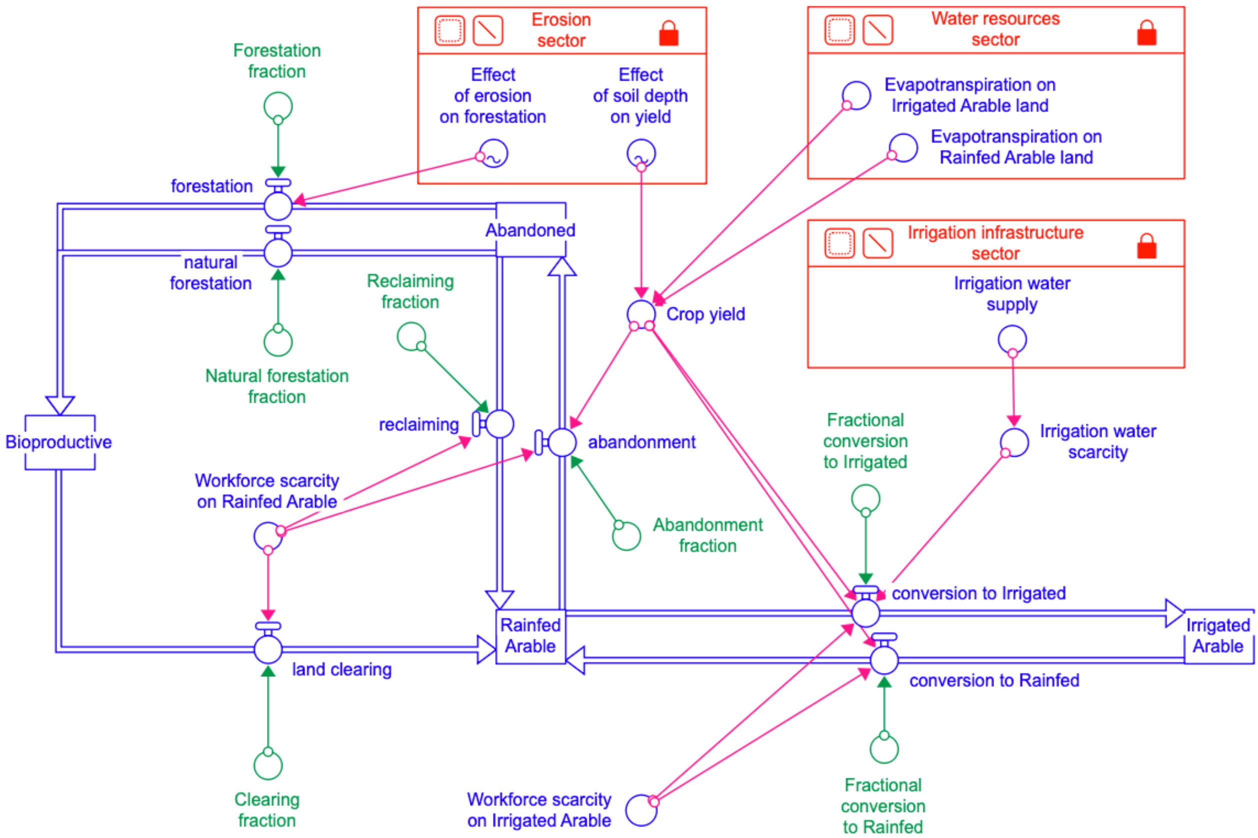


Figure 7.17. Overview of the *land use* sector. The stock-flow diagram illustrates the four land stocks and the main drivers of flows in-between the land stocks. Exogenous variables are highlighted in green color.

Bioproductive land is increased by the conversion of abandoned land into bioproductive as it both regenerates naturally and is aided by human forestation efforts. Bioproductive land stock is decreased by land clearing and converting it into arable land with a rate that factors in the effect of workforce scarcity:

$$Bioproductive_t = Bioproductive_{t-1} + natural\_forestation + forestation - land\_clearing \ \{m^2\}.$$

$$natural\_forestation = Abandoned * Natural\_forestation\_fraction \ \{m^2/year\}$$

Forestation rate may be reduced or enhanced with a factor of 0 to 100 under the effect of perceived soil erosion (*Effect_of_erosion_on_forestation*), as shown in Figure 7.18. The effect of soil erosion on forestation is described as the pressure or urgency to act, which the community feels after accessing information on the intensity of soil erosion. As a result of that, the community mobilizes to intensify efforts of planting trees, thereby building up bioproductive land:

*forestation = Abandoned * Forestation_fraction * Effect_of_erosion_on_forestation* {m^2/year}.

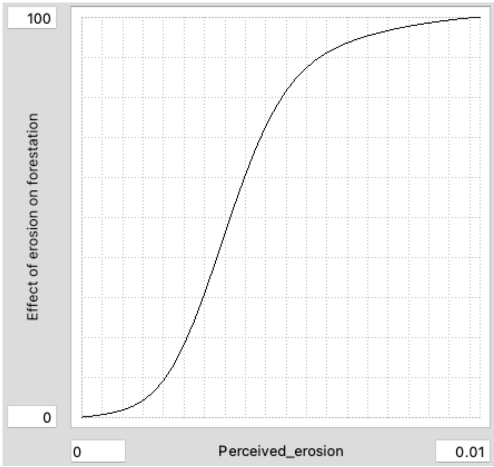


Figure 7.18. Representation of the graphic function for *Effect_of_erosion_on_forestation* variable. In Ikel CliRes, we assume that when there is no perceived soil erosion, no efforts are invested in tree plantation. However, when the perceived soil erosion reaches 10 kg/m^2/year, the societal efforts to plant trees increases 100-fold.

*land_clearing = Bioproductive * Clearing_fraction * Effect_of_workforce_scarcity_on_reclamation* {m^2/year}.

The effect of workforce scarcity on land clearing of bioproductive land is described as the impact of agricultural workforce availability on reclaiming this land for agricultural use. In this situation, so long as there is no workforce scarcity (*Workforce_scarcity_on_Rainfed_Arable* < 1), the land clearing rate is equal to usual *Clearing_fraction*. This variable is defined as a graphic function (Figure 7.19).

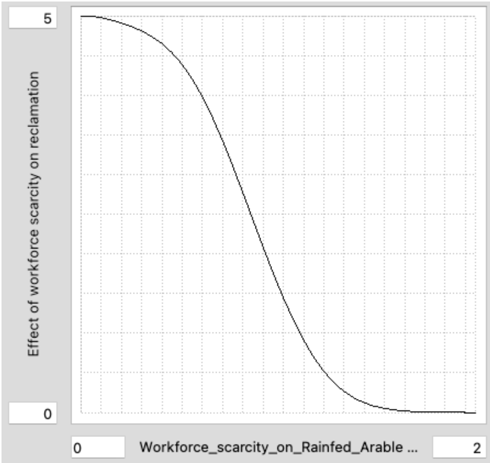


Figure 7.19. Representation of the *Effect_of_workforce_scarcity_on_reclamation* variable. If the workforce availability becomes very high, the effect increases the *Clearing_fraction* up to 5 times. However, once scarcity appears, the reclaiming rate drastically decreases and even stops when availability is two times smaller than the demand for workforce on rainfed arable land.

The *Abandoned* land stock increases with conversion from *Rainfed Arable*, as the latter is being abandoned due to loss of productivity/soil degradation and/or because of lack of workforce to cultivate it. The abandonment rate is given by an abandonment fraction, and is either reduced or increased by the effect of yield and by the effect of workforce scarcity:

$Abandoned_t = Abandoned_{t-1} + abandonment - natural\_forestation - forestation - reclaiming$ {m^2}.

$abandonment = Rainfed\ Arable * Abandonment\_fraction * Effect\_of\_yield\_on\_abandonment * Effect\_of\_workforce\_scarcity\_on\_abandonment$ {m^2/year}.

The effect of yield on the abandonment of rainfed arable land is a graphic function (Figure 7.20). It is to be understood as the effect that the actual annual yield from rainfed arable lands (*Rainfed_yield*) has on the decision of farmers to keep cultivating or to abandon the cultivated land.

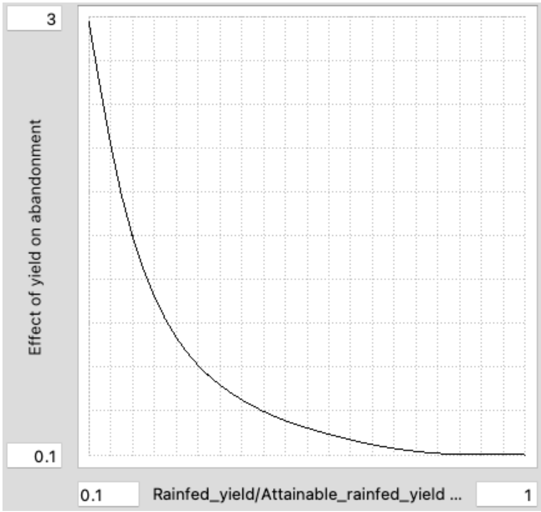


Figure 7.20. Representation of the graphic function for *Effect_of_yield_on_abandonment* variable.

The assumption is that if *Rainfed_yield* is the same as or close to the attainable yield (*Attainable_rainfed_yield*), the abandonment rate is very small, and can be as small as 10 % of the usual conversion rate. That is to say, if the lands are productive, the farmers do not abandon their lands. However, if the actual yield is significantly smaller than attainable yield, the abandonment rate increases. It is also assumed that the abandonment rate can increase up to 3 times compared to the regular abandonment fraction when the actual/attainable yield ratio is equal to or less than 0.1.

The effect of workforce scarcity on the abandonment of rainfed arable land (Figure 7.21) also influences the speed of abandonment. When *Workforce_scarcity_on_Rainfed_Arable* is smaller or equal to 1, it means that there are sufficient people who can cultivate the lands so that the crops can be properly farmed and harvested. When this scarcity increases above 1, there are not enough people to cultivate the lands and the abandonment rate increases.

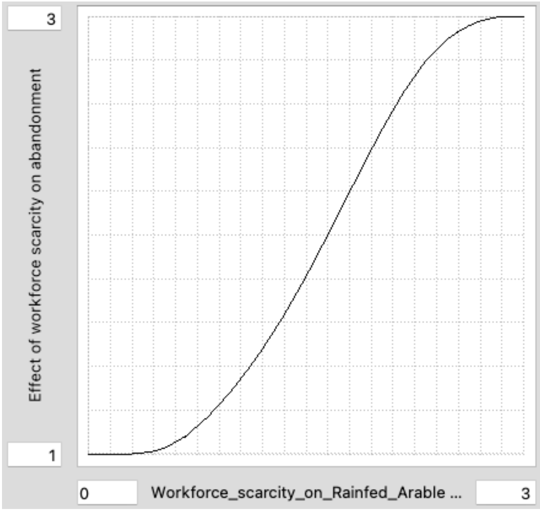


Figure 7.21. Representation of the *Effect_of_workforce_scarcity_on_abandonment* variable. In this graphic function, it is assumed that when the workforce demand on rainfed arable land is equal to or more than 3 times relative to its availability, the rate of abandonment increases up to 3 times the usual abandonment fraction.

In addition to forestation, *Abandoned* land stock decreases with conversion from abandoned to *Rainfed Arable* land (*reclaiming*), as the uncultivated land is being reclaimed for agricultural use. The reclaiming rate is given by the *Reclaiming_fraction* and is either accelerated or reduced by the effect of workforce scarcity (*Effect_of_workforce_scarcity_on_reclamation*). The effect is the same as in the case of *land_clearing* (Figure 7.19).

*reclaiming = Abandoned * Reclaiming_fraction * Effect_of_workforce_scarcity_on_reclamation* {m^2/year}.

Rainfed Arable land stock increases with *land_clearing* of *Bioproductive* land, with *reclaiming* of *Abandoned* land, as well as with the abandonment of irrigation on the *Irrigated Arable* land stock, turning it into rainfed arable land (Figure 7.22). Because abandoned land stock is also made up of abandoned arable land, it is commonly the first option for a source of land in case farmers wish to increase their arable land stock. At the same time, rainfed arable land stock decreases with abandonment and with conversion into irrigated arable land.

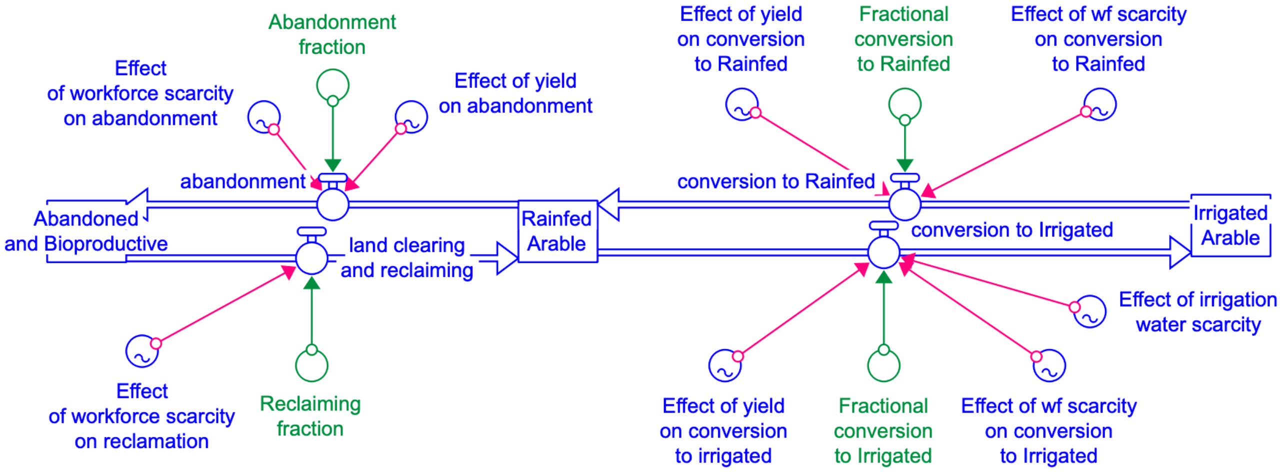


Figure 7.22. Stock-flow diagram depicting the factors that determine the flow rates to / from rainfed and irrigated arable lands.

$$Rainfed\ Arable_t = Rainfed\ Arable_{t-1} + land\_clearing + reclaiming + conversion\_to\_Rainfed - abandonment - conversion\_to\_irrigated\ \{\mathrm{m}^2\}.$$

The speed of conversion from irrigated to rainfed arable land is given by the conversion fraction and is influenced by the effect of yield and by the effect of workforce scarcity:

$$conversion\_to\_Rainfed = Irrigated\ Arable * Fractional\_conversion\_to\_Rainfed * Effect\_of\_yield\_on\_conversion\_to\_Rainfed * Effect\_of\_wf\_scarcity\_on\_conversion\_to\_Rainfed\ \{\mathrm{m}^2/\mathrm{year}\}.$$

The effect of yield on the conversion of arable land from irrigated to rainfed (Figure 7.23) describes a process similar to the *Effect_of_yield_on_abandonment* (Figure 7.20). Namely, it is influenced by the ratio between the actual yield and the attainable yield on irrigated land.

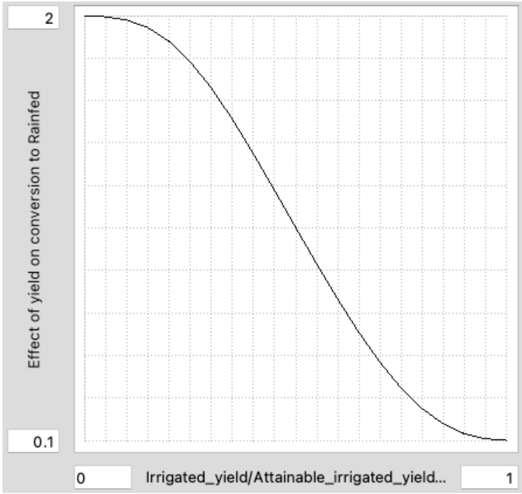


Figure 7.23. Representation of the graphic function for *Effect_of_yield_on_conversion_to_Rainfed* variable. It is assumed that when the *Irrigated_yield* becomes less than half of the *Attainable_irrigated_yield*, the conversion to rainfed land is intensified by a factor of up to 2. That means that when the yield is half or less than what would be attainable, the farmers switch to rainfed cultivation. Likewise, when *Irrigated_yield* is over 50 % of the *Attainable_irrigated_yield*, the conversion of irrigation land to rainfed decreases up to the point that no conversion happens when the actual yield is close or equal to the attainable one.

The effect of workforce scarcity on the conversion from irrigated to rainfed land (Figure 7.24) is similar to the same effect on the abandonment of rainfed land described above (Figure 7.21). Commonly, irrigated crops are more labor-intensive than rainfed ones.

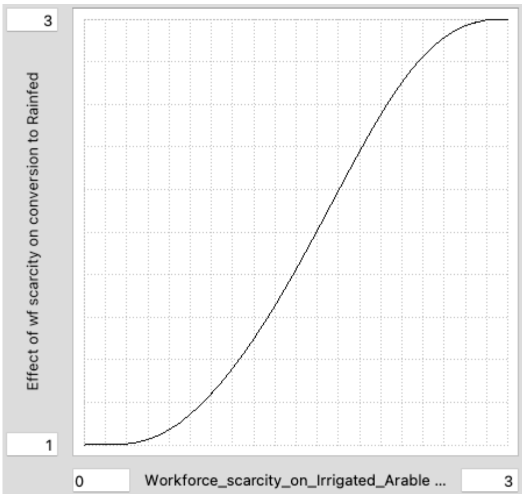


Figure 7.24. Representation of *Effect_of_wf_scarcity_on_conversion_to_Rainfed* variable. With increasing workforce scarcity on irrigated land (*Workforce_scarcity_on_Irrigated_Arable* > *1*), the conversion from irrigated to less labor-intensive rainfed land increases by multiplying the *Fractional_conversion_to_Rainfed* by a factor of 1 to 3.

The decrease in *Rainfed Arable* stock due to abandonment has been described above. Additionally, this stock decreases due to the *conversion_to_Irrigated* rate. This rate is given by a conversion fraction and influenced by the effect of yield, by the effect of workforce scarcity, and by the effect of irrigation water scarcity:

*conversion_to_Irrigated = Rainfed_Arable * Fractional_conversion_to_Irrigated * Effect_of_yield_on_conversion_to_irrigated * Effect_of_wf_scarcity_on_conversion_to_Irrigated * Effect_of_irrigation_water_scarcity* {m^2/ year}.

The effect of yield on the conversion of arable land from rainfed to irrigated (Figure 7.25) describes the attractiveness of irrigating the land when irrigated crops result in significantly higher yields compared to the rainfed ones.

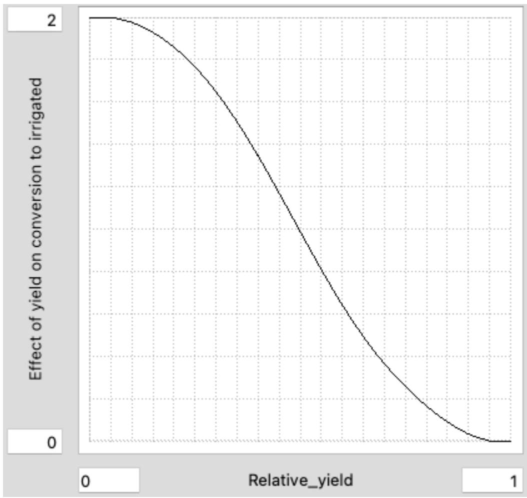


Figure 7.25. Representation of the graphic function for *Effect_of_yield_on_conversion_to_irrigated* variable. In Ikel CliRes model, we assume that the bigger the difference between *Rainfed yield* and *Irrigated yield*, the more attractive it will be for farmers to start irrigating their lands: the conversion speed from rainfed to irrigated land will increase up to two times. Similarly, if the difference between the two types of crop yield is small or nonexistent, the conversion will be close or equal to 0. That is, if yields on irrigated lands are not much higher than those on rainfed lands, farmers have no incentive to start irrigating, and prefer to continue cultivating crops on rainfed arable lands.

The effect of workforce scarcity on the conversion of arable to irrigated (Figure 7.26) is similar to the *Effect_of_workforce_scarcity_on_reclamation* (Figure 7.19). With no scarcity, the conversion rate is high. Increasing scarcity leads to a decrease or cessation in farmers' choice to cultivate crops that require irrigation.

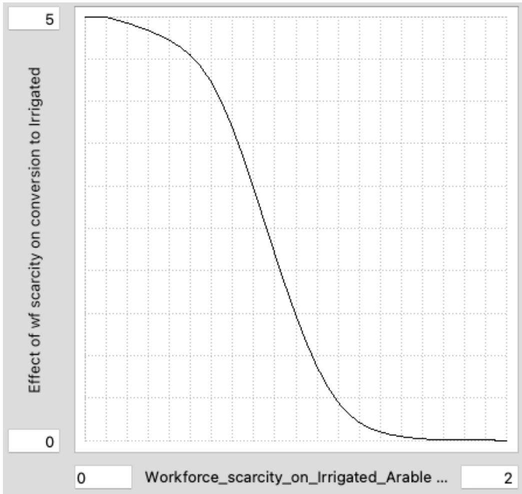


Figure 7.26. Representation of *Effect_of_wf_scarcity_on_conversion_to_irrigated* variable. So long as there is no workforce scarcity (*Workforce_scarcity_on_Irrigated_Arable* < 1), the conversion rate is high. With very high workforce availability, the effect may increase up to 5 times. However, with increasing scarcity, the reclaiming rate drastically decreases or even stops when the availability of workforce is two times smaller than the demand.

The effect of irrigation water scarcity on the conversion of arable land from rainfed to irrigated (Figure 7.28) is influenced by the extent to which the supply of water for irrigation meets the demand (Figure 7.27).

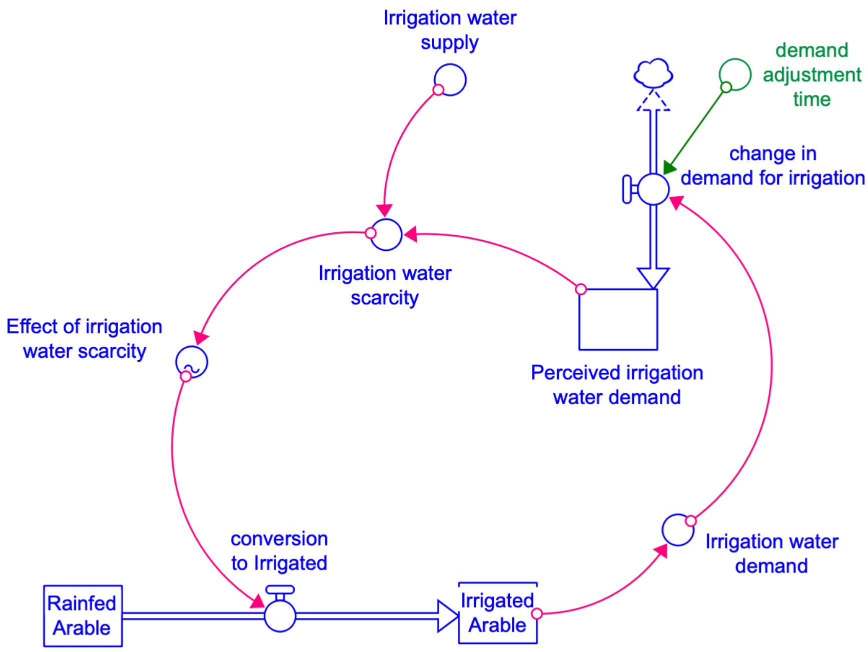


Figure 7.27. Stock-flow diagram illustrating the formation of irrigation water scarcity and its effect on conversion from rainfed to irrigated arable land. As the water scarcity increases, the farmers become less willing to open additional land for cultivation of irrigated crops, opting to cultivate rainfed crops instead.

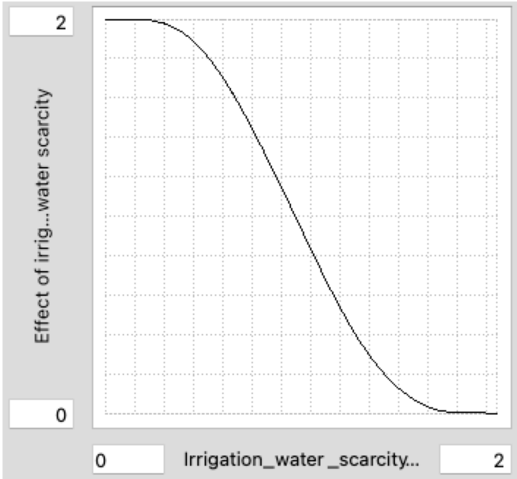


Figure 7.28. Representation of the graphic function for *Effect_of_irrigation_water_scarcity* variable. It is assumed that when the supply is equal to the demand, the conversion rate is the usual one. When the supply is plentiful, the attractiveness to start irrigating increases and the effect of this abundance increases the speed of conversion to irrigated land up to two times. Conversely, when less irrigation water is supplied than what is needed (scarcity increases above 1), the conversion slows down and may even stop if the need is two times higher than the supply.

Lastly, the *Irrigated Arable* land stock only increases with conversion from and decreases with conversion to *Rainfed Arable* land stock:

$$Irrigated\_Arable_t = Irrigated\_Arable_{t-1} + conversion\_to\_irrigated - conversion\_to\_Rainfed \; \{m^2\}.$$

Because no data is available on conversion fractions for different land uses on a yearly basis in Ikel SES, assumed values are assigned to all yearly conversion fractions (Table 7.26), and the model is tested for sensitivity to the value of these fractions. The sensitivity tests are presented and discussed in more detail in the "Validation" and "Policy Analysis" chapters.

In this model, crop yields play an important role in conversion rates to/from irrigated and rainfed arable lands, as well as in the abandonment of cultivated lands altogether. According to Hengsdijk and Langeveld (2009), 30 % (±3 t/ha) of the difference between potential yield and actual yield is explained by a suboptimal knowledge systems, 20 % - by the soil nutrient constraint, another 20 % - by water availability constraint (± 2 t/ha), 20 % - by the (mis)use of mechanization, and only 10 % (± 1 t/ha) - by pests, weed and diseases. Rainfed crop yield (*Rainfed_yield*) and irrigated crop yield (*Irrigated_yield*) in this sector are conceptualized as being primarily determined by 1) the maximum attainable yield in rainfed and irrigated conditions respectively, 2) the effect of soil depth (Figure 7.29), and 3) the effect of evapotranspiration (Figure 7.30):

*Rainfed_yield = Attainable_rainfed_yield * Effect_of_soil_depth_on_yield * Effect_of_ET_on_rainfed_yield* {kg/m^2}.

*Irrigated_yield = Attainable_irrigated_yield * Effect_of_soil_depth_on_yield * Effect_of_ET_on_irrigated_yield* {kg/m^2}.

We use attainable yield values for the corn/maize as a reference crop due to it being one of the most commonly cultivated crop in the area. Values for attainable yield of irrigated maize differ depending on both the variety and the geography. In Ikel CliRes model, we set the attainable yield values for irrigated and rainfed corn yield (Table 7.26) based on the ones shown in Table 7.24. Other values are being tested during sensitivity analysis.

Table 7.24. Attainable yield values for irrigated and rainfed corn.

<table>
<tr><th>Attainable corn yield on rainfed land (t/ha)</th><th>Attainable/potential corn yield on irrigated land (t/ha)</th><th>Source</th></tr>
<tr><td>2-5 times less than irrigated</td><td>10-12</td><td>Vronschih et al., 2009</td></tr>
<tr><td>2.6 – 6</td><td>14.4 – 17.6</td><td>FAO and DWFI, 2015</td></tr>
<tr><td colspan="2">9.5 – 11.9</td><td>Hengsdijk and Langeveld, 2009</td></tr>
</table>

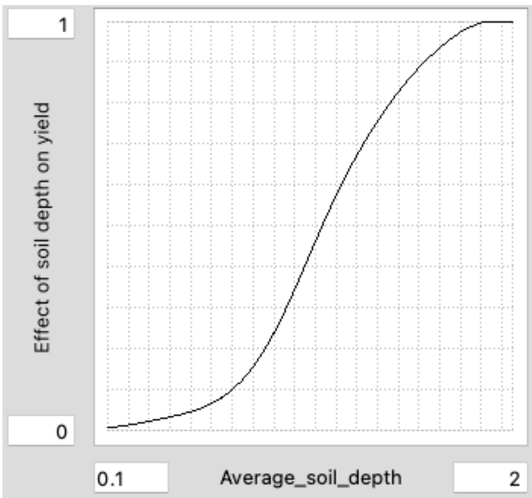


Figure 7.29. Representation of the graphic function for *Effect_of_soil_depth_on_yield* variable. The effect of soil depth on crop yields is calibrated based on the estimation that: 1) 0.025m of soil loss reduces crop production by 5.3 - 6.3 % (Ford, 1990); 2) in R. Moldova, crop production may decrease by 10 – 60 % year on year due to erosion, with an average of 30 % (ICAS, 2015).

The effects of evapotranspiration on *Rainfed_yield* and on *Irrigated_yiel* are, in turn, determined by the relative evapotranspiration on rainfed and irrigated lands respectively – a ratio between actual evapotranspiration and potential evapotranspiration (both described in Section 7.2.1 *Water resources*):

Relative_ET_on_Rainfed_Arable = ET_on_Rainfed_Arable / PET {dimensionless}.

Relative_ET_on_Irrigated_land = ET_on_Irrigated_land / PET {dimensionless}.

a. b.

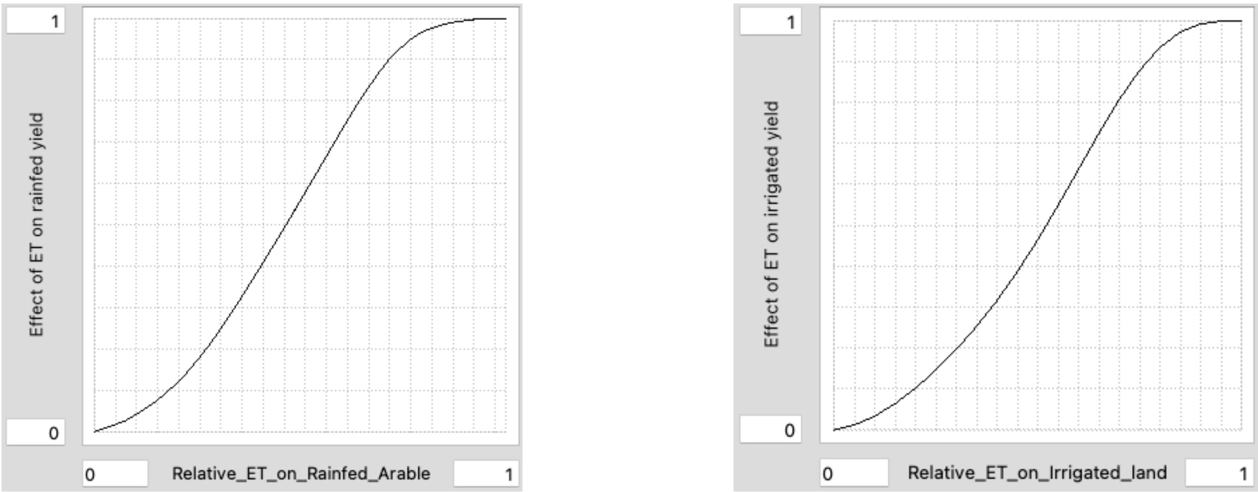


Figure 7.30. Representation of the graphic function for variables *Effect_of_ET_on_rainfed_yield* (a) and *Effect_of_ET_on_irrigated_yield* (b). The effects take values from 0 to 1, depending on the *relET_RFA* ratio, which also takes values from 0 to 1. When the *Relative_ET_on_Rainfed_Arable* and/or *Relative_ET_on_Irrigated_land* and their effects are close or equal to 0, no yields are produced. When the effect is close or equal to 1, the yield produced is equal to the maximum attainable yield, all things being equal.

While for rainfed crops, the sole source of water is the one supplied by precipitations, water availability for irrigated crops is complemented by irrigation water supply. As seen in Section 7.2.2 *Irrigation Infrastructure*, the supply (*Irrigation_water_supply*) is influenced by the irrigation water demand, more precisely – *Perceived_irrigation_water_demand* (Figure 7.31). The perceived demand differs from the actual demand as it is adjusted with a certain perception delay:

Perceived_irrigation_water_demand $_t$ = Perceived*_irrigation_water_demand* $_{t-1}$ + *(Irrigation_water_demand - Perceived_irrigation_water_demand* $_{t-1}$*) / demand_adjustment_time* {m^3/year}.

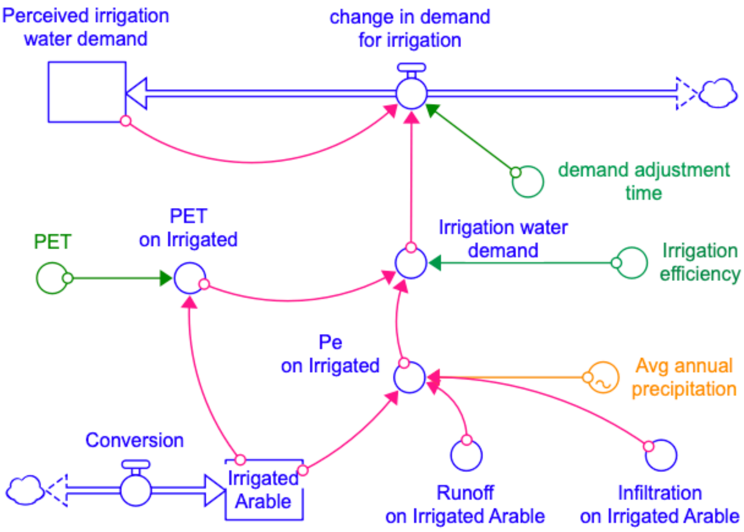


Figure 7.31. Stock-flow diagram illustrating the factors that influence the actual and perceived irrigation water demand.

Irrigation water demand is either 0, when effective precipitation (*Pe_on_irrigated*) provides sufficient water that ET on irrigated land is equal to PET for the given crop, or the difference between PET and effective precipitation. The actual demand also factors in the efficiency of irrigation:

Irrigation_water_demand = [MAX (PET_on_Irrigated - Pe_on_Irrigated, 0)] / Irrigation_efficiency {m3/year}.

This equation is an adaptation of a recommended method for estimating irrigation need, proposed by FAO (1986):

$$IN = ET\ crop - Pe \tag{7.4}$$

Where:

IN = irrigation water need

ET crop = crop water need

Pe = effective precipitation

*Pe_on_Irrigated = (Avg_annual_precipitation * Irrigated_Arable) - Runoff_on_Irrigated_Arable - Infiltration_on_Irrigated_Arable* {m^3/year}

Irrigation_efficiency is to be understood as the fraction of water effectively used by the plant from the total water applied from irrigation. For example, drip irrigation would be considered the most efficient method, with minimal water loss, while flood irrigation – the least efficient manner of irrigation. Because no data on this parameter is available for Ikel SES, it is assigned an assumed value in Ikel CliRes model (Table 7.26), and sensitivity tests are conducted for different values ranging from 1 (maximum irrigation efficiency and no water losses) to 0.1 (extremely inefficient irrigation practices).

As shown earlier in this section, workforce scarcity is impacting the conversion rate to / from both rainfed and irrigated arable lands. We define the workforce scarcity as the ratio between the demand and the supply of workforce needed to grow crops on these lands. Both workforce demand and supply are aggregated proxies for low-skilled agricultural workforce (people needed to cultivate the land) and qualified workforce (engineers, technicians, scientists, etc.). Workforce demand is given by the arable area and the workforce needed to cultivate a unit of it.

Workforce_scarcity_on_Rainfed_Arable =
= Workforce_demand_on_Rainfed / Workforce_on_Rainfed {dimensionless}.

Workforce_scarcity_on_Irrigated_Arable =
= Workforce_demand_on_Irrigated / Workforce_on_Irrigated {dimensionless}.

Workforce_demand_on_Rainfed = Rainfed_Arable Workforce_required_on_Rainfed* {people}.

Workforce_demand_on_Irrigated = Irrigated_Arable Workforce_required_on_Irrigated* {people}.

Irrigated arable land is relatively more labor intensive compared to rainfed agriculture. We assign values for *Workforce_required_on_Rainfed* and *Workforce_required_on_Irrigated* parameters (Table 7.26) based on figures provided by the farmers in Ikel watershed during interviews for model conceptualization and validation, when they underlined that often times their decision to cultivate irrigated crops depends on the availability of workforce. Available workforce is defined in this model as the minimum of either the demand or the actual existing workforce in the watershed. The latter is a fraction of the total Ikel population:

*Ikel_SES_workforce = Ikel_SES_population*Fraction_of_population_in_agriculture* {people}.

Ikel_SES_population is defined as a time series (Table 7.25), mirroring the actual population dynamics in the region (Table 2.1). For future projections, we consider the estimates and probabilistic projections for the population of R. Moldova provided by the UN Department of Economic and Social Affairs (Figure 2.9).

Table 7.25. Values assigned to Ikel SES population parameter in Ikel CliRes model.

Year	**Ikel_SES_population (people)**
1990	146,924
1991	145,646
1992	144,379
1993	143,122
1994	141,877
1995	140,643
1996	139,419
1997	138,206
1998	137,004
1999	135,812
2000	134,631
2001	133,459
2002	132,298
2003	131,147
2004	121,816
2005	115,360
2006	115,166
2007	116,810
2008	116,716
2009	116,582
2010	116,635
2011	116,680
2012	117,037
2013	117,852
2014	118,221
2015	117,965
2016	117,629
2017	117,346
2018	116,857
2019	116,514
2020	115,500

For the fraction of population engaged in agricultural activities in Ikel watershed, we estimate this parameter (Table 7.26) based on the percentage of Moldova's population engaged in agricultural activities between 2013-2019 (Table 7.23) and adjust it to account for unofficial engagement in cultivation of arable land (small hold subsistence farming, unofficial employment, day workers).

Within the boundaries of this sector, there are two important balancing loops. One of them – water scarcity impact on irrigated arable land area – is responsible for the reduction in conversion to irrigated land due to irrigation water scarcity. Specifically, with increasing area of irrigated arable land, the demand for irrigation water increases, which determines an increase in the water scarcity. Unless the supplied water meets the demand, the increased scarcity contributes to a decrease in the conversion of rainfed to irrigated arable land (Figure 7.32).

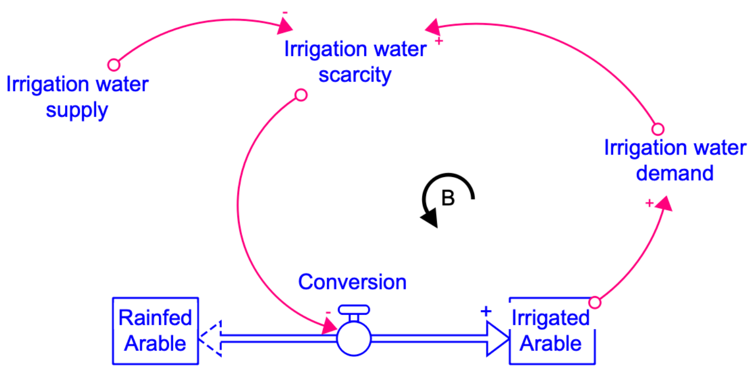


Figure 7.32. Balancing loop in the land use sector describing the water scarcity impact on irrigated arable land area.

Another important balancing process encompassing two major causal loops – the impact of workforce scarcity on rainfed and irrigated arable land area – influences the conversion to/from arable land illustrates the impact of workforce scarcity on conversion to/from irrigated arable land, and on conversion to/from rainfed arable land (Figure 7.33). The essential dynamics in this case is that increased arable lands demand for more workforce to be available. Since workforce within Ikel SES is limited, this causes an increase in workforce scarcity, and thereby a decrease in the conversion to irrigated and rainfed land respectively.

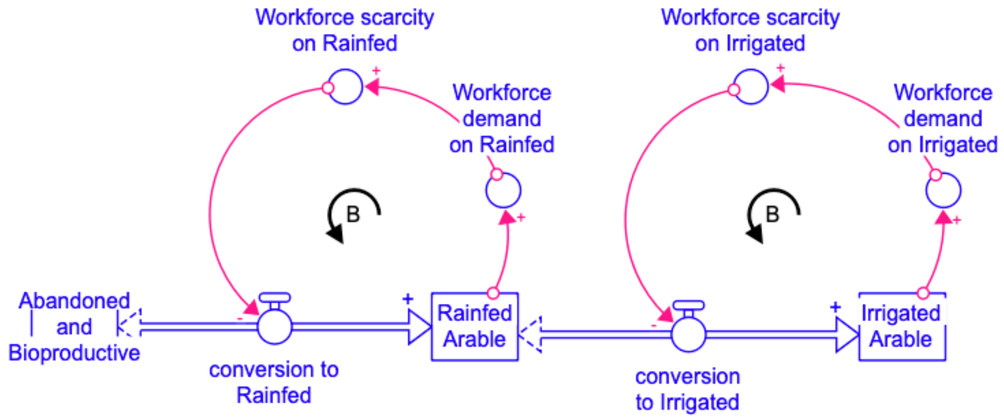


Figure 7.33. Balancing loops in the land use sector describing the impact of workforce scarcity on rainfed and irrigated arable land area.

Table 7.26. List and description of parameters: *land use* sector.

Variable	Description	Value	Units	Source
Abandonment_fraction	Reference abandonment fraction of rainfed arable land	0.001	1/year	Assumed
Attainable_irrigated_yield	Attainable reference crop yield (corn) on irrigated land	1.2	kg/m^2	Vronschih et al., 2009 FAO and DWFI, 2015 Hengsdijk and Langeveld, 2009
Attainable_rainfed_yield	Attainable reference crop yield (corn) on rainfed land	1	kg/m^2	Vronschih et al., 2009 FAO and DWFI, 2015 Hengsdijk and Langeveld, 2009
Clearing_fraction	Conversion fraction from bioproductive land to arable land	0,00001	1/year	Assumed
demand_adjustment_time	The time it takes decision-makers to collect and adjust information regarding irrigation water demand	0.25	year	Assumed
Forestation_fraction	Reference fraction of human-led forestation efforts	0.0001	1/year	Assumed
Fraction_of_population_in_agriculture	Fraction of Ikel population that is engaged in land cultivation activities	0.02	dmnl	Based on NSB data
Fractional_conversion_to_Rainfed	Reference fractional change from irrigated to rainfed land	0.02	1/year	Assumed
Fractional_conversion_to_Irrigated	Reference fractional change from rainfed to irrigated land	0.02	1/year	Assumed
Ikel_SES_population	Population in Ikel watershed	See Table 7.25	people	Based on NSB data
Irrigation_efficiency	Fraction of irrigation water used by crops from the total irrigation water applied.	0.9	dmnl	Based on literature and interviews with local farmers
Natural_forestation_fraction	Fraction of abandoned land returning to bioproductive land naturally	0.0001	1/year	Assumed
Reclaiming_fraction	Fraction of reclaiming abandoned land for agricultural use	0.05	1/year	Assumed
Workforce_required_on_Rainfed	Workforce requirement for rainfed crop cultivation	0.00002	$people/m^2$	Estimated based on interviews with farmers
Workforce_required_on_Irrigated	Workforce requirement for irrigated crop cultivation	0.0002	$people/m^2$	Estimated based on interviews with farmers

8. MODEL VALIDATION

A SD model embodies a theory about the way in which a system works with regards to some of its aspects (Barlas and Carpenter, 1990). Because the validity of the simulation results depends on the validity of the model, validation is central to model building. It is important to note that, in system dynamics modeling, validation is not meant to establish whether the model is “correct” or “incorrect”, but rather to gradually build confidence in its usefulness (Barlas, 1996). Model validation is therefore a gradual process by which model validity is enhanced systematically.

Generally, validation methods are categorized into two large groups: structure validity and behavior validity (Barlas, 1996). Structure validation tests are aimed at assessing if the logic of the model, its internal structure showing how the behavior is generated, is attuned to the corresponding structure in the real world. Behavior validation tests compare simulation outcomes with data from the real system under study; they are relevant only insofar as model’s structural validity is established. Based on such empirical tests with real-life data, the adequacy of the model can be inferred. It should be remembered that both structure and behavior validation tests should be conducted with reference to the purpose of the model, which in the case of Ikel CliRes is to support policy development for resilience building to climate change impacts while enhancing learning about Ikel SES itself.

A range of validation tests have been put forward by system dynamicists to closely scrutinize the models being developed. In this research, we have applied a selection of tests corresponding to the structural and behavioral validation as systematized by Barlas (1996) in Figure 8.1.

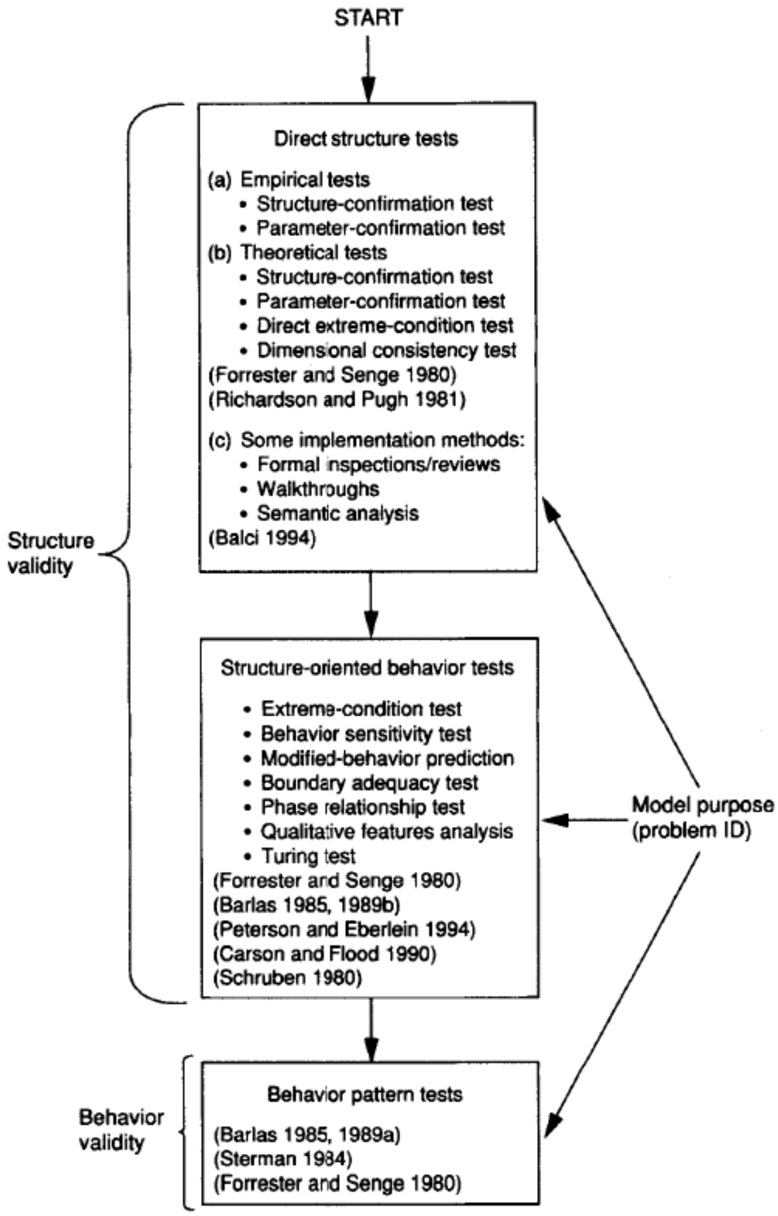


Figure 8.1. Overall nature and selected tests of formal model validation (Barlas, 1996).

Building on the above, Both Barlas (1996) and Groesser and Schwaninger (2012) further discuss what tests to apply and when. The latter propose heuristic principles for the choice of methods as a function of the complexity of the model to be validated, a complexity hierarchy of validation tests (Figure 8.2), and an integrative validation process (Figure 8.3).

Figure 8.2 depicts how distinct levels in the hierarchy of model complexity match the distinct types of tests. This hierarchy has informed my choice of tests at various stages in model development. Overall, continuous testing at different stages in Ikel CliRes model development ensured the validity and good quality of the model as it was being built.

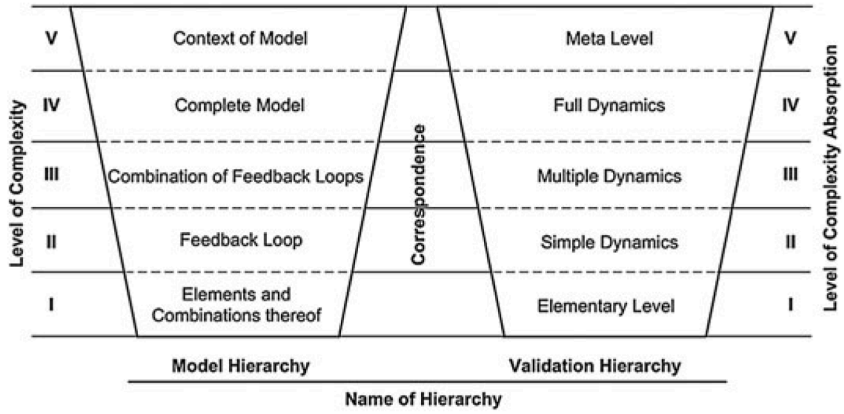


Figure 8.2. Correspondence of the complexities along the model and validation hierarchies (Groesser and Schwaninger, 2012). Ikel CliRes has gone through all stages before becoming a complete model.

The integrative process represented in Figure 8.3 describes the iteration of various tests that accompany the continuous process of model validation during its development, which I have followed in the validation of Ikel CliRes model, as well. For example, when an error has been identified during the structure-oriented behavior validation of the full model dynamics of Ikel CliRes, several changes have been made in the formulation, addition or removal of a converters. As a converter was being adjusted, I conducted tests specific for earlier stages of model validation (e.g., unit consistency, direct extreme condition tests, and others).

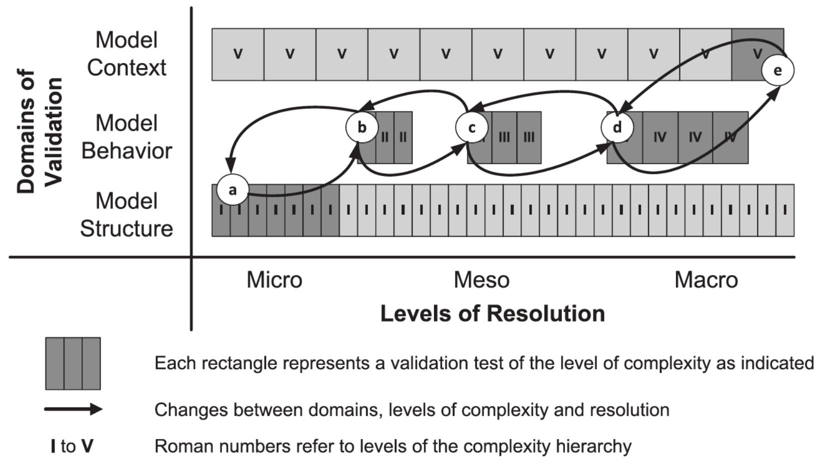


Figure 8.3. An idealized representation of the integrative validation process (Groesser and Schwaninger, 2012). As the modeler progresses from simple model elements to more complex models, corresponding tests are being applied at each stage. This may prompt revision of previously integrated elements, and iterative testing of the model at different stages of its development and complexity (from *a*: validation of elementary model structure to *e*: validation of the model with respect to its context).

In this research, structural validation tests were conducted on each sector (water resources, irrigation infrastructure, erosion, and land use change), as well as on sector groups combined. Behavior validation tests were conducted on the comprehensive model. I ceased the validation process when a validation ceasing threshold was reached (Groesser and Schwaninger, 2012). In the following sections, we provide more details about the tests that were applied to check and enhance the validity of Ikel CliRes model.

8.1. Structural Validation

In this section, the structural validation of the simulation model is demonstrated based on stakeholder engagement in the validation, as well as based on isolated sector runs, and runs for the overall model. I showcase snapshots of the process for structure-oriented behavior tests including extreme-condition, parameter sensitivity and phase-relationship tests.

Structural validation of Ikel CliRes included:

- *Direct structural validation tests* carried out by means of direct comparison to qualitatively assess any discrepancies between the real-life system and the structure of the proposed model.
- *Indirect structure validity tests,* which require computer simulation to assess the validity of the model structure by examining model generated outcome behaviors (Schwaninger and Grosser 2018).

Direct structural validity performed on Ikel CliRes included a structural examination of the model: a theoretical one, whereby we cross-checked the model structure with theoretical knowledge from literature, and an empirical one, whereby we conducted validation interviews with various stakeholders. Among these were participants of the group model building and external experts who are knowledgeable of the different areas of inquiry. Furthermore, both individually and with the support of stakeholders, we conducted direct boundary adequacy tests, and conceptual parameter examination to confirm that Ikel CliRes parameters have real system equivalents. Additionally, at every stage of model development, we performed direct extreme condition, and dimensional consistency tests.

Indirect structural validity tests were performed subsequently, as indicated in the SD literature (Barlas, 1996; Schwaninger and Groesser, 2018).

8.1.1. Water Resources Sector

Extreme condition tests are done by assigning unrealistically high and/or low values to certain parameters and analyzing whether the model generated behavior matches the anticipated behavior of the real system under similar conditions. If the test shows no contradictions, we can reasonably assume that there are no structural flows from this point of view.

By applying behavior sensitivity tests, we can determine those parameters to which the model is very sensitive. If the high sensitivity reflects what the sensitivity of the real system, we can reasonably assume that the model passes this test.

The behavior of groundwater stock is demonstrated under extreme weather conditions in Ikel SES. In the first run, precipitation is set to 0 m/year, which stands for no precipitation falling on Ikel watershed territory (it is assumed that precipitation does not change in upstream territories where groundwater is recharged). The expectation is that under these conditions, the level of groundwater would decrease, as the infiltration and percolation from precipitations is non-existent. The groundwater stock would only be recharged by the water inflowing from upstream underground basins. The corresponding graphs (Figure 8.4. a) depict a decrease in the groundwater, and an increase in the inflowing rate (Figure 8.4. b) up to when the stock reaches an equilibrium level.

a. b.

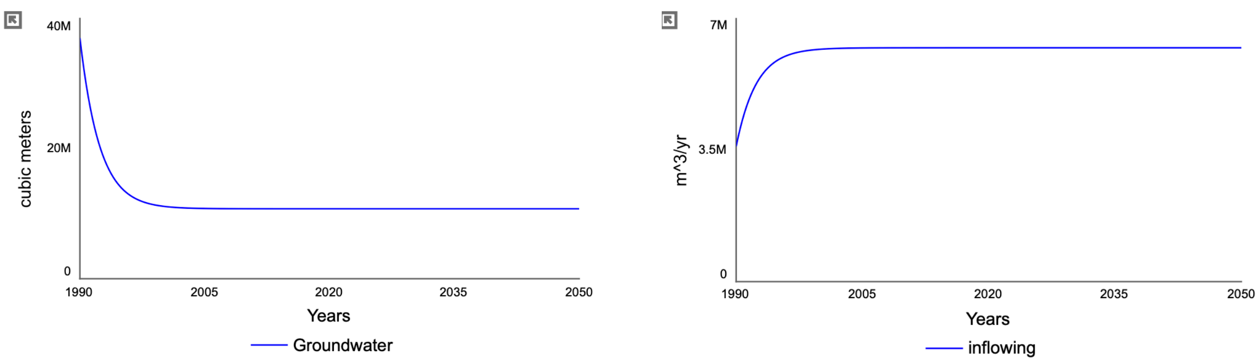


Figure 8.4. Groundwater stock (a) and inflow rate (b) under extreme drought conditions.

Following this, we tested the extreme condition of excessive precipitations on Ikel SES territory (Figure 8.5) and increased it 100-fold. The resulting behavior confirms once again the expected dependence of the confined aquifer located in under Ikel SES territory on inflows from and outflows to other basins. Under these circumstances, the inflows from other basins are reduced to zero, meaning that groundwater stock (Figure 8.5. a) is too full to allow for additional inflows. The outflow to other basins, on the other hand, increases until the stock reaches an equilibrium level (Figure 8.5. b). In real life, this would suggest increased risk of floods in and around Ikel SES.

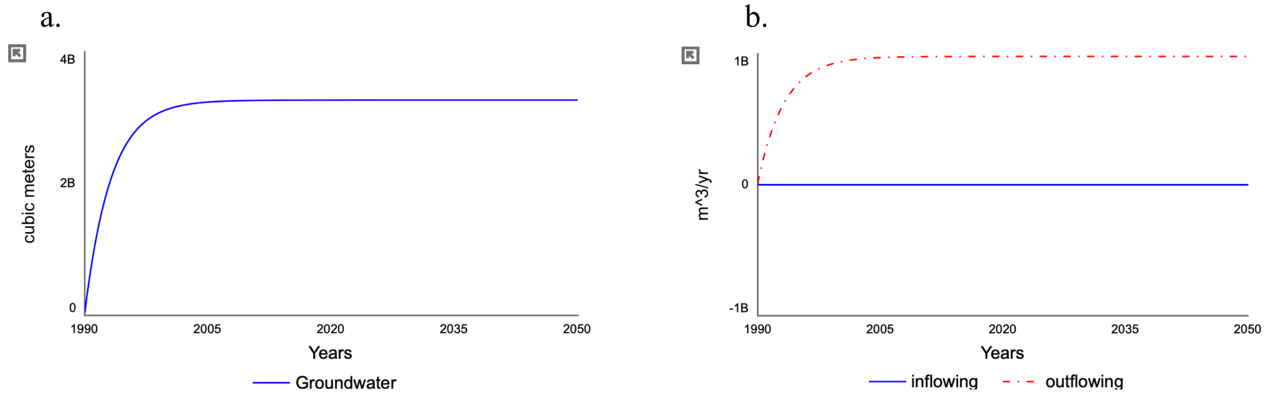


Figure 8.5. Groundwater stock (a) and inflowing and outflowing rates (b) under extreme precipitation conditions on Ikel SES territory.

Similarly, structure-oriented behavior tests in this sector were applied to the groundwater stock. As mentioned before, if the sensitivity in this test reflects the sensitivity of the real system, we can reasonably assume the model passes this test. For the groundwater stock, we tested its sensitivity to different initial stock values, to the stock's recharge time, to the equilibrium level of the stock, to the rate of outflow, to percolation rate, to annual precipitation in Ikel watershed, and to the exploitable groundwater fraction.

For the first test, the expectation is that due to the existence of a theoretical equilibrium level for the groundwater stock, the latter should exhibit a goal-seeking behavior, and thus be sensitive to its different initial values. Additionally, as the stock is not recharged instantly, but rather requires a certain time to happen, it has been expected that the stock be sensitive to recharge time (including the percolation fraction of the infiltrated water) – the longer it takes for the stock to recharge, the lower will be the value of the stock. This has been confirmed following the sensitivity test. Figure 8.6 illustrates the behavior of groundwater in Ikel SES under different initial values of this stock and Figure 8.7 – the stock's sensitivity to different recharging time values. Here it should be noted that the stock is also sensitive to the percolation fraction - a behavior similar to the one illustrated in Figure 8.7.

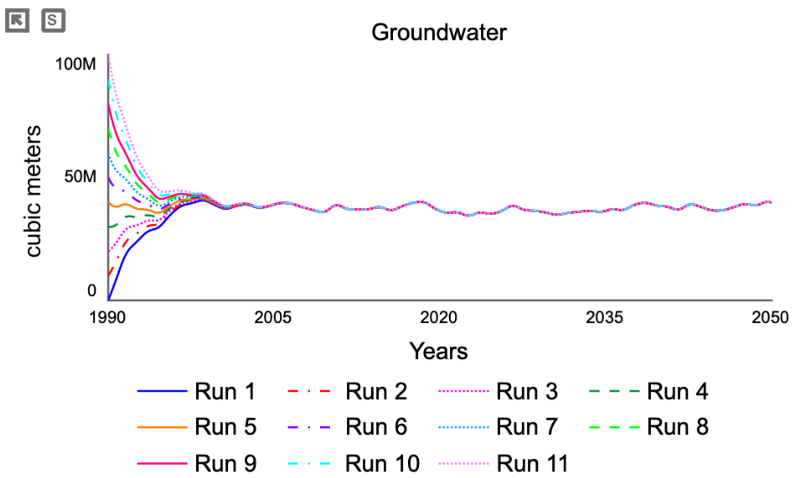


Figure 8.6. Sensitivity of groundwater stock to different initial values of the stock. Different test runs are illustrated with different line colors.

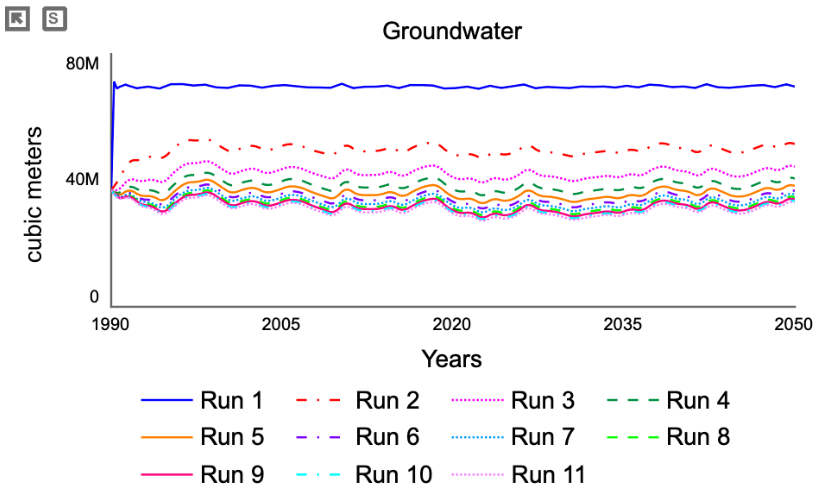


Figure 8.7. Sensitivity of groundwater stock to the recharging time. The shorter the recharge time, the more water there is in the groundwater stock, as it becomes easier for the stock to reach.

In addition to the recharging time, I have checked the stock's sensitivity to the equilibrium level. The expectation is that with a higher equilibrium level, the stock of groundwater will increase, as it tends to reach that level. The sensitivity test, demonstrated in Figure 8.8, confirms the expected behavior of the groundwater stock.

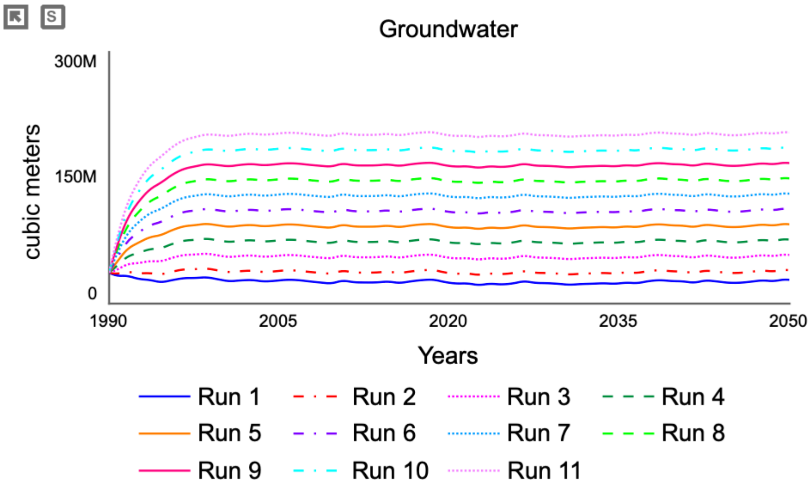


Figure 8.8. Sensitivity of groundwater stock to different equilibrium levels of the stock: lower equilibrium levels determine smaller volumes of the stock. The different test runs are illustrated with different line colors.

Groundwater is also expected to be lower when the outflowing fraction is small as compared to when this fraction is larger. Figure 8.9 below illustrates that Ikel CliRes model accounts for this sensitivity.

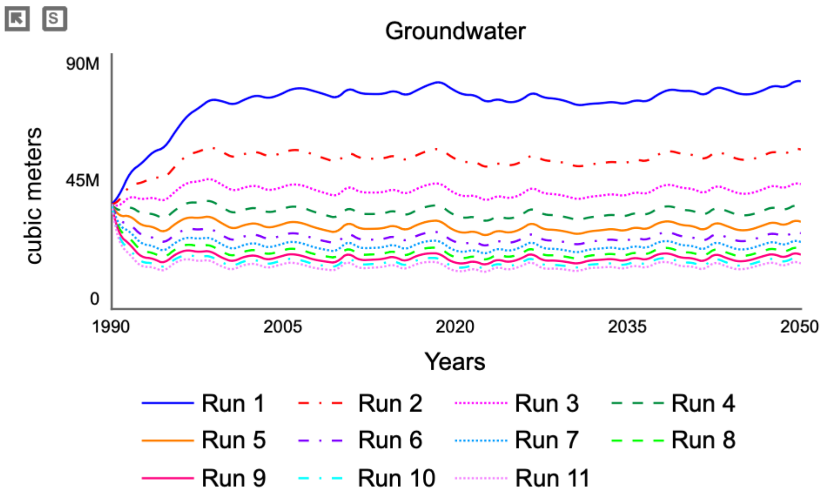


Figure 8.9. Sensitivity of groundwater stock to the rate of outflow.

8.1.2. Irrigation Infrastructure Sector

For this sector, several extreme condition tests were applied. For purposes of model development and testing, the irrigation water demand and available water resources were defined as constant in this sector. In the overall model, they are dynamic variables.

In Figure 8.10 we demonstrate the behavior of surface water and groundwater supply capacity stocks under conditions of extreme drought. Supply capacity (Figure 8.10.a) is the expression of usable irrigation infrastructure in m^3/year. To simulate extreme drought conditions, we set the exploitable runoff at 0, while the demand was set at a level that was higher than the combined supply capacity from surface and groundwater sources. The results of this test run confirmed our expectation that surface water supply capacity would wear out and decrease over time for not being used since there is no available surface water to harness and supply (Figure 8.10. b). Meanwhile, groundwater infrastructure capacity and supply would increase, on condition that it is allowed to use groundwater for crop irrigation.

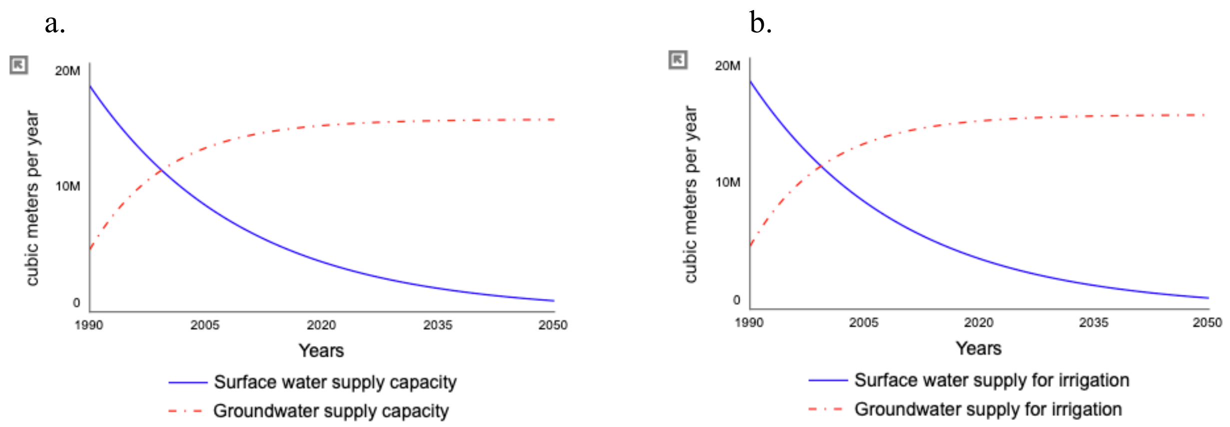


Figure 8.10. Irrigation infrastructure stocks (a) and water supply for irrigation (b) under extreme drought conditions.

Figure 8.11 below illustrates the behavior of both surface water and groundwater capacity stocks and irrigation water supply when water resources are present, but there is no demand for irrigation water. This extreme condition test run confirms the expectation that supply from both sources should cease, while infrastructure should decline should wear out.

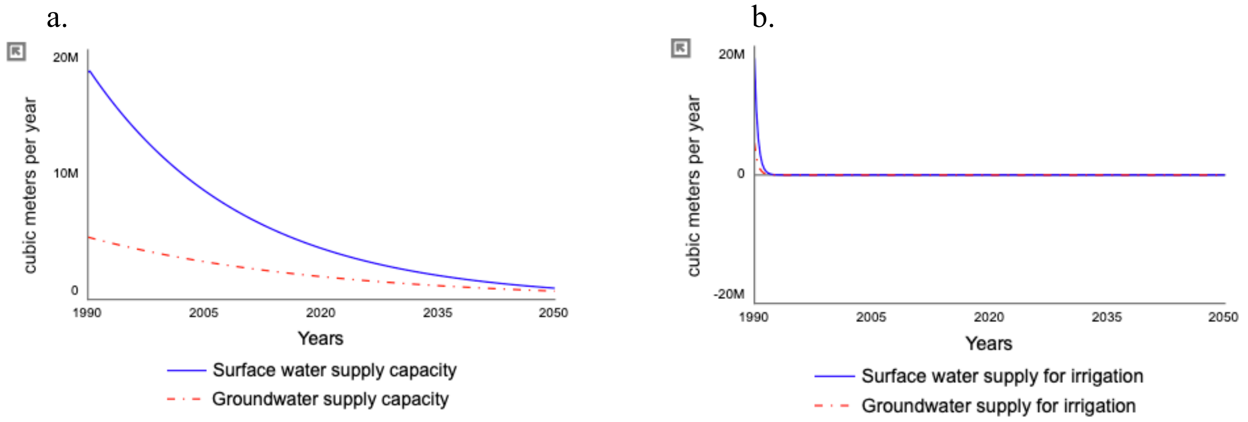


Figure 8.11. Irrigation infrastructure stocks (a) and water supply for irrigation (b) under conditions when resources are available, but there is no irrigation water demand.

Further, extreme condition test for exploitable runoff is demonstrated by assigning values to the runoff that are 200 times above demand. The test run confirmed the anticipated behavior: surface water supply capacity would increase to meet the demand, while groundwater supply capacity would decrease by being rendered unnecessary and wearing out (Figure 8.12. a). Simultaneously, the irrigation water would be supplied increasingly from surface water resources (Figure 8.12. b).

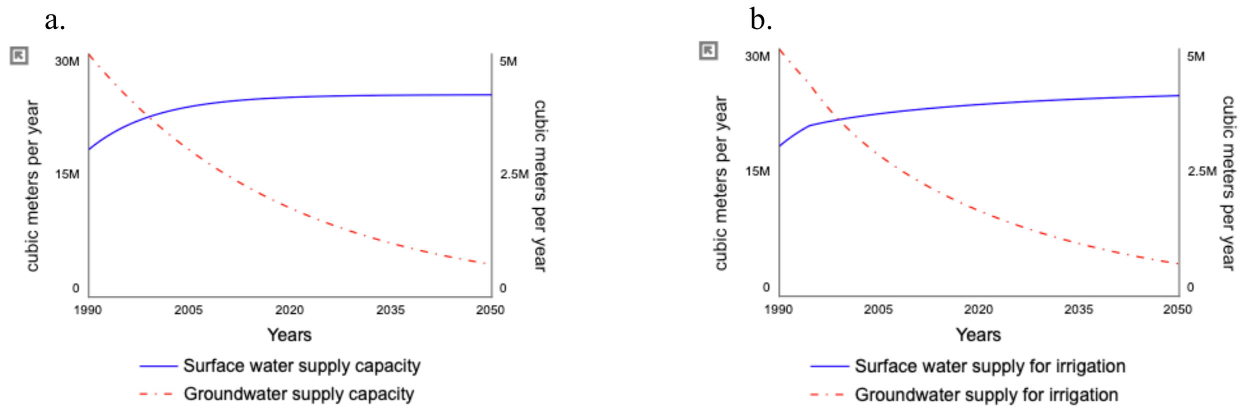


Figure 8.12. Irrigation infrastructure stocks under conditions of extremely high precipitations.

Parameter sensitivity was tested for irrigation water supply, which is the sum of irrigation water supply from surface and from groundwater resources to adjustment time for surface water supply capacity (Figure 8.13.a) and to adjustment time for groundwater supply capacity (Figure 8.13.b). The expectation is that the longer it takes for investments in infrastructure to happen, in particular with regards to surface water supply capacity, the longer it will take for the irrigation water supply to form (assuming that the demand remains high). The test runs show that irrigation water supply is indeed sensitive to the time it takes to provide the necessary irrigation infrastructure, with investments in surface water supply capacity playing a more important role due to the fact that a higher fraction of irrigation water supply is provided from exploitable runoff.

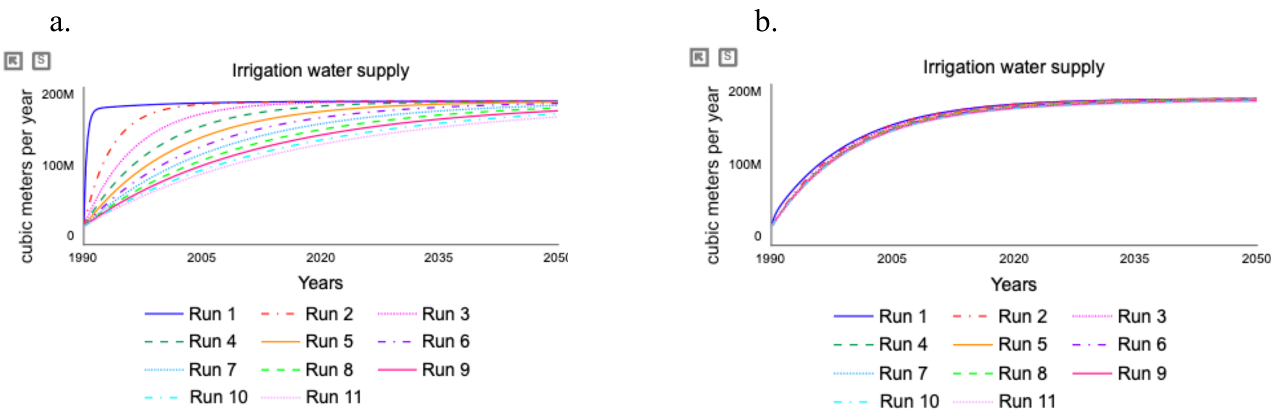


Figure 8.13. Sensitivity of irrigation water supply to the adjustment time for surface water supply capacity (a) and to the adjustment time for groundwater supply capacity (b).

8.1.3. Erosion Sector

In this sector, we test the behavior of the average soil mass stock under the extreme conditions of no precipitations, and extremely intensive precipitations. For "no precipitation" scenario, we set the rainfall erosivity factor R (based on USLE equation) to 0 and expect no erosion caused by rainfall to happen. Following the test run, the topsoil mass remained constant, as it was expected (Figure 8.14.a). For extremely intensive precipitations scenario, we set the same variable to a value 10 times higher than the current one and expect the stock to decrease constantly until topsoil is fully eroded. The extreme test run shows average soil mass being reduced to 0, as expected (Figure 8.14.b).

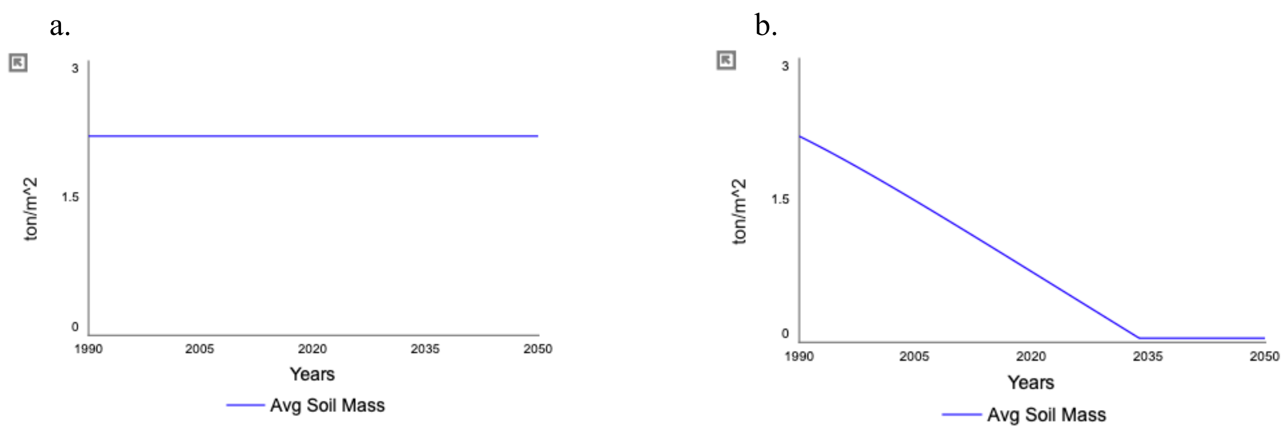


Figure 8.14. Topsoil mass stock under conditions of no (a) and extremely intense (b) precipitations.

8.1.4. Drivers of Change in Land Use Sector

We have conducted multiple extreme condition tests on this sector, given that it is the biggest sector in our model, and that it has four land use stocks. Overall, the stocks in this sector behave as expected under various extreme conditions. Below, we demonstrate the results of some of the test runs.

In one of the tests, we considered the draught scenario, meaning that no rainfall is happening in Ikel SES. With no rainfall, defined in this sector as relative evapotranspiration on arable land (ET / PET) = 0, we expected that the extreme draught would lead to crop failure (Figure 8.15.a), and to the increase in the abandonment of the arable land, with the subsequent conversion to bioproductive land (Figure 8.15.b). Following the test run, Ikel CliRes behaved as expected.

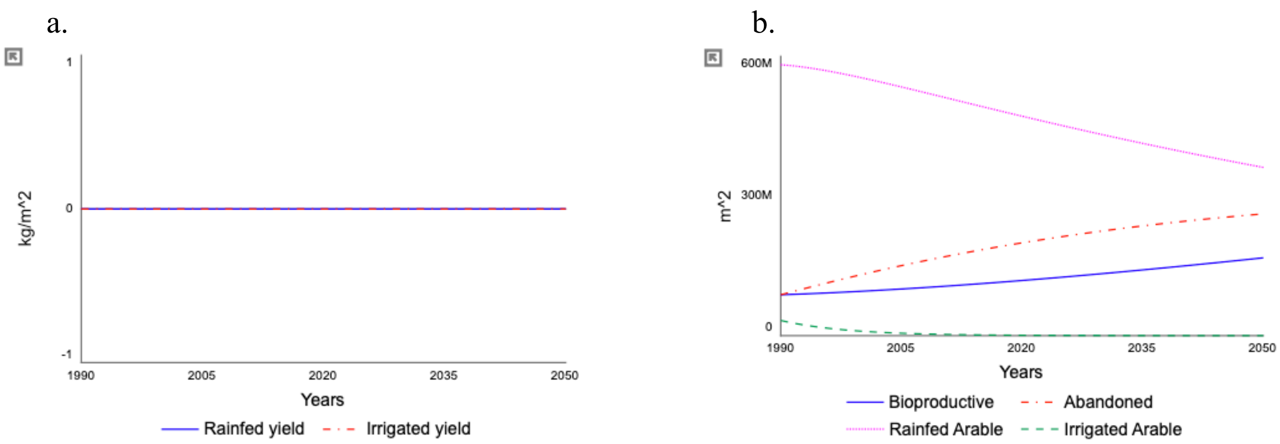


Figure 8.15. Crop yield (a) and land use stocks (b) under the extreme conditions of draughts.

Figure 8.16 demonstrates the test run for the intensive precipitation scenario. To model this extreme scenario in the land use sector, relative evapotranspiration was multiplied by a factor of 10. The expectation was that with more than enough precipitation, crop yields on both irrigated and rainfed lands would achieve their maximum attainable values (Figure 8.16.a), which would result firstly, in no rainfed land to be abandoned and secondly - in irrigated land somewhat decreasing due to satisfactory yields on rainfed (Figure 8.16.b). The simulation results were as expected.

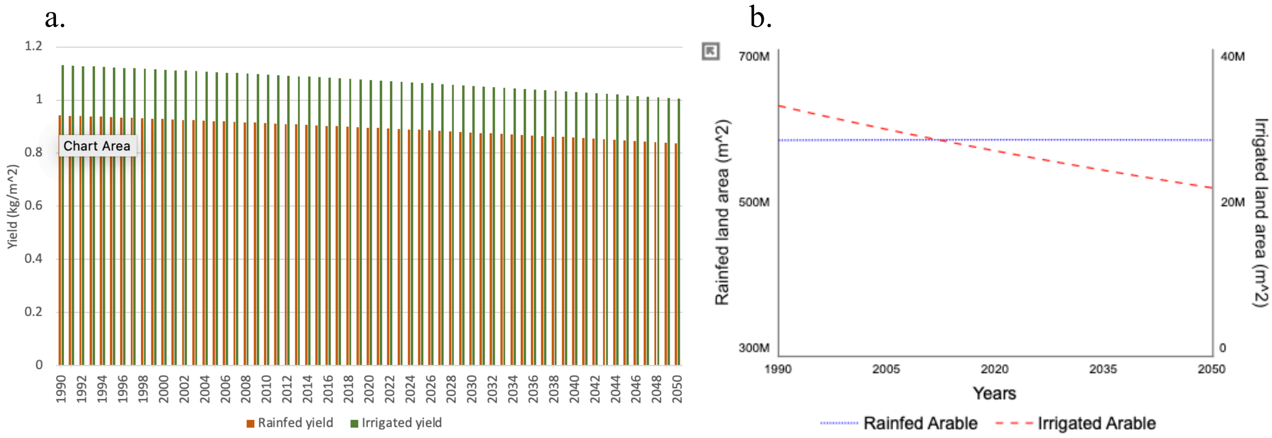


Figure 8.16. Crop yield (a) and arable land stocks (b) under the conditions of plentiful precipitation.

Sensitivity tests conducted on rainfed yield looked at this key variable's relationship to attainable rainfed yield, to potential evapotranspiration, to infiltration coefficient on rainfed arable land, and to average topsoil mass. With regards to attainable yield, it is expected that actual yield will vary depending on how large the attainable yield is under similar circumstances (e.g., same PET value). The results of this sensitivity test illustrated in Figure 8.17 confirm the expected behavior.

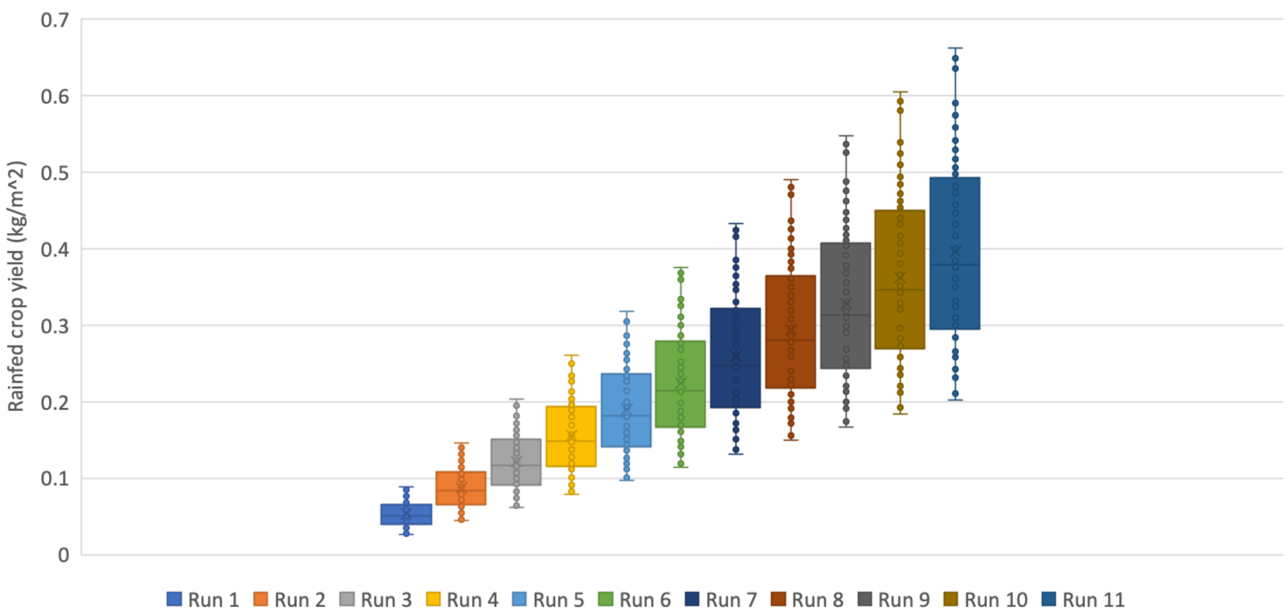


Figure 8.17. Sensitivity test runs illustrate that rainfed yield is numerically sensitive and directly proportional to attainable yield parameter. Run distribution is incremental: attainable rainfed yield value for Run 1 is the smallest (0.2 kg/m^2), while the one for Run 11 is the highest (1.5 kg/m^2).

Looking at potential evapotranspiration, the expectation was that, under the same precipitation conditions, a smaller PET value for a crop would generate higher yields, while higher PET values would result is smaller yields. Therefore, in this test we looked at how sensitive the rainfed yield is to various PET values (we assigned PET values from 0.4 to 1.2 m/year). The results confirming the expected behavior are shown in Figure 8.18 below.

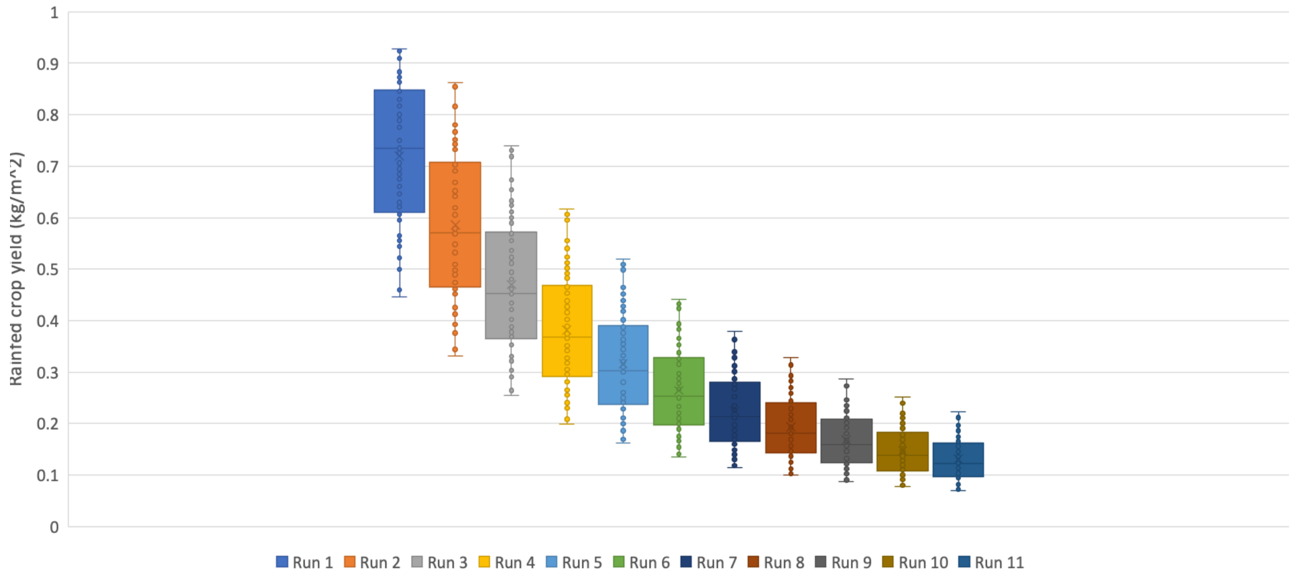


Figure 8.18. Sensitivity test runs of rainfed yield to potential evapotranspiration confirm that Ikel CliRes generates the expected behavior, with smaller PET values resulting in higher crop yields. Run distribution is incremental: PET value for Run 1 is the smallest (0.4 m/year), while the one for Run 11 is the highest (1.2 m/ year).

With regards to infiltration coefficient of precipitation on rainfed arable land, it is expected that the more water infiltrates deep into the soil and adds to the base flow, the less water there is available for the crops to use. Therefore, higher infiltration coefficients would result in smaller crop yields. Figure 8.19 demonstrates the test runs confirming that the model behaves as expected.

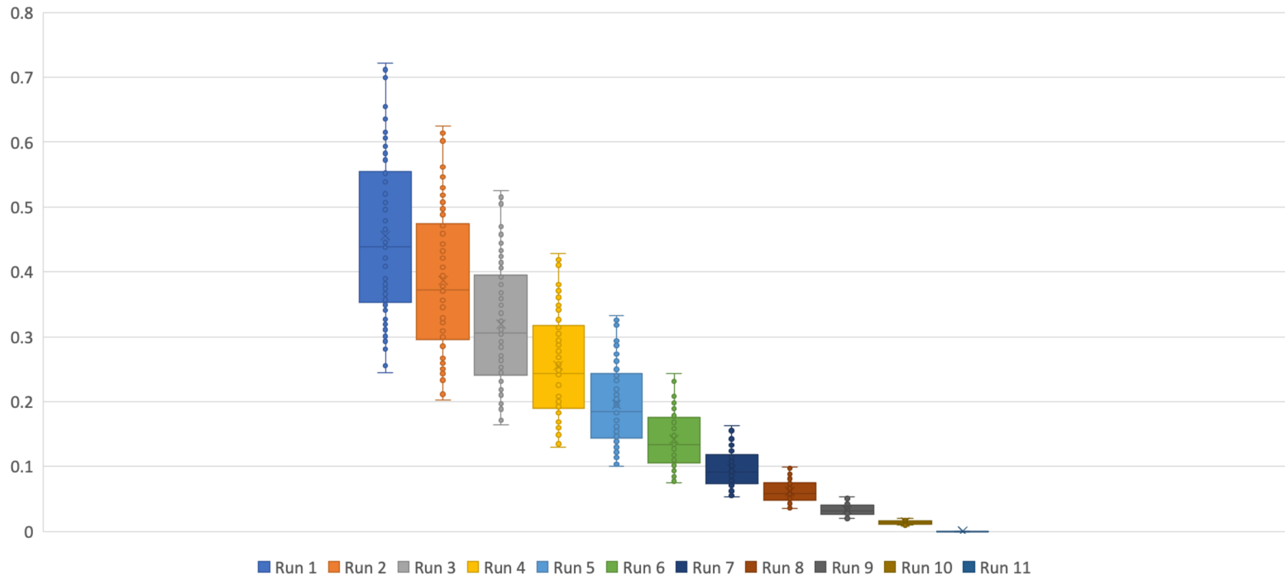


Figure 8.19. Rainfed yield is shown be sensitive to infiltration coefficient on rainfed arable land. Run distribution is incremental: coefficient value for Run 1 is the smallest (0), while the one for Run 11 is the highest (0.7).

A last demonstration is that of rainfed yield's sensitivity to average topsoil mass. This test is intended to evaluate if Ikel CliRes model captures the expected dependence of crop yield on the average soil mass. As shown in the model description chapter, average soil mass is a highly aggregated variable for all types of soils under all types of land use, and a proxy for soil quality in terms of organic matter. The expectation therefore is that crop yield should be sensitive to this variable, with higher soil mass favoring higher yields. Test runs confirm that the model captures this causal relationship appropriately.

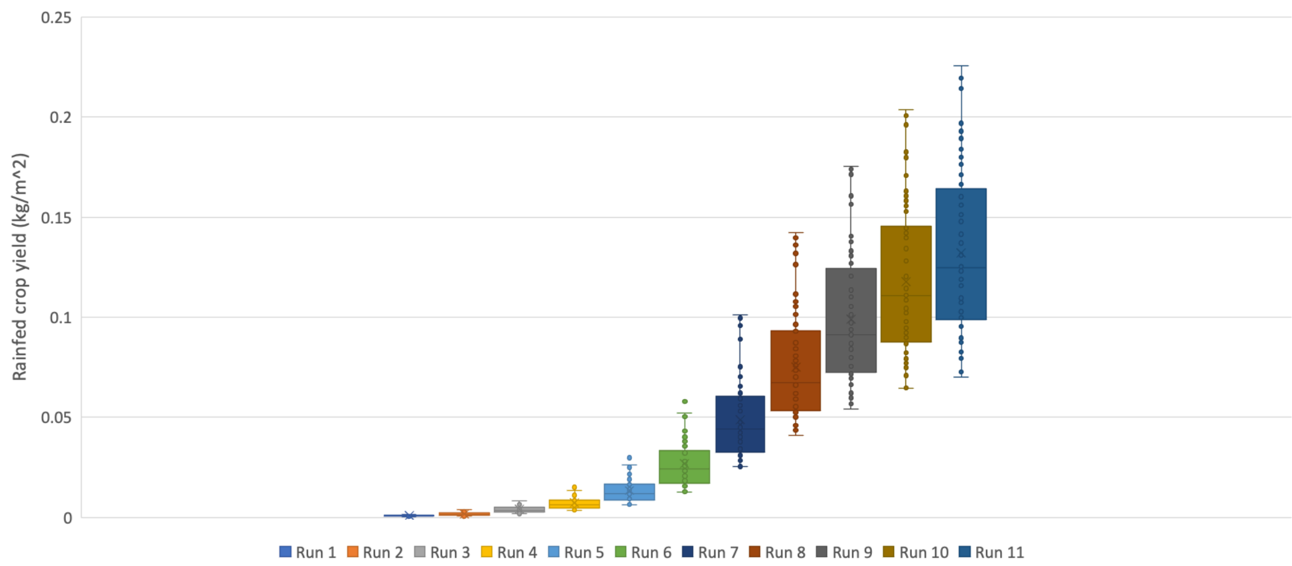


Figure 8.20. Sensitivity of rainfed yield to average topsoil mass. Run distribution is incremental: average soil mass value for Run 1 is the smallest (0.2 t/m^2), and the one for Run 11 is the highest (2.2 t/m^2).

This concludes the overview of a selection of extreme condition and parameter sensitivity tests for structural validation purposes carried out on individual model sectors. While the examples showcased above provide certain trust in the accuracy of Ikel CliRes model structure, the following tests are aimed to further strengthen its validity.

8.1.5. Phase Relationship Testing of the Model

In the case of phase relationship tests, I looked at the model-generated behavior of two or more variables and compared it with expected phase relationships. A contradiction with real-life phase relationships would indicate a flaw in the model structure. Some relevant results of these tests are presented below.

Looking at precipitation and groundwater stock, one expects that precipitation fallen on the watershed would percolate and accumulate throughout the year in the groundwater stock, contributing to the volume of groundwater available in the following year. More precipitation would thus result an increase in the stock; less precipitation would yield less water reaching groundwater stock through percolation. The results of Ikel CliRes simulation illustrated in Figure 8.21 confirm this phase relation. In this figure, the change in annual precipitation (3-year weighted average) precedes the change in the volume of groundwater stock.

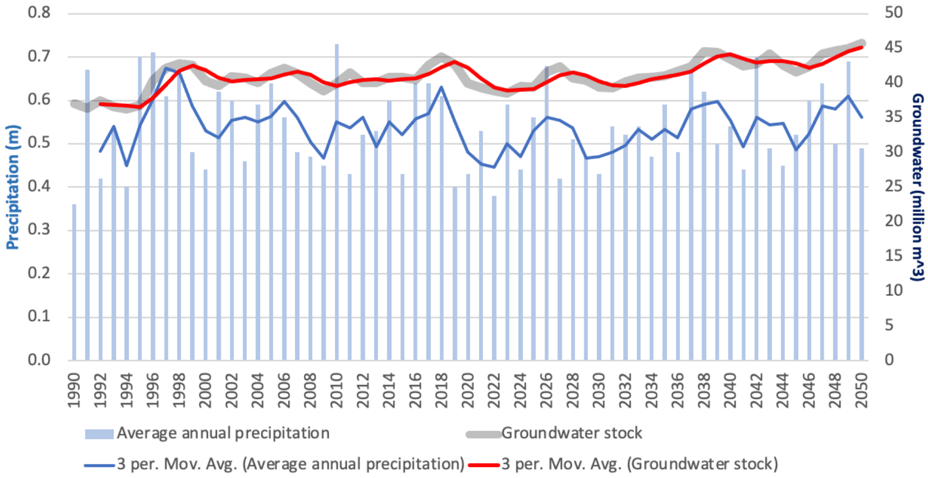


Figure 8.21. Phase relationship between annual precipitation and groundwater stock. The bars represent precipitation in individual years, while the blue line represents the 3-year weighted average. Similarly, the thick grey line illustrates the groundwater stock, while the red line – the 3-year weighted average for this variable. The graph illustrates that the change in precipitation precedes the change in groundwater stock.

Further, the phase relationship test between total crop yield on irrigated arable lands in Ikel SES and irrigation water supply has confirmed the expectation that a declining trend in total irrigated crop production would prompt a reduction in the long-term supply of water for irrigation (Figure 8.22).

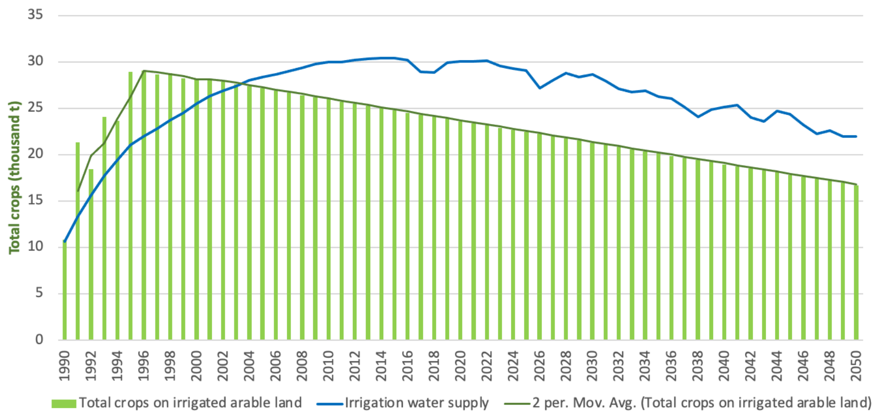


Figure 8.22. Phase relationship between total crop yield on irrigated arable lands in Ikel SES and irrigation water supply. The bars represent total crops harvested in individual years, while the green line represents the 2-year weighted average.

In Figure 8.23 below, the results of another phase relationship are showcased. In this case, the test was conducted on two variables related to irrigation: demand and infrastructure providing irrigation from surface water. In real-life, the change in demand should cause a similar change in infrastructure, albeit with some phase lag. Test runs have shown that the model captures this phase relationship.

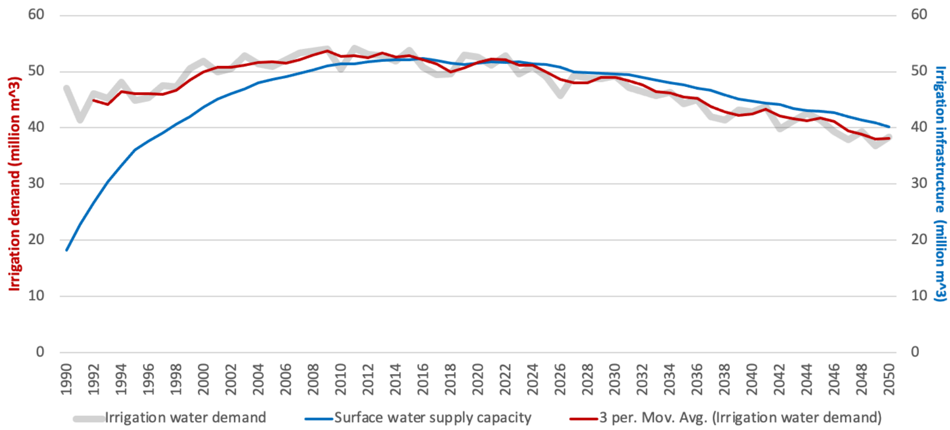


Figure 8.23. Phase relationship between irrigation water demand and irrigation infrastructure. The areas highlighted by the green circles illustrate some instances of the expected inversely proportional relation between the two variables. The grey line represents the change in actual yearly demand, while the red line represents the 3-year weighted average.

A last test showcased in this section is the one when between annual precipitation and irrigation water supply. In those years when more water is available from precipitations, the supply of irrigation water should be less, provided that sufficient infrastructure is in place to have this option. In Figure 8.24, the results of the test run are illustrated. As expected, after the irrigation water scarcity has been eliminated (year 2014 in the simulation), water supplied for irrigation is less in years with higher precipitation.

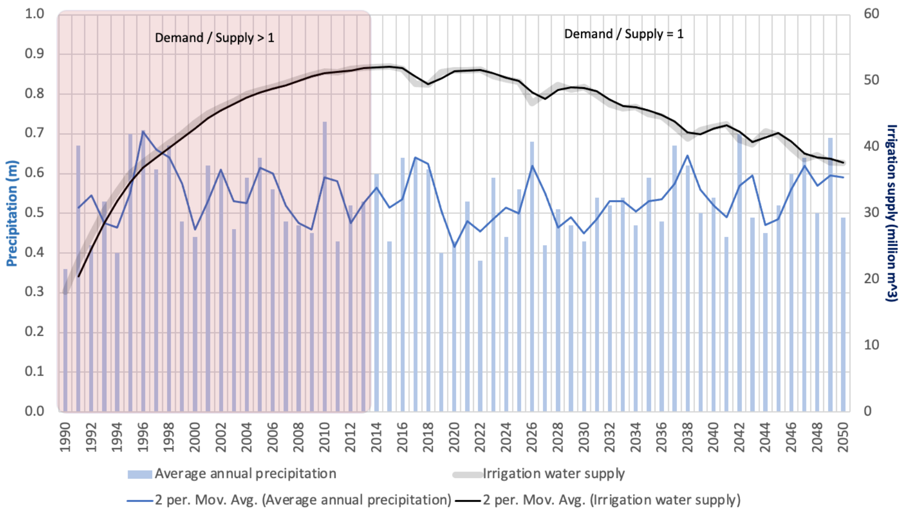


Figure 8.24. Phase relationship between annual precipitation and irrigation water supply. The graph illustrates that in those years when more water is available from precipitation, less water is supplied to irrigated crops from the irrigation system. This only happens after the irrigation system is able to supply the irrigation demand (red chart area highlights years with irrigation water scarcity). The bars represent precipitation in individual years, while the blue line represents the 2-year weighted average. Similarly, the grey line represents irrigation water supply, while the black line - the 2-year weighted average.

This concludes the overview of a selection of phase relationship tests carried out on the overall Ikel CliRes model for further validation of model structure. In the following section, a last structure-oriented behavior testing is demonstrated.

8.1.6. Structural Validation of the Model the Model Using Turing Test

In this qualitative test used for structure-oriented behavior evaluation, the knowledge of experts in various areas of this system is used in order to assess the reliability of system outputs. Experts are given a collection of simulation outputs and real behavior patterns that have been shuffled. The model passes this test if the experts are not able to easily distinguish between the real and simulated patterns of behavior.

To pass this qualitative test, experts in various areas of this system should not be able to easily distinguish between the real patterns of behavior and those generated by the model. Eight experts were given real behavior patterns and simulation outputs for the three key variables: corn yield between 1990 and 2019 (Figure 8.25.a), change in groundwater table between 1990 and 2016 (Figure

8.25.b), and change in bioproductive land stock between 1990 and 2020 (Figure 8.25.c). They were asked to distinguish between the real and simulated patterns of behavior.

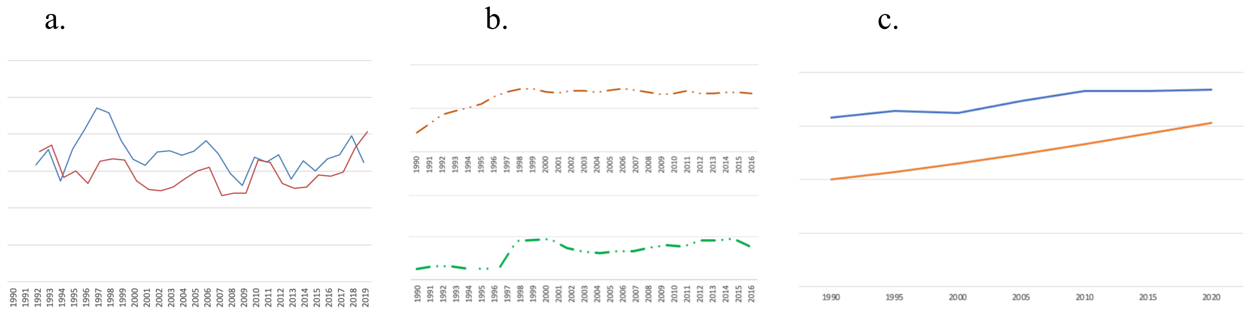


Figure 8.25. Graphs shared with experts as part of the Turing test: a. 3-year weighted average for corn yield between 1990 and 2019; b. patterns of change in groundwater table between 1990 and 2016; c. patterns of change in bioproductive land stock between 1990 and 2020.

Of the answers received from experts:

- For behavior pattern of corn yield between 1990 and 2019, 37.5 % picked the real-life pattern, 37.5 % picked the wrong pattern, while 25 % could not decide on an answer (Figure 8.26.a).
- For behavior pattern of change in groundwater table, the ratio was similar: 37.5 % picked the real-life pattern, 37.5 % picked the wrong pattern, while 25 % could not decide on an answer (Figure 8.26.b).
- For behavior pattern of change in bioproductive land, 75 % of experts gave the correct answer, while 25 % of the respondents were either wrong or could not decide on an answer (Figure 8.26.c).

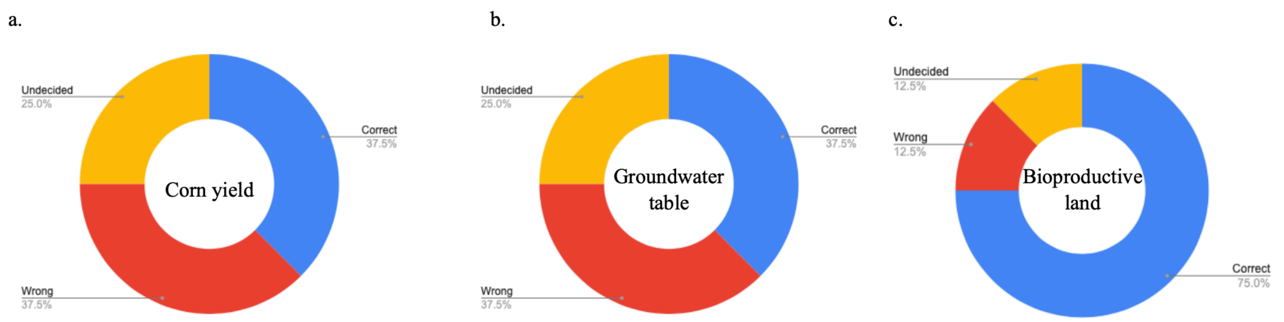


Figure 8.26. Distribution of answers received from experts for the 3 variables that were selected for the Turing test.

The fact that over 62 % of answers for corn yield and groundwater table were either wrong or indecisive shows that the model generates a realistic behavior for these variables. At the same time, the reasoning behind the percentage of correct answers for bioproductive land has been mostly related to the linearity of simulated behavior rather than to it being wrong as a trend. Therefore, we can reasonably assume that the model has passed the Turing test.

Based on the conducted structural validation tests, it is possible to conclude that structurally, Ikel CliRes does not yield unrealistic, unexplainable behaviors, and is therefore reasonably valid.

8.2. Behavior Validation of the Model

Behavior validation tests compare simulation outcomes with data from the real system under study. Based on such empirical tests with real-life data, the adequacy of the model can be inferred. In this section, we showcase how the behavior of Ikel CliRes for the period 1990 - 2019 is used for its validation by comparing it to relevant real-life data of certain parameters wherever such data are available.

In this section we demonstrate the behavior validation of the simulation model based on runs for the overall model. We include snapshots of the process for some of the behavior tests. Behavior validation of Ikel CliRes included:

- *Behavior reproduction test,* which checks if and how well the behavior generated by the model matches the historical behavior observed in the real system. With this test, modelers seek to examine the behavior pattern rather than point-by-point match. We consider that the test is passed if Ikel CliRes generates similar patterns to the ones observed from the available data.
- *Pattern anticipation test,* in which we verify that Ikel CliRes generates future behavior patterns "assumed to be qualitatively correct" (Schwaninger and Groesser, 2018).

8.2.1. Behavior Reproduction Tests

To conduct this test, we have selected quantitative and qualitative data. Where quantitative data was available, we plotted it to generate the behavior over time graph. Where only qualitative data was available, we considered the general behavior it described, and checked the model-generated behavior against the qualitatively described one.

Data on yield was available from the National Bureau of Statistics for the period 2000 to 2019. As mentioned in the previous sections, we considered corn as the reference yield in our model. In this case, we conduct a specific type of behavior reproduction test known as *symptom generation test*. According to Schwaninger and Groesser (2018), this test indicates if the model "produces the symptom of difficulty that motivated the construction of the model" and that passing this test "is a pre-requisite for considering policy changes". One way to operationalize this test is by using Theil inequality statistics, which decomposes the mean-square-error between the behavior generated by the model and historical time series data (Sterman, 1984). It helps evaluate the historical fit of the model, indicating whether or not a major part of the error is systematic. In case the error is likely to be unsystematic, the model needs not be rejected (Schwaninger and Groesser, 2018).

In this test, the deviation is decomposed into the following three sources of error:

- Bias (U_M)
- Unequal variation (U_S)
- Unequal covariation (U_C)

$U_M + U_S + U_C = 1$, U_M, U_S and U_C reflecting the fraction of the mean-square-error due to bias, unequal variance and unequal covariance, respectively (Sterman, 1984).

$U_M = 0.03$, and is calculated as follows:

$$U_M = \frac{(\bar{S}-\bar{A})^2}{\frac{1}{n}\Sigma(S_t-A_t)^2} \qquad (8.1)$$

where:

$\bar{S}$ and $\bar{A}$ = the means of S and A

S = simulated series

A = actual series

S_t = simulated value at time t

A_t = actual value at time t

n = number of observations

U_S = 0.01, and is calculated in the following way:

$$U_S = \frac{(S_S - S_A)^2}{\frac{1}{n}\sum(S_t - A_t)^2} \tag{8.2}$$

where:
S_S = standard deviation for S
S_A = standard deviation for A

U_C = 0.96, and is calculated according to the following formulation:

$$U_C = \frac{2(1-r)S_S S_A}{\frac{1}{n}\sum(S_t - A_t)^2} \tag{8.3}$$

where:
r = correlation coefficient between simulated and actual data

Figure 8.27 below replicates the simulated yield pattern and the pattern of corn yield as observed in real life. The mean-square error for corn yield is 0.01, a rather small one. The sources of error, as see above, are U_M = 0.03, U_S = 0.01, U_C = 0.96. The small values of U_M and U_S, and the concentration of the majority of the error in U_C indicate that although the model-generated behavior does not match point-by-point values of the historic yield data, it captures the average historical values and the dominant corn yield trends. In this case, a major part of the already small error is likely unsystematic (Sterman, 1984). Therefore, we can reasonably assume that the model captures the fundamental dynamics of the variable in focus (Schwaninger and Groesser, 2018), which is equally the key variable of top concern for the GMB participants.

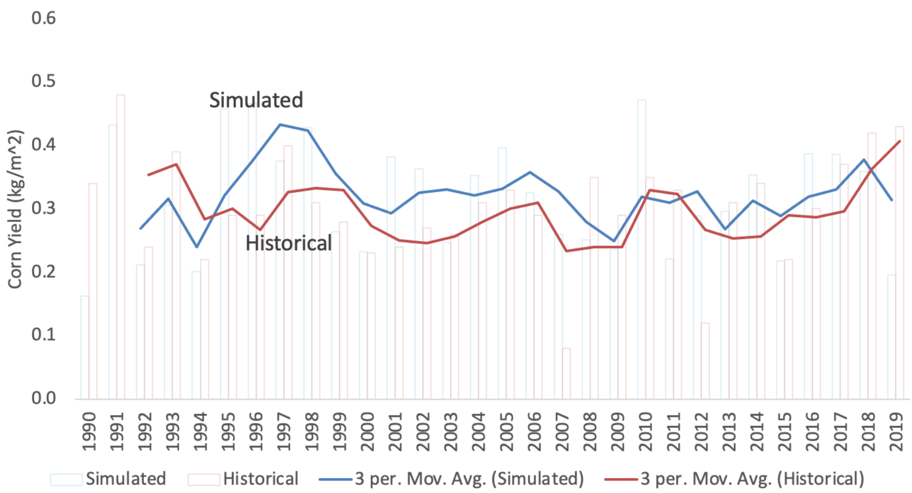


Figure 8.27. Comparison of simulated and historical data for yield. The bars represent the simulated (blue) and actual (red) yield in individual years, while the lines represent the 3-year weighted averages.

To assess the behavior reproduction for groundwater levels - another key variable of concern for the stakeholders - we make use of information provided by the National Agency for Geology and Mineral Resources. This information includes qualitative assessments and graphs illustrating the dynamics of groundwater levels for selected monitoring wells between 1996 and 2016 (Figure 8.28.a). On average, monitoring wells located in Ikel SES show a general increasing trend in the groundwater levels before the years 2000, and then oscillating around what can be visually estimated as a relative stable average. These wells register a change of roughly +10 m over 20 years (Figure 8.28.a). Monitoring wells located in the proximity of Dniester river indicate a slightly decreasing trend of the groundwater table. However, in this case, the difference is of roughly -2-5 meters over a 20-year period. Consequently, it can be assumed that on average, in Ikel watershed, groundwater stocks have been slightly increasing with less than 10 m between 1990 and 2016. The qualitative description by local stakeholders and experts of the evolution of groundwater stock levels across the country also indicates a general increasing trend, owing to a decrease in industrial activity after the collapse of Soviet Union in 1991.

Similarly, the behavior generated by Ikel CliRes model (Figure 8.28.b) indicates a generally increasing trend in the average groundwater stock. Based on this information and on the visual assessment of the actual and simulated behavior illustrated in Figure 8.28, it can be reasonably assumed that the model-generated behavior matches the general trend in the observed behavior of the Ikel watershed groundwater system.

a. b.

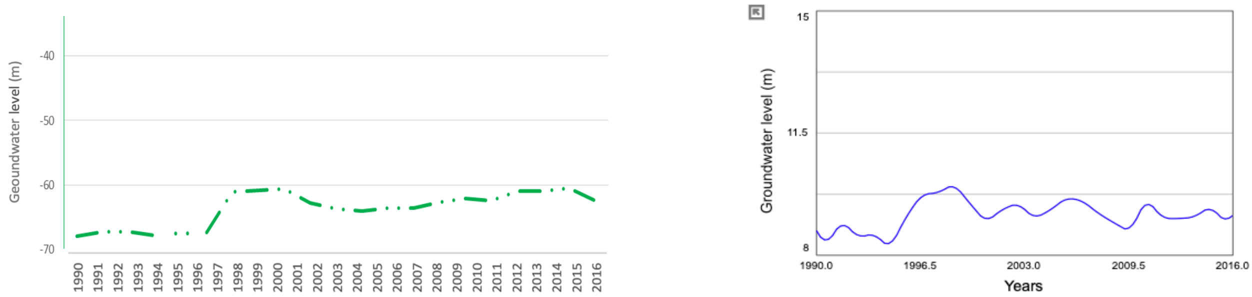


Figure 8.28. a. Historical data provided by the National Agency for Geology and Mineral Resources illustrating the behavior of the Badenian-Sarmatian aquifer under Ikel watershed as captured by the monitoring well no. 19-909 located in Cricova town, upstream of Ikel outflow to Dniester. Similar to other upstream monitoring wells, it indicates an increase in the level of groundwater table over the past 20 years; b. Simulated behavior of the groundwater stock under Ikel watershed as generated by Ikel CliRes model. In a manner similar to the real-life behavior, the groundwater stock displays a general increasing pattern before the years 2000, and then oscillating around what can be visually estimated as a relative average.

In addition to groundwater stock, we also check if the groundwater supply capacity – a stock that represents the infrastructure necessary to supply groundwater for irrigation – matches the real-life situation. In this specific case, the law has been prohibiting the use of groundwater for irrigation up until the year of 2020. Consequently, the model should not generate any increase in this stock from 1990 (when it was at 0 m^3/year) until 2020. Figure 8.29 below confirms the expected behavior.

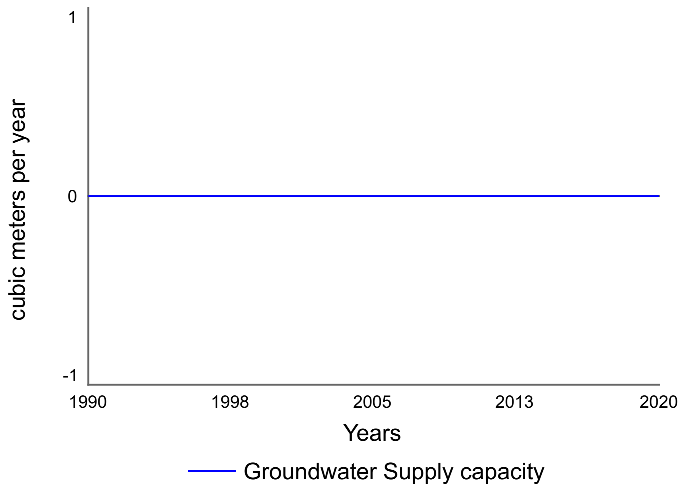


Figure. 8.29. Simulated behavior for the groundwater supply capacity stock between 1990 and 2020. The model does not increase this capacity from the initial value of 0 m^3/year.

For irrigated land area, data has been very scattered and inconsistent, as well. This is the case not only for Ikel watershed, but for the national level in general. Often times, the terms "irrigated lands" and "lands equipped for irrigation but not necessarily irrigated" are used interchangeably in many of the sources consulted. The "Apele Moldovei" agency itself has not been able to explain whether the data provided includes only irrigated lands that were, in fact, irrigated. In this circumstance, we resort again to the qualitative assessment of the situation to test the behavior pattern reproduction. All sources consulted, including GMB participants and experts, agree that while in the beginning of 1990s the area of irrigated lands has decreased due to high costs of water, the weathering of irrigation equipment has added to the decreasing trend has continued throughout the years across the country. Therefore, the consensus is that in Ikel watershed, too, there has been a continuous decreasing trend in the total area of irrigated lands between 1990 and 2020. While quantitatively we cannot confirm the accuracy of the generated values, the pattern of the model-generated behavior for this variable (Figure 8.30) is in line with the decreasing trend.

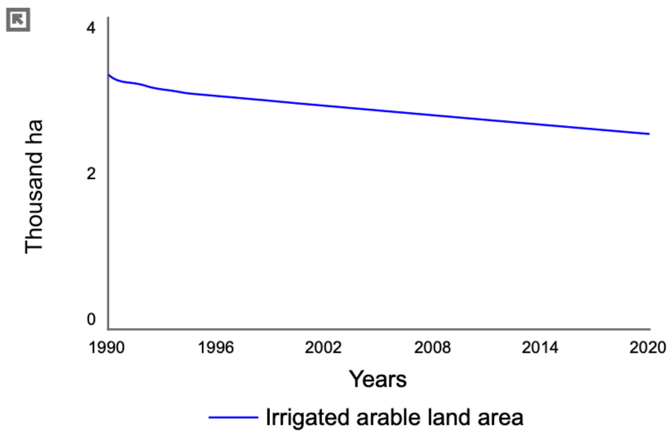


Figure 8.30. Model-generated behavior for irrigated land stock in Ikel watershed between 1990 and 2020. The generated pattern matches the trend observed in Ikel watershed by the interviewed GMB participants and experts.

Abandoned land is an aggregate stock of eroded land and arable land that has been abandoned for various reasons, including low yield and lack of workforce. We came across no official yearly data on the area of eroded land in Ikel watershed. Data at national level is available from reports and research articles, but mostly in descriptive terms or as rates of change per year rather than in year-by-year data of land stock values. Therefore, for this variable, too, we rely on the qualitative assessment of the situation and check that the model-generated pattern reflects the pattern described in the consulted sources.

Thus, according to the Environmental Agency (Ecopresa, 2020), the area of eroded land nationally has increased in the past 40 years by 283.4 thousand hectares, with an average of 7086 ha/year. It has reached 877,644 in 2019. Effectively, the eroded land stock increased by ca. 37 % in the past 40 years, or approximately 9 % per decade. In the simulated behavior of abandoned land variable in Ikel watershed (Figure 8.34), this stock increases by ca. 10 % per decade (Table 8.1).

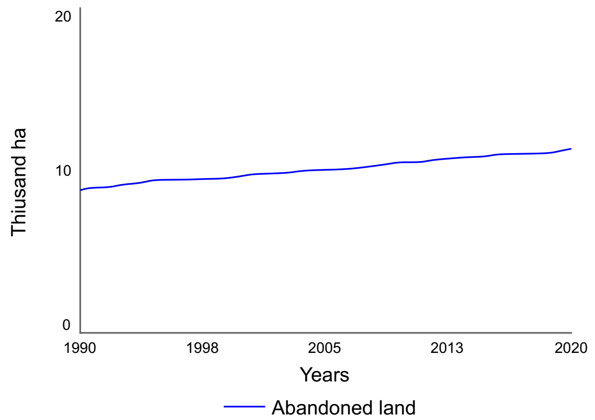


Figure 8.31. Behavior generated by Ikel CliRes for abandoned land stock in Ikel watershed between 1990 and 2020.

Table 8.1. Rates of change in eroded land nationally (historical data) and abandoned land stock in Ikel SES (simulated data).

Year	**Historical R. Moldova (thousand ha)**	**Simulated Ikel SES (thousand ha)**
1990	699 (calculated)	8.8
2000	-	9.8
2010	-	10.7
2020	878	11.6
Change between years 1990 – 2020 (%)	26 %	32 %

Given the fact that the model generates a behavior pattern for the abandoned land stock that reproduces the increasing trend in the historical data for eroded land, and the fact that rates of change for the period 1990 - 2020 are similar, we can reasonably assume that Ikel CliRes generates the appropriate pattern of behavior for this variable.

Bioproductive land stock is another variable for which behavior reproduction test was conducted. In this case, historical data for forested land was available at national level only. This limited our possibility to conduct quantitative validation. Nevertheless, data presented in Table 7.21 has allowed us to check the extent to which Ikel CliRes can generate the appropriate behavior pattern. To do so, we have considered the area of forested land and bioproductive land as percentage of total country area and Ikel SES area respectively. The outcomes are plotted on the same graph demonstrated in Figure 8.32 below. The results, showing that the general pattern of behavior is similar in both cases, increase our confidence in the usefulness of the model.

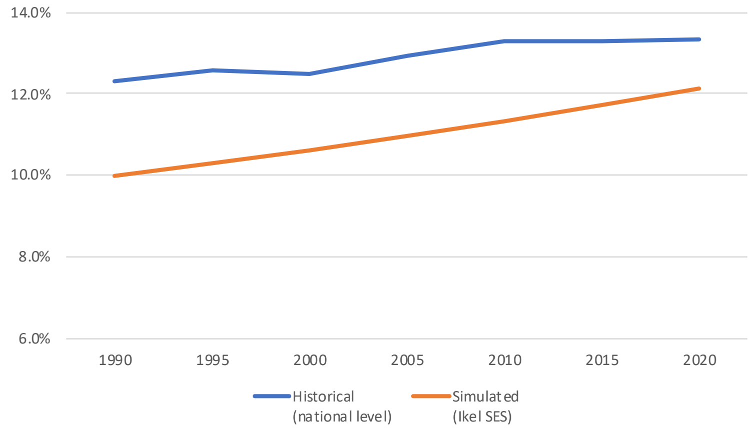


Figure 8.32. Simulated behavior for bioproductive land stock in Ikel SES between 1990 and 2018 (in % of Ikel SES area) as compared to the historical data for forested land at national level for the same period (in % of country area).

Another important stock in our model is the average soil mass, measured in tons of soil per square meter. Given the large area ok Ikel SES and the heterogeneity of its relief, landscape, slopes, etc., this stock is rather a theoretical, highly-averaged one; although it has a real life meaning, it is not at all possible and even practical to measure the real-life value of this variable on such a large area. Consequently, we validate the behavior of this variable against a measurable proxy: soil erosion.

As shown in Section 7.2.3 *Erosion*, 30 to 50 m^3 of soil are lost annually from each hectare annually, which translates to 0.0039 – 0.0065 metric tons of soil loss from each square meter of land. In line with these estimates, average soil mass decreases with 0.039 to 0.065 tons per decade, whereas from 1990 to 2020, the loss would amount to 0.117 – 0.195 tons/m^2. The behavior of average soil mass stock generated by Ikel CliRes (Figure 8.33) yields a loss of 0.15 tons/m^2 between 1990 and 2020, or an annual loss of ca. 0.005 tons/m^2. This further increases our confidence in the usefulness of the model.

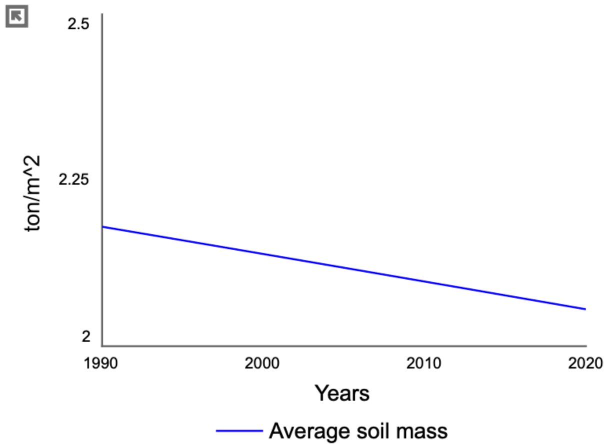


Figure 8.33. Simulated behavior for the average soil mass (tons/m^2) in Ikel watershed between years 1990 and 2020. This is an aggregated stock variable, which decreases with the ongoing soil erosion calculated by the model to be at ±0.005 t/m^2/year.

Considering the results presented above for the seven selected variables, including the three key variables (yield, level of groundwater table and bioproductive land), we can reasonably conclude that Ikel CliRes model has passed the behavior reproduction test.

8.2.2. Pattern Anticipation Tests

This test is similar to the previous one in that it compares the expected and simulated behavior. Unlike the behavior reproduction, this test entails a qualitative assessment of how correct the model-generated behavior is compared to the one expected to happen in the future. The model is considered to have passed this test if it correctly anticipates the possible future behavior when a parameter or a policy is changed.

Below, we demonstrate the model-generated behavior for the following interventions:

- Change in crop variety illustrated by a different value of PET.
- Change in policy regarding groundwater exploitation for irrigation, represented by a change in exploitable groundwater fraction.
- Change in soil conservation practices, illustrated by different values of P factor.
- Change in technologies used in agriculture, illustrated by a reduction in workforce requirement.

In case of a shift in crop variety for a less water demanding option, we expect that the crop yield would be higher. Figure 8.34 shows the case of change in yield from 2021 to 2050 when PET of the given crop is reduced by 50 %. As anticipated, all things being equal, when the PET decreases, the yield increases as compared to the base run.

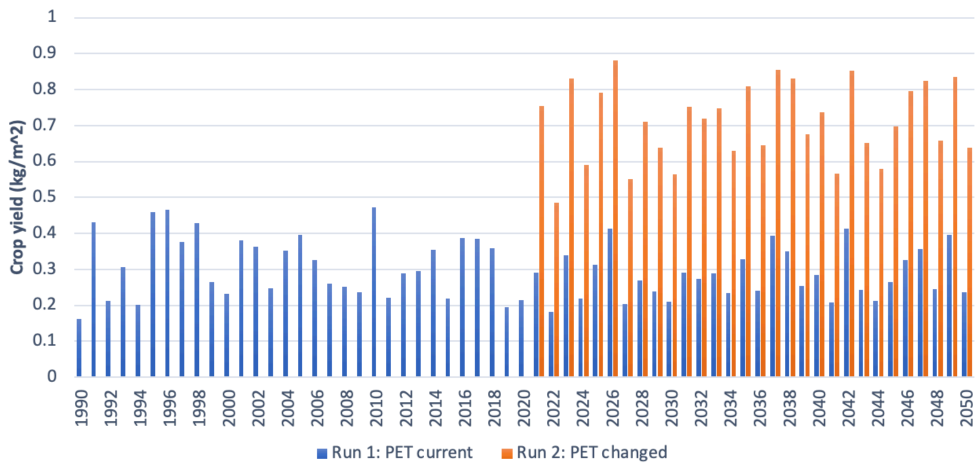


Figure 8.34. Crop yield from 1990 to 2050, including the change from 2021 to 2050 compared to the base run. As expected, if the selected crop variety from 2021 onwards would have a PET value 50 % smaller than the PET value for the base run crop, the yield would increase proportionally, as illustrated by the orange columns.

On the other hand, a policy change towards allowing the use of groundwater for irrigation purposes would be expected to lead to an increase in groundwater supply capacity, but also to a slight decrease in the level of groundwater table. Figure 8.35 below shows that the model behaves as expected. Namely, in Figure 8.35.a the groundwater supply capacity is seen to be increasing, while in Figure 8.35.b one can notice the corresponding decrease in the groundwater level.

a. b.

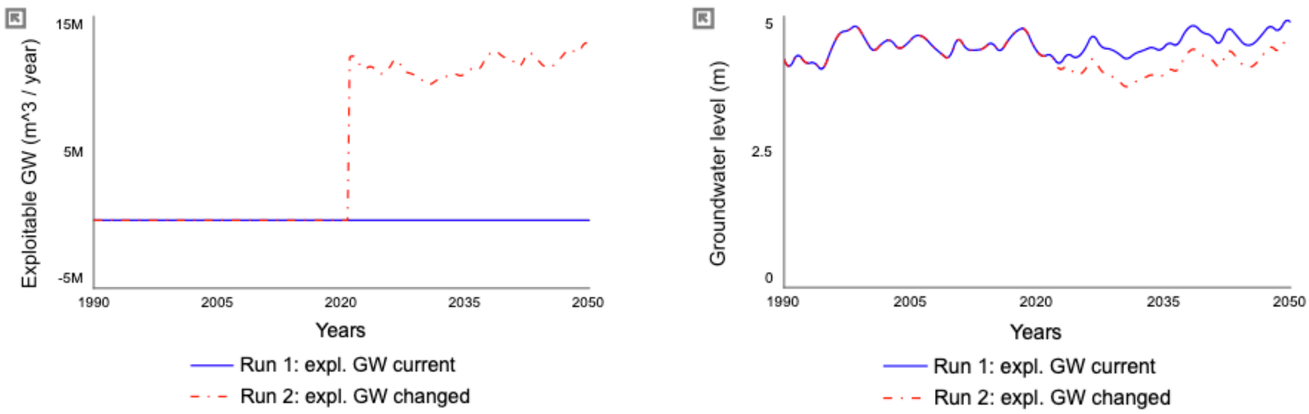


Figure 8.35. a. Groundwater supply capacity for irrigation purposes from 1990 to 2050, including the change from 2021 to 2050 compared to the base run. As anticipated, if exploitable groundwater fraction is higher than the current value of 0, the investments in this infrastructure will prompt an increase in groundwater supply capacity, as illustrated by the green dashed line; b. Change in the level of groundwater table between 2021 to 2050 (orange line) as compared to the base run (purple dashed line) in case of allowing the use of 40 % of groundwater for irrigation purposes starting from 2021.

In the case of soil erosion, more efforts towards soil conservation practices should be expected to reduce erosion and flatten the slope of decrease in average soil mass over the years. That should result in less crop loss caused by soil erosion over the years. This expectation is tested by reducing the P factor from its current value of 0.42 to the new value of 0.21 from 2020 onwards, which stands for improving soil conservation practices two-fold. The results of this test run confirm our expectations. Figure 8.36 illustrates the changed behavior of erosion and average soil mass when the P factor is halved from 2020 onwards. As expected, better soil conservation policies and / or practices lead to less soil erosion (Figure 8.36.a). In turn, this is reflected in the conservation of average soil mass (Figure 8.36.b) and, subsequently, in better yield figures (Figure 8.37).

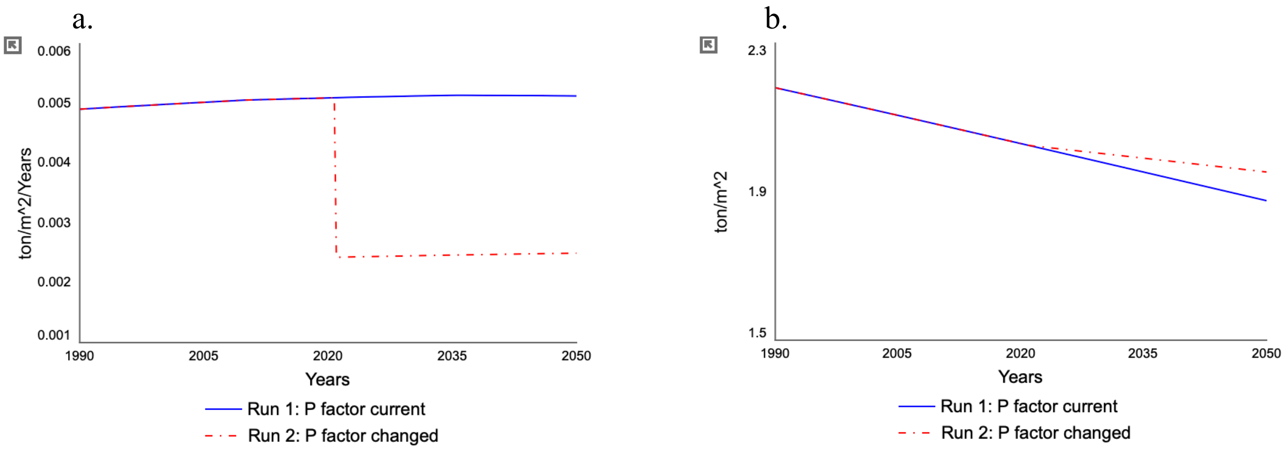


Figure 8.36. Erosion rate (a) and average soil mass (b) from 1990 to 2050, including the change between 2021 and 2050 in case of 50 % improvement in soil conservation practices from 2020 onwards. As anticipated, the erosion rate decreases noticeably and the slope of decrease in average soil mass becomes more flattened over the years.

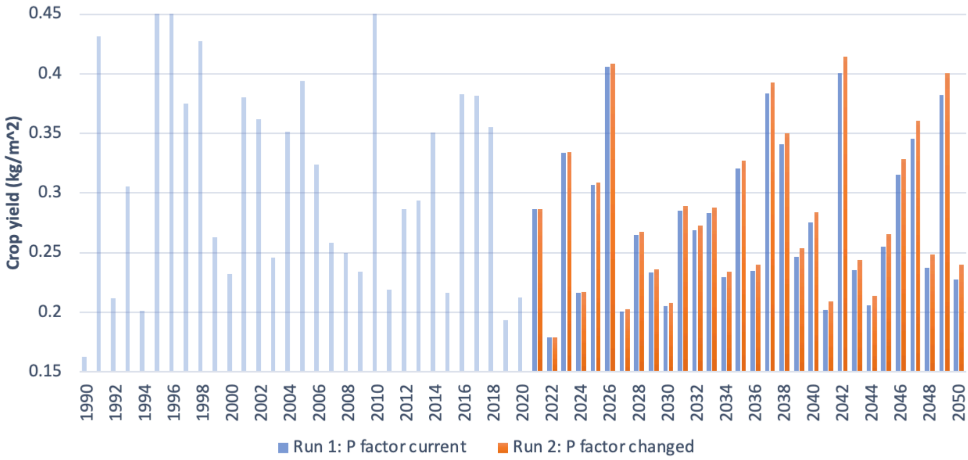


Figure 8.37. Crop yield from 1990 to 2050, including the change between 2021 to 2050 in case of 50 % improvement in soil conservation practices from 2020 onwards. As expected, all things being equal, better soil conservation practices result in yield gains over the years.

I also test for sudden deployment of technologies that allow for less workforce-intensive agricultural practices from 2021 onwards. Theoretically, this would mean that less workforce will be needed to cultivate both irrigated and rainfed lands. With no other factors changing, the expectation in this case is that there would be a sudden increase in the land stock used for irrigated crops (Figure 8.38) and in the demand for irrigation water (Figure 8.39). With less arable lands being abandoned, this would also mean that the area of bioproductive land would increase at a slower rate (Figure 8.40). As illustrated by the corresponding graphs, the model generates the expected change in the behavior patterns of the three variables mentioned above.

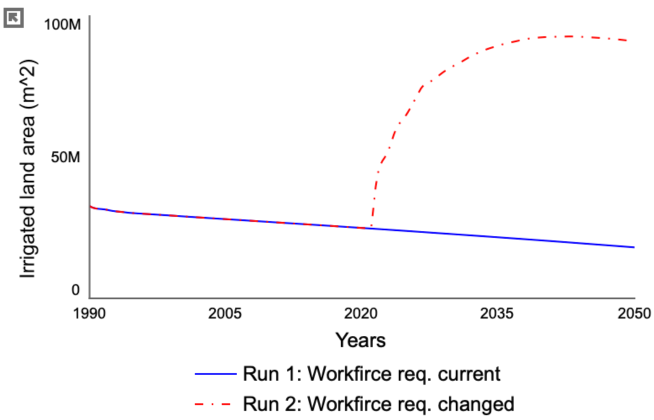


Figure 8.38. Irrigated land area from 1990 to 2050, including the change from 2021 to 2050 in case of sudden deployment of agricultural technologies and practices that are 10-times less workforce intensive then those used prior to year 2020.

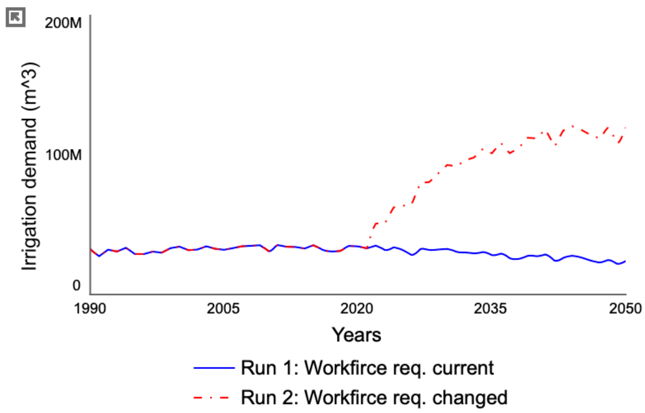


Figure 8.39. Irrigation water demand from 1990 to 2050, including the change from 2021 to 2050 (orange line) in case of sudden deployment of less workforce-intensive agricultural technologies and practices after the year 2020.

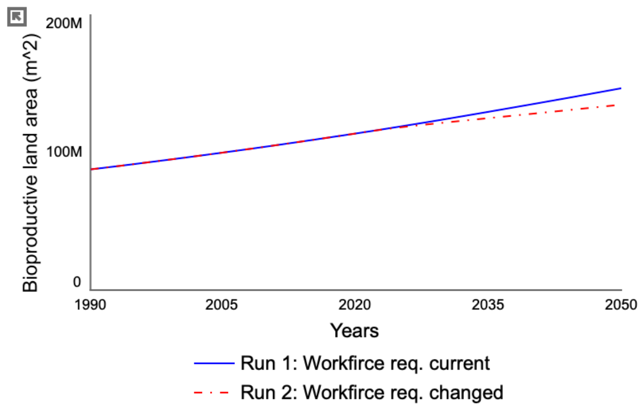


Figure 8.40. Bioproductive land area from 1990 to 2050, including the change from 2021 to 2050 (orange line) in case of sudden deployment of less workforce-intensive agricultural technologies and practices after the year 2020.

The results presented above illustrate the impact of change in four selected parameters: potential evapotranspiration of a crop variety, exploitable groundwater fraction for irrigation purposes, soil conservation practice and workforce requirement. The model generated the anticipated change in the selected range of impacted variables. Based on this, we can deduct that Ikel CliRes is able to anticipate how the behavior of the real system would change in case of changes in certain governing policies.

As stated, multiple times in SD literature, validation is a process of rigorous application of a set of structural and behavior tests by which the confidence in the model is enhanced gradually, i.e., the more tests are applied and passed, the more confident we can be in the model. As Schwaninger and Groesser (2018) put it: “Validity […] is always a matter of degree, never an absolute property.” The number and diversity of tests that could be applied is high and constantly enriched by SD practitioners, and it is very rare – if at all – that all existing tests are applied to a model. Instead, cessation of formal validity testing is a matter of modeler's heuristic for this decision (Groesser and Schwaninger, 2012).

With the validation tests demonstrated above, we consider having reached the validation cessation threshold (VCT) for the Ikel CliRes. Medium model size and relatively low expectations of the client and target group resulted in medium costs for validating the model. However, problematic data availability, coupled with extensive data gathering significantly increased the time and resource cost of this model. This resulted in a relatively low level of VCT (Groesser and Schwaninger, 2012), which led to fewer tests being needed and applied as compared to more complex, more data-intensive and more budget-rich projects.

These things being considered, we conclude that we have obtained sufficient confidence in the validity of Ikel CliRes for its intended use.

9. POLICY ANALYSIS

This chapter focuses on the analysis of the model with respect to multiple policies: those proposed by stakeholders in Ikel SES as means of adapting to climate change impacts and alternative policies that could lead to the desired trajectory expressed by members of the GMB process. To that end, the analysis focuses on sensitivity of key variables to change in selected parameters, inputs, initial conditions and other structural changes representing alternative policies. Among these are some policies proposed by the GMB participants after the last GMB workshop. The analysis is accompanied by demonstration of model-generated behavior and followed by a discussion on the effectiveness of policies proposed.

The policy analysis results are structured based on the two Representative Concentration Pathways (RCP) scenarios included in the Vulnerability Assessment and Climate Change Impacts in the Republic of Moldova (Țăranu et al., 2018): RCP 2.6 and RCP 8.5. According to RCP 8.5 projections, the UNFCCC target of keeping the global average warming under 2.0°C above pre-industrial levels will be exceeded before 2050. RCP 2.6, on the other hand, implies strong reductions in greenhouse gas emissions.

In the following sections, I first look into the trend in the behavior of the three key variables – crop yield, groundwater table and bioproductive land – under the two RCP scenarios. I then analyze the impact of policies proposed by GMB participants on the key variables. Going forward, I check the sensitivity of key variables to data-scarce parameters, as well as to other model parameters. Lastly, I conduct alternative scenario and policy analysis to identify those helpful for adaptation and resilience building objectives. In this research, I consider that an adaptation policy seeks helps achieve an objective (as stated by GMB participants) under projected temperature and precipitation trends of RCP climate scenarios. A resilience-building policy involves doing the same under specific impact circumstances accompanying future climate trends: more frequent storms, higher evaporation rates or both

9.1. Reference Model Behavior

In this section, I showcase the reference behavior of Ikel CliRes model. In particular, the focus is on the behavior of key variables under two RCP scenarios. These reference behaviors are dependent upon model assumptions, which were presented in detail in Chapter 7. “Formal Model Description”.

For R. Moldova, there are three RCPs highlighted in the Vulnerability Assessment and Climate Change Impacts in the Republic of Moldova (Ţăranu et al., 2018) as being the most representative: RCP 2.6, RCP 4.5 and RCP 8.5. All of them project similar temperature in the near-term decades: +0.9 - 1.1°C (Tables 9.1 and 9.2), while distinguishable patterns of the three RCPs are observable only after 2050. Because this model focuses on the period up to 2050, only the projections corresponding to the analyzed period are considered in this research.

Table 9.1. Projected CMIP5 21 GCMs ensemble annual and seasonal mean air temperature changes (ΔT, °C) presented for two future 20-year time periods (2016–2035 and 2046–2065) for Representative Concentration Pathways RCP 8.5, RCP 4.5, and RCP 2.6, relative to the 1986–2005 climatological baseline period (Ţăranu et al., 2018).

Season	**Average 1986-2005**	**Scenario**	**Projected changes by the 2035 (ΔT, °C)**		**Projected changes by the 2065 (ΔT, °C)**	
			Min	**Max**	**Min**	**Max**
Annual	10.1°C	RCP 8.5	0.5	2.1	1.4	3.6
		RCP 4.5	0.5	2.1	0.9	3.0
		RCP 2.6	-0.7	2.2	0.2	2.8
Dec-Jan-Feb	-1.1°C	RCP 8.5	-0.4	1.9	0.8	4.3
		RCP 4.5	-0.5	2.0	0.4	3.0
		RCP 2.6	-1.1	2.1	-0.3	2.8
Jun-Jul-Aug	21.3°C	RCP 8.5	0.4	2.5	1.4	4.7
		RCP 4.5	0.6	2.0	0.8	4.1
		RCP 2.6	-1.2	2.5	0.1	2.6

Table 9.2. Projected CMIP5 21 GCMs ensemble annual and seasonal mean precipitation changes (%) presented for two future 20-year time periods (2016–2035 and 2046–2065) for Representative Concentration Pathways RCP8.5, RCP4.5, and RCP2.6, relative to the 1986–2005 climatological baseline period (Ţăranu et al., 2018).

Season	**Average 1986-2005**	**Scenario**	**Projected changes by the 2035 (%)**		**Projected changes by the 2065 (%)**	
			Min	**Max**	**Min**	**Max**
Annual	550.4 mm	RCP 8.5	-8.2	14	-16.5	18.2
		RCP 4.5	-9	19.2	-8.1	15.2
		RCP 2.6	-8.8	24.1	-5.8	15.1

The expectation is that by mid-century, the average annual temperatures would be the highest under RCP 8.5 and the lowest under RCP 2.6 scenario. On the other hand, projections for precipitation are less certain. The highest variability is for RCP 8.5, the lowest – for RCP 2.6, with all scenarios suggesting more a slight increase in average annual precipitation for the upcoming decades.

Ikel CliRes model includes the climate parameters shown below. Except for the R factor, all the above parameters are considered jointly for each of the three RCP scenarios.

- Annual precipitation
- Average annual temperature
- Mean temperature of the hottest months
- Mean temperature of the coldest months
- Rainfall erosivity factor (R factor in USLE)

To conduct model analysis, projected climate data for these RCP scenarios has been downloaded from MarkSim® DSSAT website (ILRI, 2021) – a daily weather generator accompanied by data for generating future characteristic weather series. MarkSim® generated downscaled daily weather data. The daily data was aggregated to produce annual series from 2021 to 2050. Because MarkSim® has been shown to either underestimate or overestimate the annual rainfall variance by a small amount (Jones and Thornton, 2013), annual data was treated for bias correction using Delta change method. Unlike historical station data, projected annual data showed a smooth trend rather than fluctuations. For this reason, I calculated the trends in the two projected annual data sets. Specifically, the TREND function in Excel was used to derive the line of best fit (using the method of least squares) for the historical data and for future annual temperature and precipitation data.

Further, due to poor data quality for RCP 4.5 scenario and considering the higher relevance of the RCP 2.6 and RCP 8.5 scenarios for the purpose of this research, only data for the latter two scenarios was kept within the scope of policy and resilience analysis using Ikel CliRes model. Tables with annual climate data and the derived line of best fit data used in Ikel CliRes are provided in Appendix B.

Figures 9.1 and 9.2 below give an overview of the difference between trends in climate data of the two RCP scenarios. Figure 9.1 includes the trends in values for annual precipitation. In this model, under RCP 2.6 scenario average annual precipitation is anticipated to increase slightly over the next decades, while RCP 8.5 scenario is anticipated to bring a certain decrease in annual precipitation. This is consistent with the findings described above that projections for precipitation are less certain, that it is likely to see a certain increase in average annual precipitation for the upcoming decades, and that in the case of RCP 8.5 the decline in average annual precipitation would be the most significant (Table 9.2).

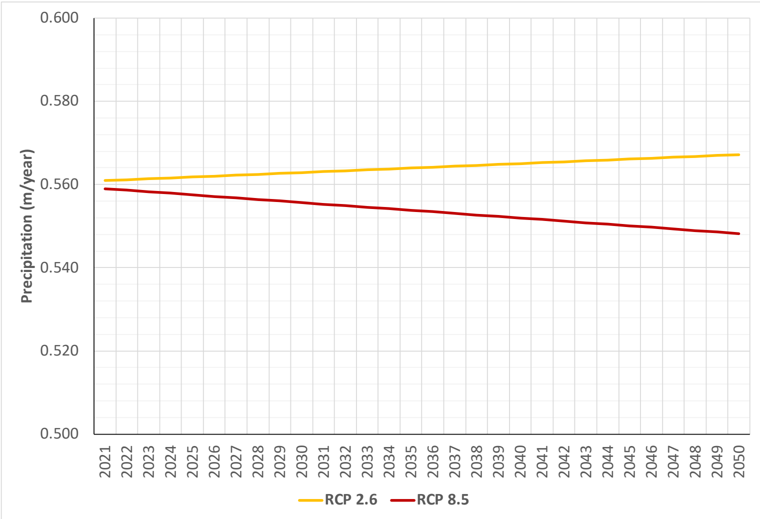


Figure 9.1. Comparative representation of trends in annual precipitation between 2021 and 2050 for RCP 2.6 and RCP 8.5 scenarios.

Figure 9.2 below illustrates the trends in average annual temperature according to the two RCP scenarios. Consistent with the findings in the Vulnerability Assessment and Climate Change Impacts in the Republic of Moldova, both scenarios project similar temperature in the coming decades (Table 9.1). Of the two scenarios, the highest average annual temperatures would be under RCP 8.5.

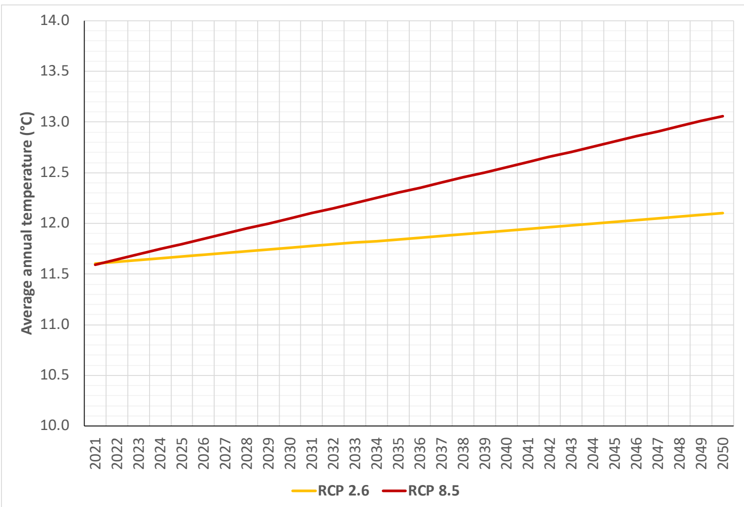


Figure 9.2. Trends in average annual temperature between 2021 and 2050 for RCP 2.6 and RCP 8.5.

Going forward, key variables are analyzed for the upcoming 30-year period under RCP 2.6 and RCP 8.5 scenarios.

Figure 9.3 illustrates the trend in crop yields expected under the two RCP climate scenarios. Of these, the RCP 8.5 scenario would have the most negative impact on the representative crop yield, which can be explained at least partly by the strong dependance of yields on the availability of water. On the other hand, there is a visible decreasing trend in yields under both scenarios even though RCP 2.6 projects a slight in increase in annual precipitation. The other two significant factors in this case are soil erosion and the availability of workforce, as shown in model validation chapter above.

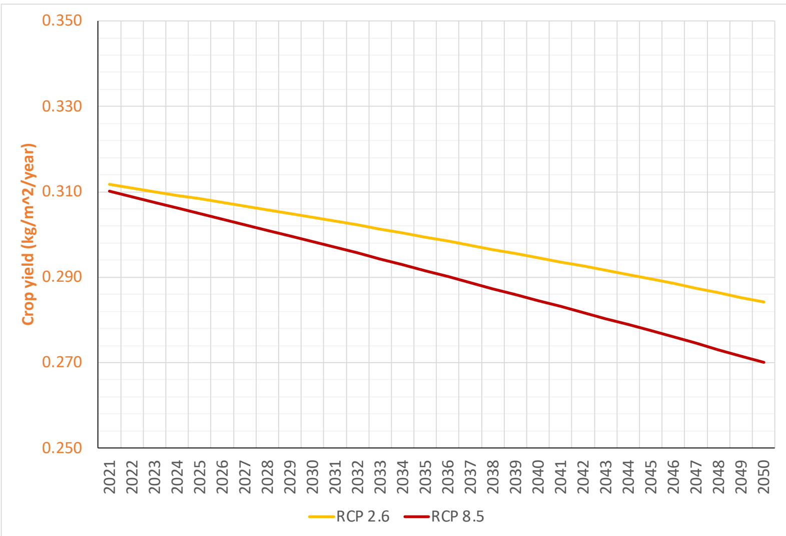


Figure 9.3. Trends in crop yield behavior under RCP 2.6 and RCP 8.5 scenarios between 2021 and 2050.

Figure 9.4 provides an overview of the trend in groundwater table behavior under these scenarios. In this case, a slight increase is projected under both scenarios, with Ikel CliRes anticipating RCP 2.6 to favor somewhat higher levels of groundwater than RCP 8.5 due to higher levels of precipitation that percolates underground to replenish the stock. The anticipated increase is explained mostly by the underground communication with other basins and the inflowing underground water from those basins. The projection does not account for possible future decreases in the underground inflowing rates that might occur following decreased precipitations in upstream regions.

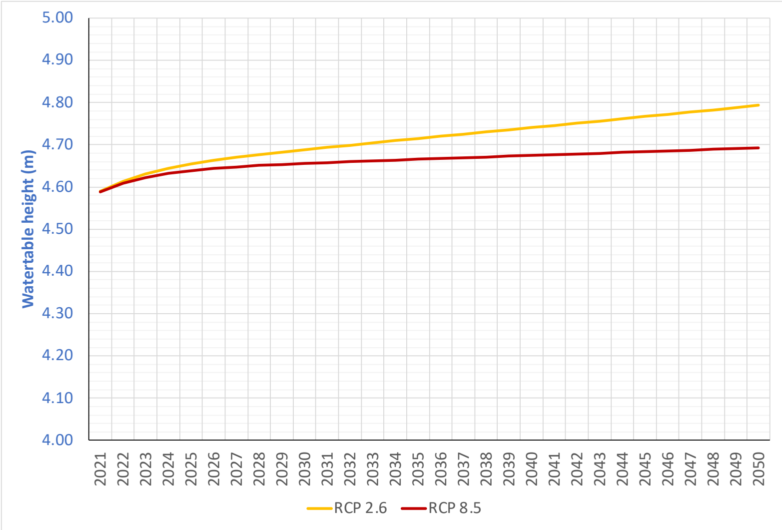


Figure 9.4. Change in groundwater table between 2021 and 2050 under RCP 2.6 and RCP 8.5 climate scenarios.

Figure 9.5, on the other hand, shows how the increasing trend in bioproductive land stock is not envisaged to differ noticeably under the climatic conditions projected by the two RCP scenarios in question. The increase happens on account of arable land being abandoned and being subject to both natural and human-led reforestation.

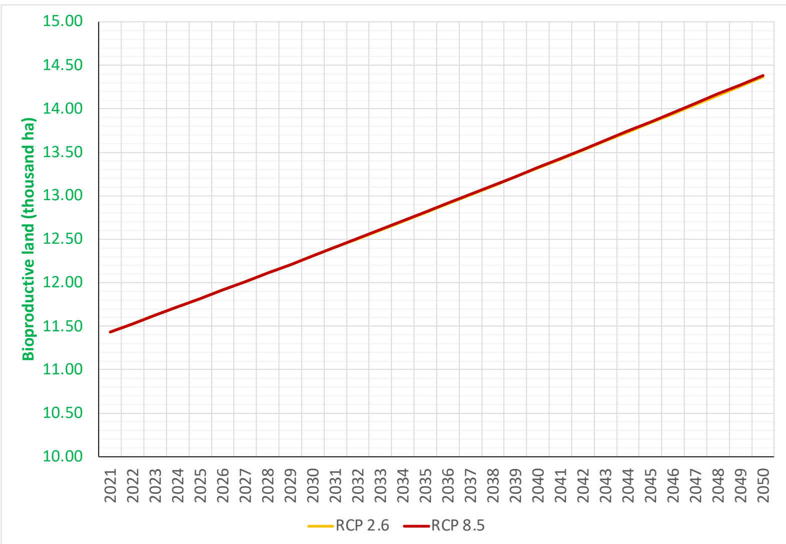


Figure 9.5. Bioproductive land area under RCP 2.6 and RCP 8.5 scenarios between 2021-2050.

Analyzing the behavior of the three key variables under the three RCP scenarios as base runs, a first conclusion is that while crop yields and levels groundwater table are already expected to vary depending on the climate conditions, the dynamic of bioproductive land is expected to be roughly the same under the different climate scenarios.

9.2. Analysis of Policies Proposed by GMB participants

This section focuses specifically on the impact of certain policies on the key variables. These policies were proposed by GMB participants earlier in the participatory process. Namely, as shown in Section 4.2 and Table 4.1, during the third GMB workshop, we analyzed and discussed the conceptual model that preceded Ikel CliRes model. Based on those discussions, a list of policy proposals was elicited from GMB workshop participants (Table 6.1). The policy options put forward in that workshop were suggested to increase the resilience of Ikel SES to climate change impacts.

In this section, the performance of these policies is analyzed against the two RCP scenarios, looking at how they contribute to the desired behavior of crop yield, groundwater table and bioproductive land area. To do so, the policies are first operationalized in a way that allows for their simulation in Ikel CliRes: each policy is defined as a specific change in one or more model parameters (Table 9.3).

Table 9.3. Operationalization of policies proposed by GMB participants in preparation of their simulation.

#	Proposed policy or measure	How it is operationalized for analysis in Ikel CliRes	Explanation
1	Increasing of forested area and involving citizens in reforestation.	*Forestation fraction*: • Base run: 0.0001/year (current value) • Value for testing policy performance: 0.01/year (100 x current value)	These four proposed policies refer to what is defined as the increased (re)forestation effort undertaken by various stakeholders in different locations within Ikel SES. To test the increased reforestation efforts, a most optimistic scenario is assumed: (re)forestation efforts are increased 100-fold.
2	Increasing/rehabilitation of forest strips (for the protection of arable land) with walnut/fruit/melliferous tree species.		
3	Increasing the length and surface of forested area in sanitary protection areas of rivers and lakes.		
4	Rehabilitation of natural wetlands.		
5	Increasing the access to water supply systems	*Fraction of GW allowed for exploitation:* • Base run: 0 (current value) • Value for testing policy performance: 0.1 **and**	This policy refers to increasing farmers' access to water for irrigation. In the base run, water for irrigation is only supplied from exploitable runoff, while the use of groundwater is not allowed. To test this policy, three parameters are changed simultaneously: up to 10 % of groundwater stock is allowed to be used

		Time to adjust Surface Water Supply capacity **and** *Time to adjust Groundwater Supply capacity*: • Base run: 10 years (current value) • Value for testing policy performance: 5 years (0.5 x current value)	for irrigation purposes, and the speed of investment is increased to twice of the current value for irrigation infrastructure from both groundwater and surface water resources.
6	Reducing land abandonment of productive arable land and support its reintroduction into the production circuit	*Abandonment fraction*: • Base run: 0.001/year (current value) • Value for testing policy performance: 0.0005/year (0.5 x current value) **and** *Reclaiming fraction*: • Base run: 0.05/year (current value) • Value for testing policy performance: 0.25/year (5 x current value)	This policy seeks to maintain a larger stock of arable land by preventing or reducing its conversion to abandoned land. To test this policy, abandonment is reduced to the half of its current value, while at the same time increasing the reclaiming fraction (back from abandoned stock) five-fold.
7	Improving environmental law enforcement to reduce illegal logging and breaching of existing environmental legislation	*Clearing fraction*: • Base run: 0.00001/year (current value) • Value for testing policy performance: 0.000005/year (0.5 x current value)	To test this policy, the clearing fraction is reduced to half of the current value. This stands for law enforcement having been twice as effective as it is in the base run scenario.

9.2.1. Increasing Reforestation Efforts

The increased reforestation efforts policy is the sum of four proposals suggested by GMB participants during the third GMB workshop. All four proposals imply an increase in bioproductive land, albeit focusing of different facets of this effort. One proposal refers to the location in Ikel SES where these efforts should be concentrated; another – on actors to involve in this undertaking; a third one – on the types of vegetation to use in the process; the fourth one – on the types of biotope to (re)generate. Because Ikel CliRes model does not differentiate between the efforts of separate stakeholder groups, the spatial distribution of these efforts or the types of biotopes generated in the process of converting abandoned land to bioproductive land, we consider all these proposals as part of a single comprehensive policy.

The performance of this policy is tested against the base scenario for both RCPs. To understand how it would impact the crop yield, the height of groundwater table and the total area of bioproductive land, an increase in reforestation efforts is simulated starting with year 2021. The increased effort is presumed to be 100 times larger than the base effort and is maintained at this increased level throughout the 30-year period, i.e., from 2021 to 2050.

Figure 9.6 illustrates the impact of this policy on the trends in crop yield under RCP 2.6 and RCP 8.5 scenarios following the consistent and continuous implementation of increased (re)forestation efforts between 2021 until 2050 (Figure 9.6.a) alongside the change in soil erosion (Figure 9.6.b). As it was seen already in the base run, this key variable is expected to perform differently under different RCP scenarios (solid line). As a result of this policy, the crop yield increases slightly under both RCP scenarios while still maintaining the same decreasing trend over time. The most desirable outcome for crop yield is under RCP 2.6 climate scenario that includes the implementation of this policy. The least favorable outcome is under RCP 8.5 climate scenario that does not include a substantial increase in (re)forestation efforts.

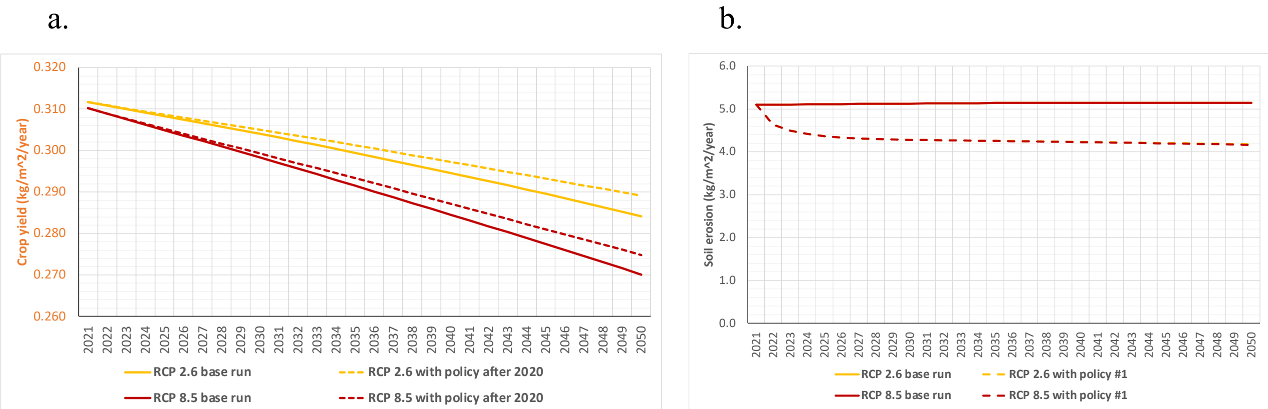


Figure 9.6. Crop yield behavior between 2021 – 2050 under RCP scenarios (a), and soil erosion (b) following the implementation of (re)forestation policy.

The main reason behind the increase in yields following reforestation efforts is the slowing-down of soil erosion (Figure 9.6.b). Increased vegetative cover that would come with (re)forestation has a lower crop management factor than the abandoned and the cultivated land (Table 7.19), reducing the speed of soil erosion and conserving soil. Better soil conservation maintains the nutrient-rich topsoil cover, which, in turn, favors better crop yields. However, preserving soil by changing the land use in some areas alone is not sufficient. As the soil continues to be eroded crop yields continue to decrease.

At this point, it should be kept in mind that Ikel CliRes model operates with average values for the entire watershed. Consequently, the performance of this policy vis-à-vis crop yields is to be interpreted from the perspective of (re)forestation happening in areas that are most conducive to soil conservation (e.g., shelterbelts on arable lands where both wind and rainfall displace more intensely the topsoil exposed to their effects, trees and subsequent vegetative cover on steeper slopes where it is easier for soil to be washed away).

The impact of the same policy on the trends in groundwater table height under the two RCP scenarios is illustrated in Figure 9.7. As in the case of crop yields, this policy has a positive impact on increasing the level of groundwater table, provided that the intense (re)forestation efforts are sustained throughout the 2021-2050 period. Although the watertable increases under both RCP scenarios, climate conditions under RCP 2.6 combined with the implementation of this policy yield the best outcome for the desired behavior of this key variable. RCP 8.5 without reforestation efforts is the least favorable scenario.

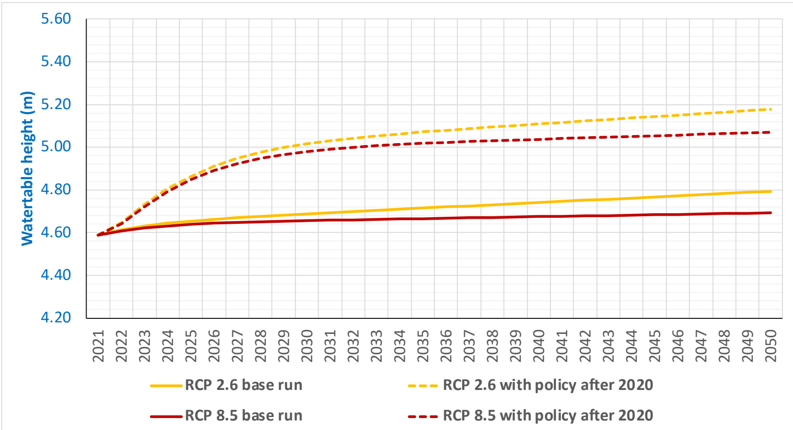


Figure 9.7. Behavior of groundwater table height under both RCP scenarios following the implementation of increased (re)forestation efforts.

The reason for this positive outcome of the policy is that areas having a denser vegetative cover, as would be the case for those areas covered by the (re)forestation policy, favor the infiltration of water more than cultivated and abandoned land do (Table 7.6). This leads to a higher amount of precipitation water percolating to deeper groundwater layers and, subsequently, to larger groundwater stocks that translate to higher levels of groundwater table.

Lastly, the performance of this policy is checked in relation to the bioproductive land area and illustrated in Figure 9.8. The simulation results for the impact of increased (re)forestation efforts on bioproductive land confirms the obvious: this policy helps increase the bioproductive area under all RCP scenarios. What the simulation results highlight is that the exponential growth in bioproductive land stock that follows immediately after the initial implementation of the policy cannot be sustained for the entire period. Instead, it reaches a certain plateau after the first years of implementation. The cause for that is the limited stock of abandoned land – the primary source of land that can be reforested. It can also be observed that this policy results in virtually the same impact on the bioproductive land area regardless of the RCP climate scenario.

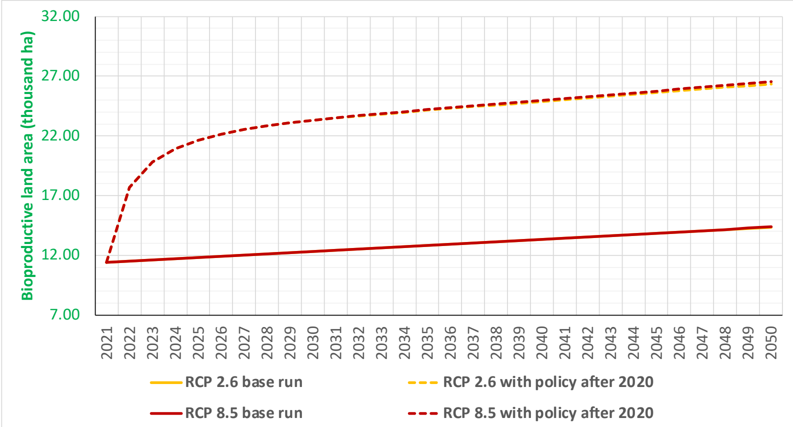


Figure 9.8. Behavior of bioproductive land stock under both RCP scenarios following the implementation of increased (re)forestation efforts.

All in all, the policy focused on significant increase in and sustaining of (re)forestation efforts has a positive impact on all three key variables under both RCP scenarios.

9.2.2. Increasing Farmers' Access to Irrigation Water Supply Systems

Thinking of what would help improve the situation over the next, hotter decades, of the three key variables – crop yields in particular, GMB participants suggested increasing the access of farmers to water supply systems for irrigation. The way it can happen is by both larger investments in irrigation infrastructure and providing access to additional water resources. Larger investments result in shorter times to meet the demand for additional infrastructure. Because Ikel CliRes already allows for a very high level of surface water resource use, access to additional water resources means opening the groundwater stock for use in irrigation.

Prior to 2020, farmers were not allowed to use groundwater for irrigation, owing to the increased concentration of various salts in these confined aquifers, which would have long term negative effects on soil health. Nevertheless, in 2020 this restriction was lifted, allowing farmers to start investing in irrigation infrastructure and use groundwater resources to irrigate the crops.

To understand how this policy would impact the crop yield, the height of groundwater table and the total area of bioproductive land, I simulate the increased access to irrigation water supply systems from 2021 onward. Increased access is defined as allowing 10 % of groundwater stock to be used for irrigation purposes every year, while the speed of investment is reduced to half of the current value for irrigation infrastructure from both groundwater and surface water resources. This policy is maintained from 2021 to 2050.

Figure 9.9 is the graphical representation of the impact on crop yield of increased farmers' access to irrigation water supply systems. Contrary to the wish and expectation of GMB participants, this policy does not have a visible positive impact on average crop yield.

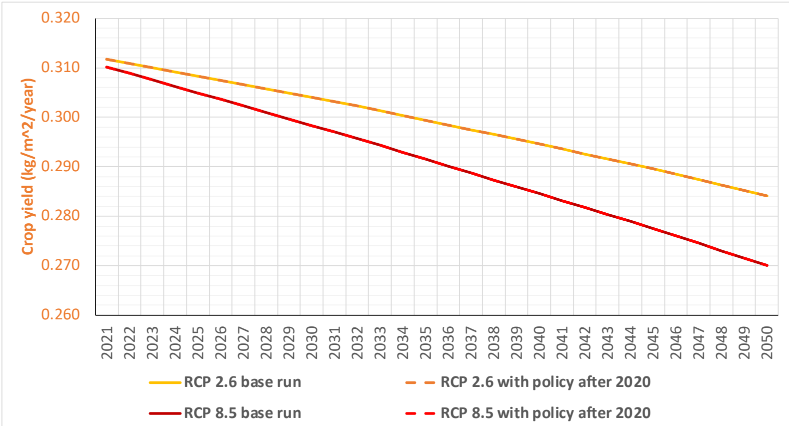


Figure 9.9. Behavior of crop yield following the implementation of GMB policy #2 - increased access to irrigation water supply systems.

Average crop yield in Ikel SES is calculated as a weighted average of crop yields on both irrigated and non-irrigated lands. The fact that increasing access to irrigation water supply systems does not have as big an impact as intended denotes that irrigated land does not increase significantly, and that there might be other factors preventing an increase in the weight of irrigated lands in the total arable land stock. In any case, the variability in climate conditions (RCP scenarios) would have a much bigger impact in average crop yield than this policy alone.

The impact of increased access to irrigation water supply systems on groundwater table is not only unaccommodating of the desired outcome, but is, in fact, opposite to it. As illustrated in Figure 9.10, the implementation of this policy from 2021 onwards leads to a decrease in the watertable height under all RCP scenarios. Climate conditions under RCP 8.5 coupled with this policy is the most counterproductive of the three possible outcomes of its implementation.

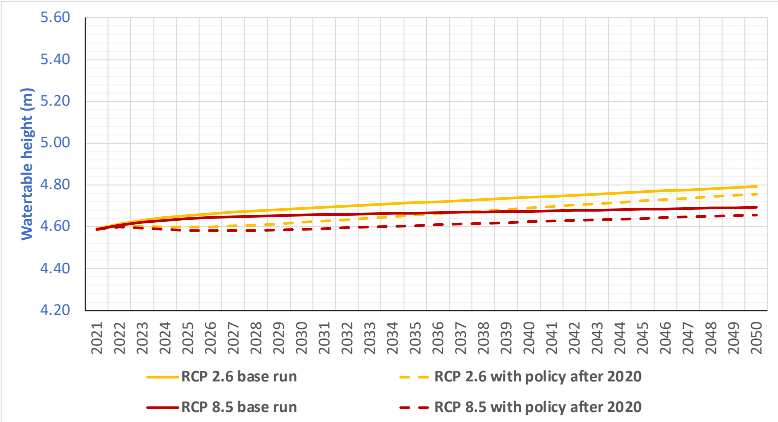


Figure 9.10. Change in groundwater table height as a consequence of increased access to irrigation policy's implementation between 2021-2050.

What leads to this consequence is increase in the amounts of water for irrigation extracted from the groundwater stock. While the total amount of irrigation water does not increase in absolute terms, the ratio of irrigation from groundwater to irrigation from gauged runoff water increases, putting more pressure on the former.

As far as the impact of this policy on bioproductive land is concerned, it does not make any noticeable difference. Figure 9.11 shows how neither any of the RCP base scenarios themselves, nor the RCP scenarios coupled with this policy are helpful to increasing this stock faster than it would already increase. That is owing to the fact that both rainfed and irrigated arable land stocks are decreasing on account of decreasing workforce, which results in the cultivated area being abandoned and taken over by the spontaneously growing plant species.

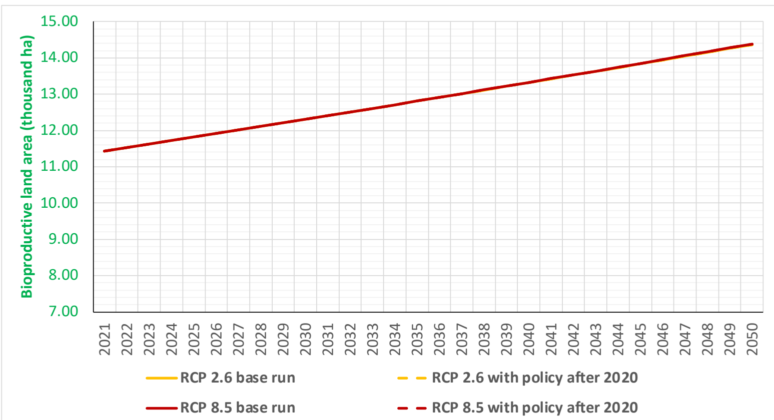


Figure 9.11. Behavior of bioproductive land stock before and after the implementation of policy that increases farmers' access to irrigation.

In conclusion, a policy focused on increasing farmers' access to irrigation water supply systems does not have a positive impact on the three key variables beyond the already anticipated, base run change: while for average crop yield and for bioproductive land the policy is devoid of impact whatsoever, for groundwater table the policy results in a slower increase of watertable height compared to the base run.

It should be noted here that Ikel CliRes does not account for salinity levels of groundwater. Consequently, the impact of this policy on the key variables assumes a relatively more optimistic outcome compared to the outcome that would also account for soil health degradation arising from salinization or solonetization processes.

9.2.3. Encouraging the Reclaiming of Abandoned Land for Agricultural Purposes

This policy proposed by GMB participants seeks to reduce the abandonment rate and to increase the reintroduction of already abandoned land back into the arable land stock. The main expectation behind this is that it would come as a counterbalance to the clearing of bioproductive land, while also contributing to increased yield. To analyze this policy, between 2021 to 2050, the abandonment fraction of rainfed arable land in Ikel CliRes is halved, while the fraction of reclaiming the abandoned land for agricultural purposes is multiplied by a factor of five.

Figure 9.12 depicts the impact on average crop yield in Ikel SES and shows how a more extensive agriculture does not help increase the yield per unit of area. On the contrary – having larger areas of arable lands slightly reduces the average yield they produce.

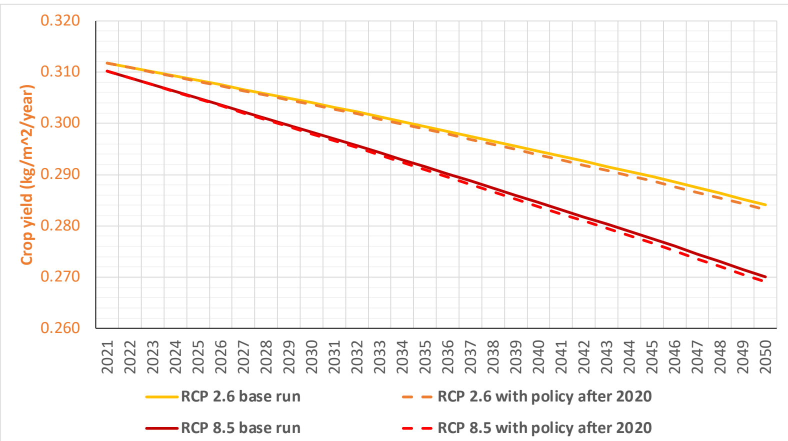


Figure 9.12. Evolution of average crop yield between 2021-2050 following the implementation of policies encouraging extensive agriculture.

This slight decrease in yield is due to the increased runoff and, consequently, reduced infiltration coefficient of arable land compared to bioproductive land. Should the abandoned land be reintroduced in the agricultural circuit rather than be used for reforestation, this would cause less water to infiltrate and eventually become available for the crops. Instead, more of the precipitation water runs off and less of it is taken up by plants, thus affecting the yields. The more humid RCP 2.6 scenario without an extensive policy agriculture remains the most conducive for crop yields of the four situations. In contrast, should the policy be implemented, and climate conditions evolve in a manner closer to the drier RCP 8.5 scenario, less soil moisture available for crops would cause a steeper decline in yields.

More runoff and less infiltration on arable lands compared to bioproductive lands as a result of this policy is also responsible for less water from precipitation reaching the groundwater table after 2021 (Figure 9.13) and for a slight decrease in the rate of bioproductive land stock change (Figure 9.14). While the general increasing trend of groundwater table level throughout the 30-yer period is maintained, this policy would reduce the rate of increase after 2021.

Similarly, as more of the abandoned land is reclaimed for agriculture, less of that land becomes available for natural or anthropic (re)forestation. As a consequence, the rate of increase in bioproductive land area is also diminished. The policy has the same effect on this key variable in case of all RCP climate scenarios (Figure 9.14).

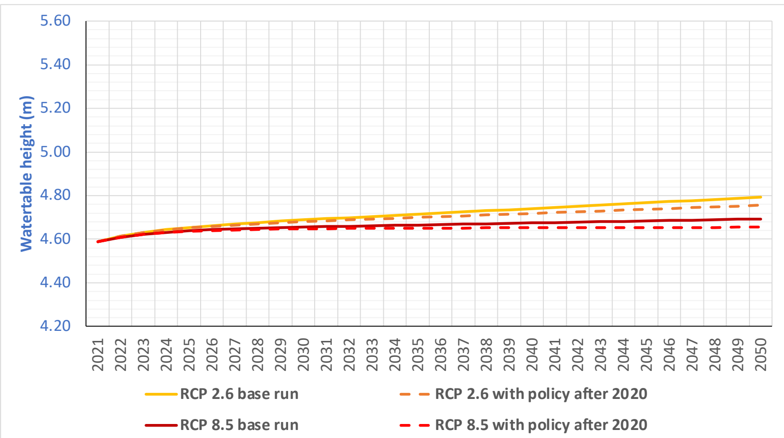


Figure 9.13. Change in the height of groundwater table under RCP scenarios following the implementation of abandoned land reclamation policy.

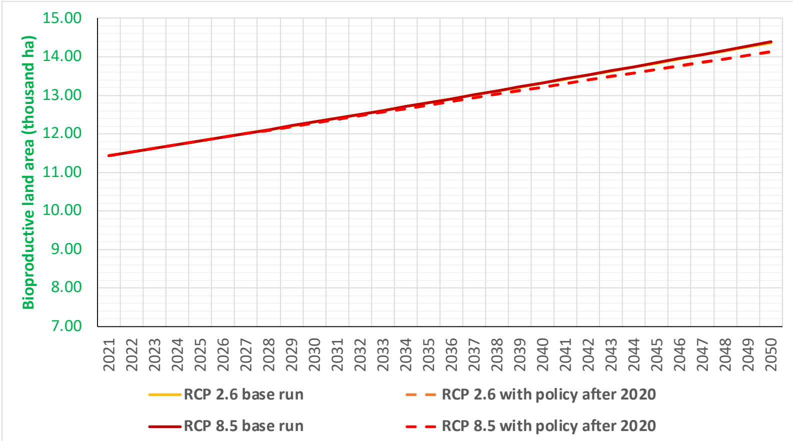


Figure 9.14. Bioproductive land stock change under both RCP scenarios with the implementation of the 2021 – 2050 policy that encourages the reclaiming of abandoned land for agricultural purposes.

Ultimately, while this particular policy does not significantly interfere with the trend in the behavior of the three key variables, it also does not bring about any improvement to either of them.

9.2.4. Stronger Law Enforcement to Reduce Illegal Clearing of Bioproductive Land

A common perception among GMB participants has been that if law enforcement is applied better to prevent illegal land clearing, that would enhance the adaptive capacity of Ikel SES. Within the scope of Ikel CliRes, the impact of this policy is tested for the three selected key variables. Land clearing fraction is decreased two-fold between 2021 and 2050, assuming that half of the land clearing is either illegal and that law enforcement institutions are effective enough or that through some state policy or a law, land clearing for agricultural purposes is reduced to preserve biodiversity.

The results, presented in Figures 9.15 – 9.17 show that this would not have any notable impact on any of the key variable. The main reason behind this is that the current rate of bioproductive land clearing is already very low: firstly, because most farmers who wish to expand their activity resort to reclaiming the abandoned land, and secondly – because there is already very little bioproductive land that is available for clearing. Therefore, any additional effort in preventing further clearing would not yield weighty additional benefits.

These things considered, it is evident that at current land clearing rates of bioproductive land, stronger law enforcement to reduce land clearing even more does not result in any significant impact – either positive or negative – on any of the three key variables.

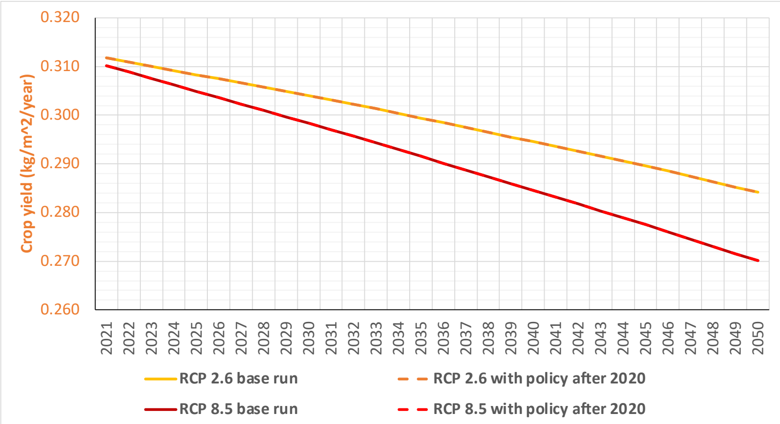


Figure 9.15. Average crop yield following the implementation of policies between 2021-2050 to reduce bioproductive land clearing.

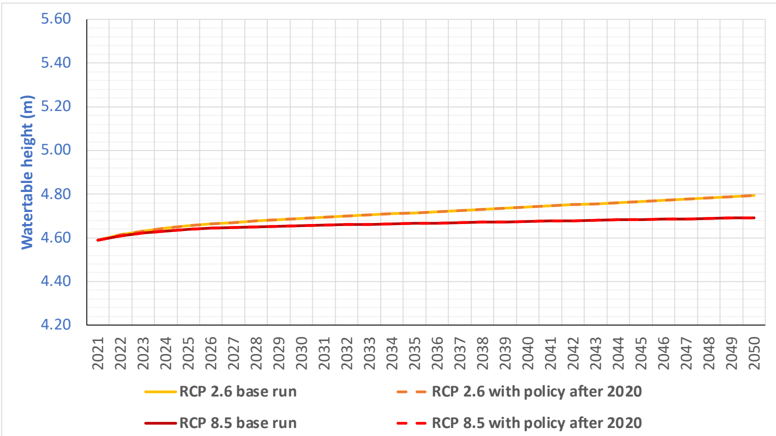


Figure 9.16. Height of groundwater table under all RCP scenarios following the implementation of this policy.

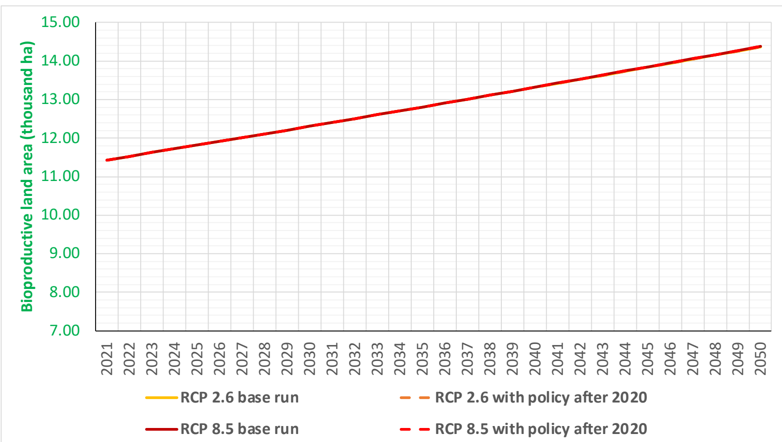


Figure 9.17. Bioproductive land under all RCP scenarios following the implementation of the policy.

9.2.5. Impact of All Policies Combined

In this section a buoyant scenario is tested, in which sufficient efforts are deployed to implement concomitantly all policies proposed by GMB participants. Their implementation is assumed to take place between 2021 and 2050, consistent with the previously tested policy impacts. The results (Figures 9.18 – 9.20) show that, if implemented together, these policies lead to positive impacts on all key variables.

In case of crop yields, a slight increase is expected for both RCP scenarios, while the general decreasing trend is maintained (Figure 9.18). This is similar to the impact of GMB policy #1 above (Figure 9.6).

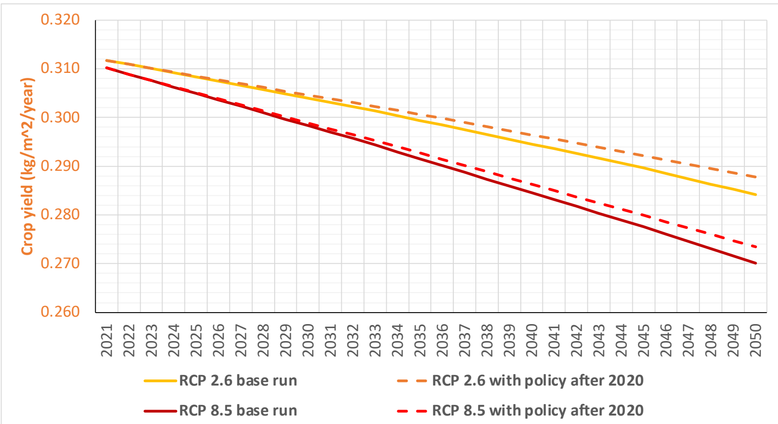


Figure 9.18. Behavior of crop yield following the simultaneous implementation of all policies proposed by GMB participants.

The same happens for groundwater table height (Figure 9.19): with policies, the stock would increase faster than it is envisaged to in the absence of these policies. The outcome for groundwater table is also similar to the outcome following the implementation of policy #1 (Figure 9.7).

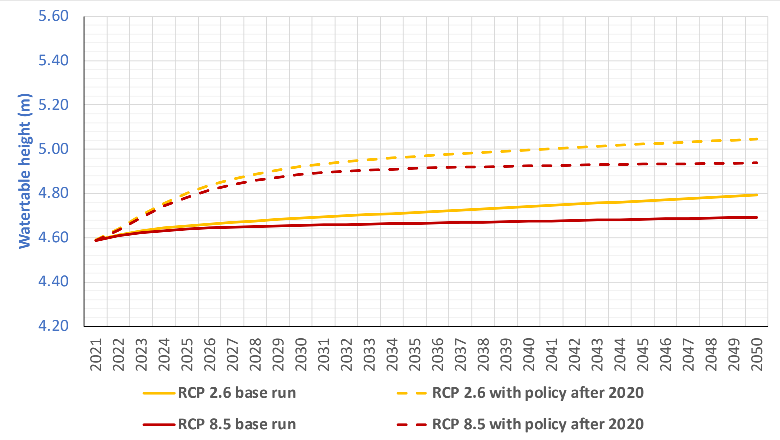


Figure 9.19. Change in height of groundwater table caused by simultaneous implementation of all policies proposed by GMB participants.

In the case of bioproductive land stock, the impact of concomitant implementation of all proposed GMB policies is the same for both RCP scenarios: an accelerated increase in the several years after the start of policy implementation, followed by a decelerated increase until the end of analyzed period in focus (Figure 9.20). This outcome, too, is similar to the performance of policy #1 in relation to bioproductive land (Figure 9.8).

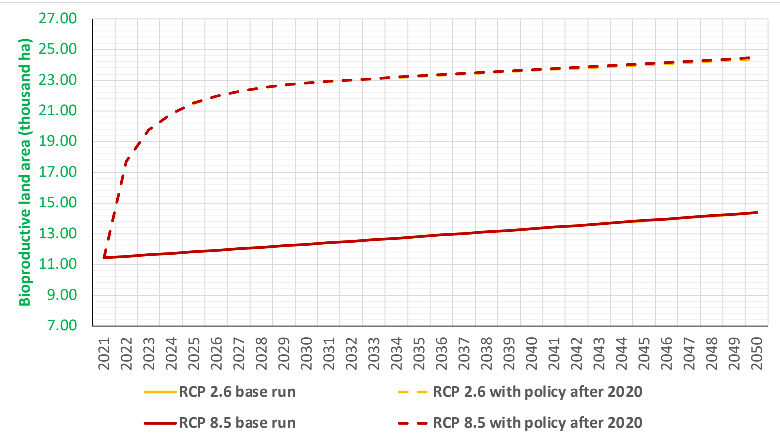
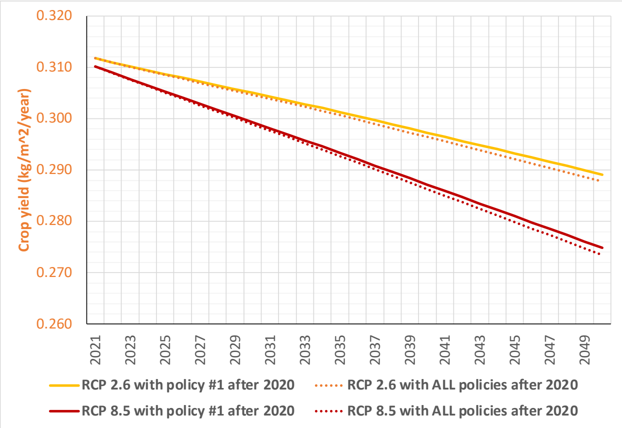


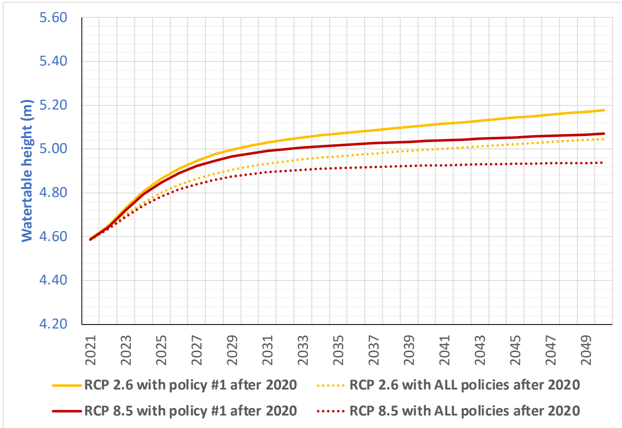
Figure 9.20. Bioproductive land stock change as a result of concomitant implementation of all proposed GMB policies.

As seen above, the synchronous implementation between 2021 and 2050 of all policies proposed by GMB participants produces similar positive impacts on all three key variables compared to the base run scenarios as does the implementation of the policy that facilitates intensive and sustained (re)forestation efforts (GMB policy #1). To understand if and how big the difference is between implementing only one policy or all of them, a comparative policy impact is illustrated Figure 9.21.

a.



b.



c.

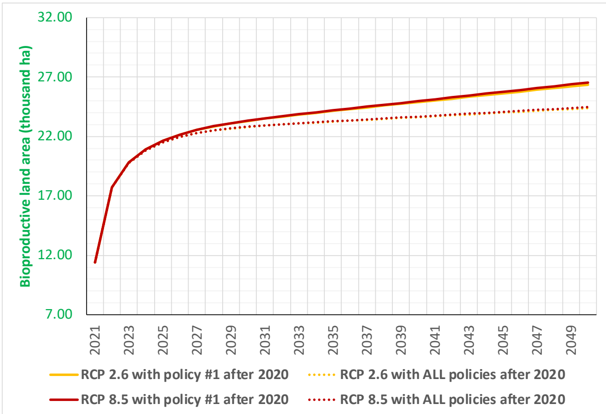


Figure 9.21. Impact on average crop yield (a), groundwater table (b) and bioproductive land (c) of the policy facilitating intensive and sustained (re)forestation efforts (solid lines) and of the simultaneous implementation of all policies proposed by GMB participants (dotted lines).

The comparative analysis reveals that the implementation of policy #1 alone has a more positive impact on average crop yield (Figure 9.21.a), groundwater table height (Figure 9.21.b) and bioproductive land area (Figure 9.21.c) than the implementation of all policies combined. What explains it is that in case of implementing all policies simultaneously, two of them would have a deleterious effect: the one increasing farmers' access to irrigation water supply systems – reducing the groundwater stock, and the one encouraging the reclaiming of abandoned land for agricultural purposes – affecting all three key variables.

On the whole, the combined implementation of all proposed policies does have a positive impact on the behavior of key variables. Yet, this impact is largely due to one policy in particular: intensive and sustained reforestation efforts. In contrast, the other policies proposed by GMB participants either have no positive effect or have an adverse impact on the behavior of key variables. Indeed, when implemented together, the latter three policies reduce the effectiveness of policy #1.

9.2.6. Discussion on Policies Proposed by GMB Participants

When looking at the policies proposed by GMB participants and the results of their performance analysis, a few important aspects should be borne in mind. These aspects are related to the basis, the context and the objective of their proposals, as well as to certain assumptions and limitations of Ikel CliRes model.

Firstly, the basis on which GMB participants proposed these policies is the set of reference modes elicited through the participatory process (Figure 5.1) and the analysis of the conceptual model developed jointly with GMB participants and external experts (Figure 6.7). The reference modes are more of a qualitative description of the estimated past behavior and of the expected and the desired behavior of key variables in the future rather than an exact reproduction of the actual behavior of those variables. Thus, the proposed policies put forward by GMB participants are based on the expectation that agricultural productivity (crop yield per unit of arable land), groundwater availability (groundwater table height) and local biodiversity (bioproductive land area) would register a decrease towards 2050 compared to 2016. They are also based on the desired goal as expressed by the stakeholders that the three key variables increase by 2050 compared to 2016. Therefore, the proposed policies are aimed to help achieve this goal.

However, simulation results indicate that of these key variables, groundwater stock and bioproductive land are generally expected to increase under both RCP scenarios in the coming period, as the base run behavior of these variables shows. It stands to reason that the simulations are based on certain assumptions, the most notable of which are following:

- Increased annual precipitation is accompanied by a temporal distribution of precipitation that is most favorable and conducive for timely and optimal development of crops.
- Rainfall erosivity factor (intensity of rainfalls) does not change with increased amounts of precipitation and does not add additional pressure on soil erosion.
- The quality of groundwater does not negatively affect the quality of soil where it is applied.
- Recharging time of groundwater stock does not change over time, i.e., sufficient water will be available from upstream sources to recharge the groundwater stock under Ikel watershed throughout the entire period in focus.

The reason for highlighting these particular assumptions is that in all likelihood they are both over-optimistic and have a significant impact on key variables in general, and on crop yields in particular, as seen in the model description and validation chapter. While a closer scrutiny of the impact of rainfall erosivity change and if decreasing recharge time for groundwater sock is carried out in the following chapter, the current version of Ikel CliRes cannot simulate a different seasonal distribution of annual precipitation, nor the impact of groundwater salinity on crop yield. Notwithstanding these limitations, the model does provide an accurate insight into the individual and joint impact of multiple policies.

Secondly, related to the context, the policies were proposed by a relatively small number of participants, which attended the second GMB workshop. The reference mode elicitation and the walkthrough of the conceptual model was carried out with all GMB participants (the latter through individual meetings). Because of the length of research time, only about a third of them participated in the workshop, where the policies were put forward following a joint discussion on the conceptual model. Therefore, the policies analyzed in the above section are proposals of a part of GMB participants. Should more participants have attended it, the number of policies proposed by them could have been larger.

The fourth workshop was also attended by a third of GMB participants. In this workshop, the performance of those policies was analyzed and discussed with the aid of Ikel CliRes simulation model. Less than half of the participants here were among those who proposed the policies. Nevertheless, the ones who only participated in the fourth, but not in the second workshop agreed that they, too, supported these policies prior to their simulation. However, after the simulation-aided policy analysis, all participants in the last workshop inquired about alternative policies. Some of those inquiries are addressed in the following section on *Alternative Policy Analysis*, while other policy inquiries, such as those related to the individual impact of certain agricultural practices or specific technologies for collecting and using surface water for irrigation, cannot be answered by the current version of the model. Table 9.4 below includes the summary information on the number of GMB workshops, their content in relation to policy proposals and the number of participants.

Table 9.4. GMB workshops carried out as part of the participatory process leading to Ikel CliRes model development and policy analysis.

Calendar of GMB workshops	Scope in relation to policy proposals	Number of GMB participants involved	% of total GMB participants
1st workshop: 26 February 2016	• Elicitation of model variables. • Elicitation of reference modes for key variables.	20	100 %
2nd workshop: 15 November 2016	• Defining model boundaries. • Joint model walkthrough and discussion. • Elicitation of policy proposals.	7	35 %
3rd workshop: 22 September 2017	• Structural validation. • Model boundary validation.	2	10 %
4th workshop: 30 June 2021	• Simulation-based analysis of policies proposed at 2nd GMB workshop. • Collecting alternative policy proposals.	7	35 %

Thirdly, the objective of policy proposals put forward by GMB participants is to increase the value of each key variable, assuming that a simultaneous increase in all three of them is desirable and that no limit on this increase is required in the specified time horizon. In the case of crop yield, this assumption is easily acceptable and desirable. For accessibility of groundwater, which in Ikel CliRes model translates as the height of groundwater table, this increase comes with the assumption that no matter how high the level might be reached in this time horizon, it does not translate into flooding, as it would be the case in a different context. Therefore, the assumption is that whatever the highest level of groundwater table, it would be rendered as being the most desirable. Similarly, bioproductive land area (a proxy for biodiversity) could, in theory, increase as much as 100 % of the green area (all Ikel SES area except for the land covered by water bodies and by constructions). The assumption in this case is that no matter how much the share of bioproductive land would increase by 2050, it is a desirable outcome of a policy. Therefore, the policy that results in the largest bioproductive land area is the best performing one in relation to this key variable.

Given the above, of all policies that have a positive impact on the three key variables, those that cause most increase in the three key variables are considered to be the ones that perform best. With this in mind, it can be stated that of all policies proposed by GMB participants in the second GMB workshop, the policy (or a group of policies) targeted at 100-fold increase in (re)forestation efforts is the best performing one.

Yet, while the policy focusing on increasing reforestation effort is the most effective one in achieving the desirable outcomes for groundwater table height and bioproductive land area (Figures 9.7 and 9.8), it is only marginally impactful in relation to the crop yield (Figure 9.6). In fact, all the other policies underperform in relation to this key variable. Most notably and counterintuitively – the policy focused on increasing farmers' access to irrigation water supply systems (Figure 9.9). The explanation for that is in the numbers. Average crop yield in Ikel SES (measured in kg/m^2/year) is calculated as a weighted average of crop yield on rainfed arable land and of crop yield on irrigated land:

$$Crop\ yield\ in\ Ikel\ SES = \frac{Irrigated\ yield\ x\ Irrigated\ arable\ land + Rainfed\ yield\ x\ Rainfed\ arable\ land}{Rainfed\ arable\ land + Irrigated\ arable\ land} \quad (9.1)$$

Increasing access to irrigation water supply is only reflected in the irrigated crop yield. Ideally, with easier access to more irrigation water, more farmers would switch to irrigated crops, which would result in a greater increase in the average crop yield in Ikel SES. However, this does not happen. In fact, the ratio of irrigated to rainfed arable land decreases both in the base run RCP scenarios and following the implementation of the policy focused on increasing farmers' access to irrigation water supply systems (Figure 9.22). Overall, the average crop yield increases only on the account of increased precipitations on rainfed arable land, as seen in the base run scenarios.

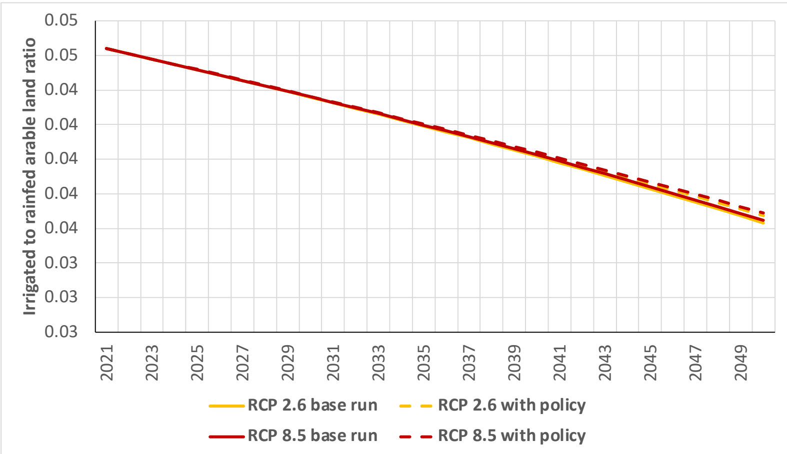


Figure 9.22. Change in ratio of irrigated arable to rainfed arable land over time.

This dynamic indicates that the dominant cause of the increase in average crop yield following the implementation of intensive (re)forestation policy is a decrease in soil erosion rate. The reduced soil erosion favors better crop yields (Figure 9.6). This is possible due to increasing bioproductive land stock. Having a larger share among the different land uses in Ikel SES and being characterized by a smaller cover management factor (C factor in USLE equation) compared to other types of land uses, bioproductive land contributes to reducing the rate of soil erosion (Figure 9.23).

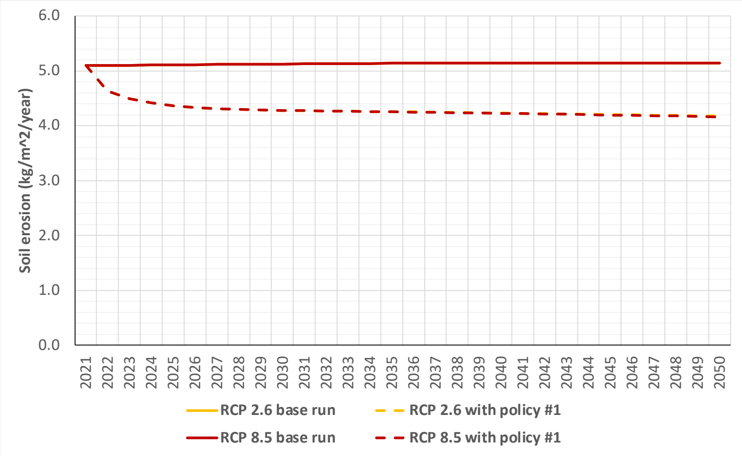


Figure 9.23. Change in soil erosion rates under both RCP scenarios as a consequence of implementing the (re)forestation policy consistently from 2021 until 2050.

On the other hand, what explains the decreasing ratio of irrigated arable to rainfed arable is the decreasing irrigated land stock. The main driver behind the latter is the increasing workforce scarcity in the labor-intensive irrigated lands and the decreasing population in Ikel SES (Figure 9.24). With insufficient workforce, farmers switch to rainfed agriculture even when water for irrigation is easily available. The change in population between 1990 – 2020 is based on historical data, while from 2020 to 2050 – on projections by UN Department of Economic and Social Affairs (Figure 2.9).

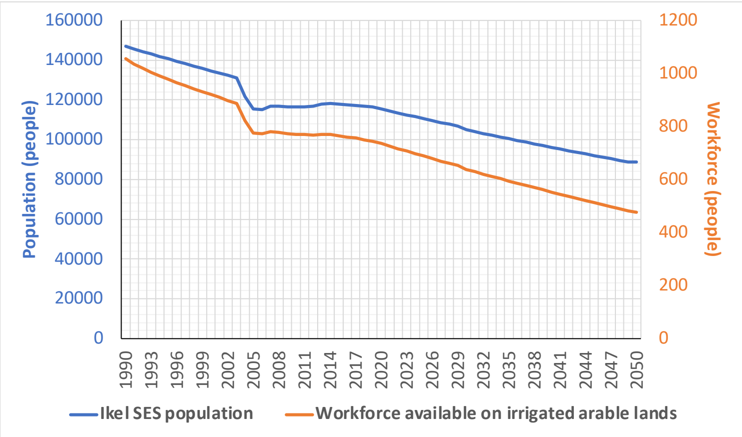


Figure 9.24. Change in Ikel population and workforce available to cultivate more labor-intensive irrigated crops.

A salient question that has come up during the fourth GMB workshop in the discussions with GMB participants is the impact of a policy that reverses population decline and / or favors the uptake of certain technologies that are less workforce demanding on irrigated land and on all key variables. These alternative policies are analyzed, among others, in the following section.

9.3. Alternative Policy Analysis

In this section, the performance of alternative policies is analyzed and discussed with respect to their impact on the desired outcomes for the three key variables. As in the case of GMB policy proposals, the impact is examined for the two RCP climate scenarios: RCP 2.6 and RCP 8.5. A scrutiny of these alternative polices is carried out to identify and recommend those, which provide the best leverage for climate change adaptation. The outcomes of this analysis also serve as a steppingstone towards resilience assessment to a selection of climate change impacts that is detailed in the next chapter.

Alternative policies investigated in this section are put together following the model validation and analysis that reveled a number of potential leverage points, as well as based on inquiries of participants in the fourth GMB workshop. These policies are presented and described in Table 9.5.

Table 9.5. Alternative policies and their operationalization in preparation of policy analysis using Ikel CliRes model.

Alternative policy description	Operationalization for policy analysis in Ikel CliRes model
Policy #1: Promote crop varieties that produce higher yields for the same water requirements. This policy encompasses investments in promotion and uptake of crop varieties that generate higher yields while consuming the same amount of water and benefiting from the same soil conditions as their less productive counterparts.	Behavior of key variables is compared between the base run scenarios and scenarios where *Attainable rainfed yield* and *Attainable irrigated yield* parameters are increased by a factor of 1.5 compared to the base run value.
Policy #2: Promote crop varieties that are less water intensive. This policy foresees a switch to crop varieties that use less water, i.e., have a smaller PET, to generate the same quantity of produce.	To test this policy, the value of *PET* (potential evapotranspiration) for the selected representative crop is reduced by 50 % compared to the base run value.
Policy #3: Adopt and maintain better soil conservation practices. This policy refers to a widespread and consistent effort to conserve the soil health by adopting the best possible practices (e.g., no-till farming, contour farming, windbreaks and others), and thus reduce the soil conservation factor (P factor in USLE).	The effectiveness of this policy in producing desired outcomes for the three key variables is tested by reducing the *P factor* (soil conservation factor) to half of its base run value.
Policy #4: Encourage and ensure that more people work in agriculture. This policy implies concerted measures to ensure that the more people are engaged in agricultural sector as unskilled, skilled and highly skilled workforce thus contributing to a larger percentage of the population being active in this sector.	By increasing the *Fraction of population in agriculture* parameter value ten-fold compared to its base run value, it is expected to see how the impact of this policy will be reflected on the average crop yield, groundwater table height and bioproductive land area in Ikel SES.
Policy #5: Halt population decline in the region. In case of this policy, various measures are taken to ensure that the trend in population decline is reversed, and more people remain active actors in this social-ecological system.	To understand if by reversing the population decline the key variables will exhibit the desired behavior trends, *Ikel SES population* table function is manipulated as follows: compared to the current base run, in the modified version, population does not decline after 2020. Instead, it is maintained at 2021 level.
Policy #6: Support the uptake of technologies in agriculture that require less workforce. This policy refers to supporting farmers in the adoption of various technologies that allow for competitive agriculture to be carried out with less workforce.	The performance of this policy is analyzed by increasing workforce efficiency five-fold, i.e., reducing the values of parameters *Workforce required on rainfed* and *Workforce required on irrigated* five times compared to their base run values.

In the following subsections the results of comparative analysis of these policies are showcased according to their impact on crop yield, groundwater table and bioproductive land between years 2021 and 2050. The impact is the performance of these alternative policies compared to the base run scenarios, two of which – as discussed in Section 9.2.6 – are somewhat optimistically anticipated to already be favorable for the key variables in question (Figures 9.4 and 9.5). A positive impact means that either there is an increase in key variables, or the increase is happening faster. In both cases the positive outcome is maintained for the entire 30-year period until 2050. A relatively negative impact means that the policy either leads to a decrease in the selected key variable, or that the increase happens slower than in the base run scenarios. If the policy does not change the base run behavior of the variable, it is deemed as neutral. It should be noted that this ranking is based on the values attributed to parameters when testing the respective policy. Consequently, the performance of a particular policy is likely to vary in most cases if the same parameters are given different values.

9.3.1. Impact on Agricultural Productivity

From the six alternative policies, all but one have a positive impact on average crop yield in Ikel SES, albeit for different reasons, and none has a negative impact. The neutral policy in this case is that which seeks to halt population decline in Ikel SES. That is, even if population in the region were to stabilize at the 2021 level, that by itself would not impact the average agricultural productivity. However, each of the other five policies can, by itself, increase average crop yield in Ikel SES. Figure 9.25 illustrates the comparative impact of these policies. Each graph in Figure 9.25 represents the impact of a single policy in order of performance ranking (Table 9.6).

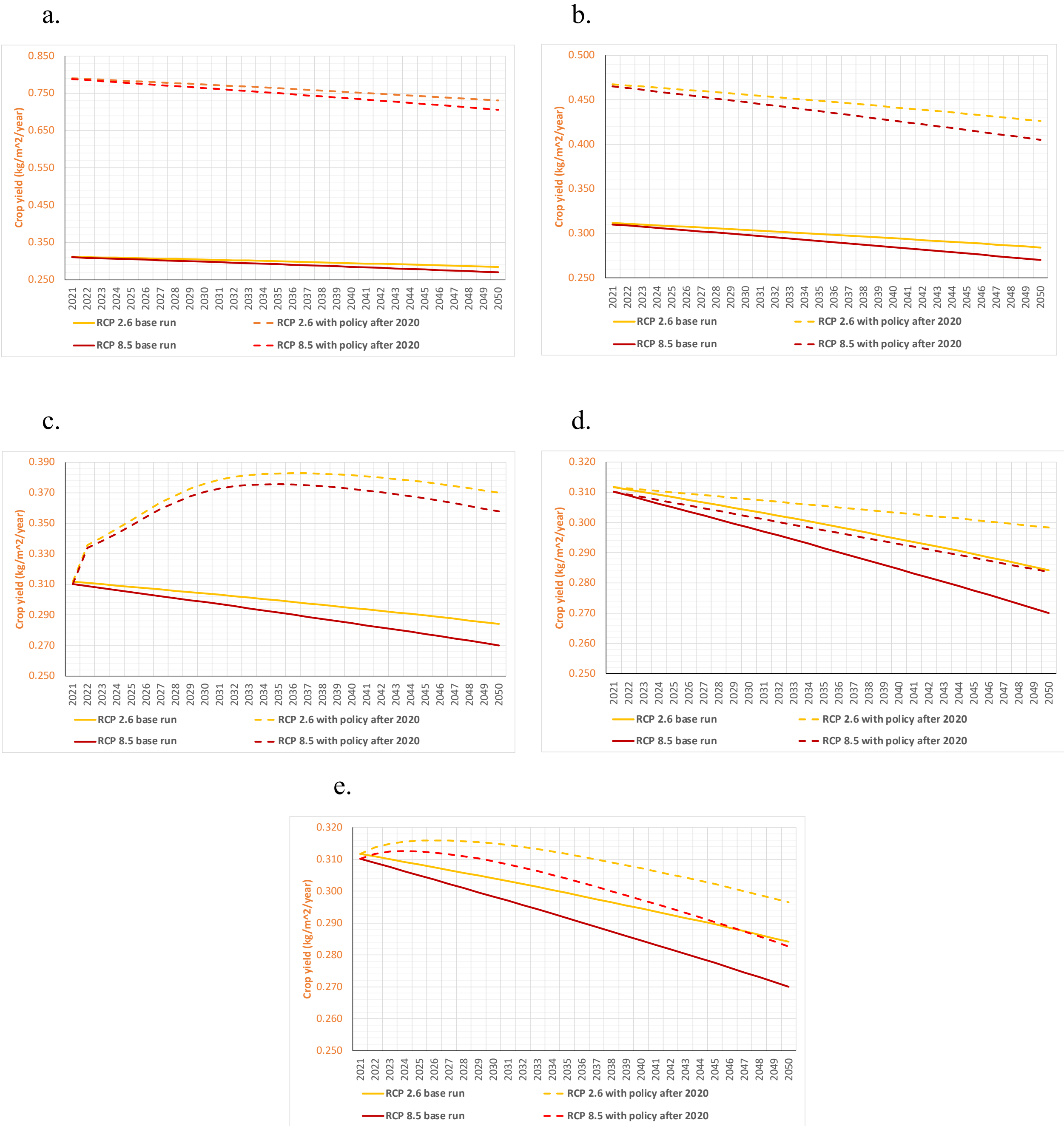


Figure 9.25. Performance of alternative policies with positive impact on average crop yield in Ikel SES compared to the base run scenarios. (a) Policy #2: promote and achieve adoption of crops with PET that is 50 % less than the base run value; (b) Policy #1: promote and achieve adoption of crop varieties that for current PET values are expected to yield 50 % more yield; (c) Policy #4: encourage and ensure that 10-times more people work in agriculture; (d) Policy #3: ensure the adoption and constant implementation of better soil conservation practices that result in a 50 % decrease in the P factor; (e) Policy #6: support the uptake of technologies that increase workforce efficiency in agriculture and require five times less workforce to cultivate both rainfed and irrigated crops.

Table 9.6. Ranking of the five alternative policies positively impacting average agricultural productivity in Ikel SES, from most impactful to the least impactful.

Performance ranking	Policy description
1	**Policy #2:** Promote and achieve adoption of crops with PET that is 50 % less than the base run value.
2	**Policy #1:** Promote and achieve adoption of crop varieties that are expected to yield 50 % more yield for the same (current) PET value.
3	**Policy #4:** Encourage and ensure that 10-times more people work in agriculture.
4	**Policy #3:** Ensure the adoption and constant implementation of better soil conservation practices that result in a 50 % decrease in the P factor.
5	**Policy #6:** Support the uptake of technologies that increase workforce efficiency in agriculture and require five times less workforce to cultivate both rainfed and irrigated crops.

As seen in Figure 9.25, the policy with the highest impact is the one that focuses on switching from cultivating crops with high PET values to cultivating crops with 50 % lower PET values, i.e., crops that require 50 % less water to achieve maximum yields (Figure 9.25.a). Crop yields depend on the availability of soil water and on soil health. Under current precipitation levels, rainfed crops don’t achieve maximum yield due to limitations in water availability. If less water intensive crops are cultivated, it is more likely and possible to achieve crop yields that are closer to maximum attainable yields on rainfed lands. This is reflected in the crop yield surge observed from 2021 onward, when the policy starts being implemented, as compared to the base scenarios, where the values of crop yield are more than two times smaller. On the other hand, it can be seen that even for these high yields there is a steady decline in the behavior of this key variable. The reason is the ongoing soil erosion, which reduces soil health and leads to declining agricultural productivity. Nevertheless, the yields under this policy are much higher than in the base run for both RCP scenarios, with RCP 2.6 climate scenario being the most favorable one.

In Figure 9.25.b, a similar surge in crop yields can be observed as a result of promoting and achieving adoption of crop varieties that are expected to yield 50 % more yield for current PET values. Although the surge has a smaller amplitude, the policy behind it is driven by the same rationale of adapting agriculture to conditions of reduced water availability for rainfed crops. Crop yields continue to decrease throughout the 30-year period due to decreasing trends in annual precipitation that have a stronger effect on yields than the soil health. The effect of soil erosion is also embedded in the relatively faster rate of decline in yield compared to that resulting from policy #3 discussed below.

Workforce scarcity on irrigated lands has been a major limiting factor that has prevented the increase in irrigated arable lands, although irrigation water is available. Figure 9.25.c illustrates the impact on average crop yield of implementing policy #4, which encourages and ensures that 10-times more people work in agriculture compared with current base run. With less workforce scarcity and, consequently, with more arable lands being used for cultivating irrigated crops, the weight of irrigated crop yield increases in the calculation of average crop yield in Ikel SES. That is to say that although crop yield (kg/m^2/year) on both rainfed and irrigated arable lands does not change dramatically, due to more workforce being available to cultivate crops on irrigated lands, the weighted average of crop yield in Ikel SES increases after 2021. The decline that follows from around 2035, on the other hand, is due to a decline in overall Ikel population. Thus, although a higher percentage of population is engaged in agriculture as a result of policy, the decline in the overall population will eventually be reflected in the abandonment of irrigated arable lands.

The impact of policy #3 – ensuring the adoption of better soil conservation practices that result in a 50 % decrease in the P factor – is mentioned above and illustrated in Figure 9.23.d. Any decrease in P factor means that soil erosion is slowed down. With less erosion, the soil is healthier, and crops produce better yields. This dynamic is reflected in the slowing down of the decrease in average crop yields form 2021 onwards. Needless to say, this smaller rate of decline is conditioned by the sustained and watershed-wide implementation of better soil conservation practices.

The impact on average crop yields of using technologies that increase workforce efficiency in agriculture and require five times less workforce to cultivate both rainfed and irrigated crops (policy #6) is reflected in Figure 9.25.e. The implementation of this policy between 2021and 2050 leads to a short-lived initial increase, followed by a continuous decline of average crop yields. This policy, too, addresses the issue of limited workforce availability and hence, impacts the calculation of average yields in Ikel SES rather than the yields on either rainfed or irrigated lands themselves. Still, compared to the base run, this policy provides better results.

All in all, the ways in which the five alternative policies discussed above impact this specific key variable are different. Policies with the highest impact are the ones that require a change in cultivated crop varieties to less water demanding ones, i.e., policies #1 and #2. However, both these policies are challenged by soil erosion, which limits the growth in agricultural productivity. This limitation is addressed by policy #3 that reduces soil erosion on both rainfed and irrigated lands. Policies #4 and #6, on the other hand, address the limitation imposed by workforce scarcity. Both of these policies help increase the average crop yield mathematically by ensuring that more of the Ikel SES crops are grown on irrigated lands, and thus drive up the average value of this key variable. In comparison with these, policy #5 that would halt population decline from 2021 onwards would have no impact on average crop yields whatsoever.

9.3.2. Impact on Groundwater Table

From the six alternative policies, two have a positive impact on the height of groundwater table, two have no notable impact, and the remaining two have a negative impact on the groundwater table compared to the base run.

The ranking of alternative policies positively impacting this key variable is presented in Table 9.7, while Figure 9.26 includes the graphs with comparative impact of these policies. Further, the performance of the two policies that have a relatively negative impact on groundwater table is illustrated in Figure 9.28.

Groundwater stock and the height of groundwater table respectively are already expected to increase under the two RCP scenarios (Figure 9.4). In case of RCP 2.6, that happens due to increasing precipitations and increasing bioproductive land area that has a larger infiltration fraction compared to other land uses. In case of RCP 8.5 – a climate scenario that forecasts a decrease in annual precipitation over the following decades, the main driver is the increase in bioproductive land area. However, two of the alternative policies can contribute to a faster increase in this key variable (Figure 9.26).

a. b.

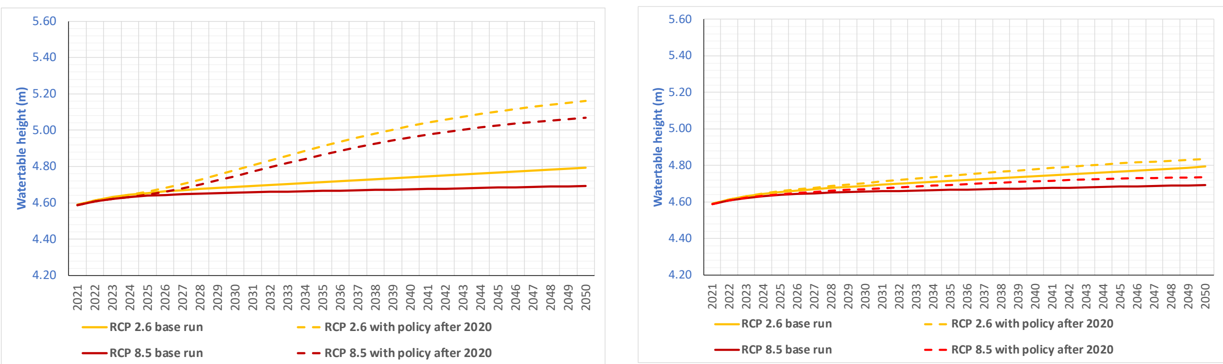


Figure 9.26. Performance of alternative policies with positive impact on the height of the groundwater compared to the base runs: a) Policy #4, aimed at ensuring that 10-times more of the Ikel SES population works in agriculture; b) Policy #6: support the uptake of technologies that increase workforce efficiency in agriculture and require five times less workforce to cultivate both rainfed and irrigated crops.

The implementation of policy #4 that ensures a 10-fold increase in the percentage of Ikel SES population working in agriculture results in the fastest increase (Figure 9.26.a). This is explained by the larger amount of water from irrigation percolating to the groundwater stock and by the fact that this water is gauged from surface water resources only. With more workforce and sufficient water being available starting from 2021, the irrigated land area is boosted. Since a fraction of all water that infiltrates into the soil percolates to the confined aquifer, a larger amount of water applied through irrigation leads to more water replenishing the stock. In other words, this policy causes additional amounts of water being "injected" from surface water to groundwater resources, which increases the groundwater stock and thus the height of the groundwater table.

Similarly, increasing workforce efficiency in agriculture by adopting technologies that require five times less workforce than currently needed to cultivate both rainfed and irrigated crops (policy #6) also has a positive impact on the speed of groundwater table rise (Figure 9.26.b). However, the rate of change in this case is much smaller.

The application of both of the above policies results in an initial increase in irrigated land area and in the additional increase of groundwater table compared to the base run. However, the increase in the latter slows down towards the end of the analyzed period because after the initial boost, the irrigated land stock starts to decrease again eventually (Figure 9.27), owing to the decrease in total Ikel SES population. Consequently, the amount of irrigation water percolating to the deep aquifer is comparatively less.

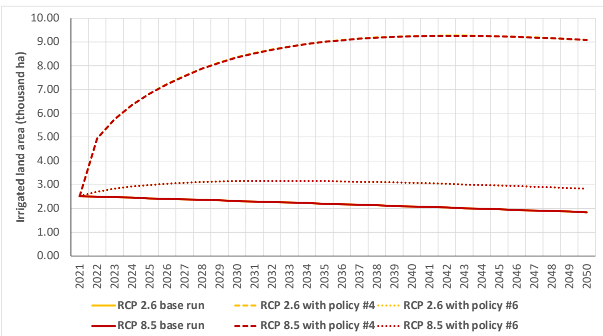


Figure 9.27. Change in irrigated arable land with the implementation of policies #4 and #6.

Table 9.7. Ranking of the two alternative policies positively impacting the groundwater table height relative to the base run scenarios.

Performance ranking	**Policy description**
1	**Policy #4:** Encourage and ensure that 10-times more people work in agriculture.
2	**Policy #6:** Support the uptake of technologies that increase workforce efficiency in agriculture and require five times less workforce to cultivate both rainfed and irrigated crops.

Two of the six policies are less conducive to the rate of increase in this key variable. Namely, cultivating crops that require 50 % less water (policy #2) and carrying out better soil conservation practices that reduce soil erosion (policy #3) cause the groundwater table height to increase slower compared to the base run under all RCP scenarios (Figure 9.28).

a. b.

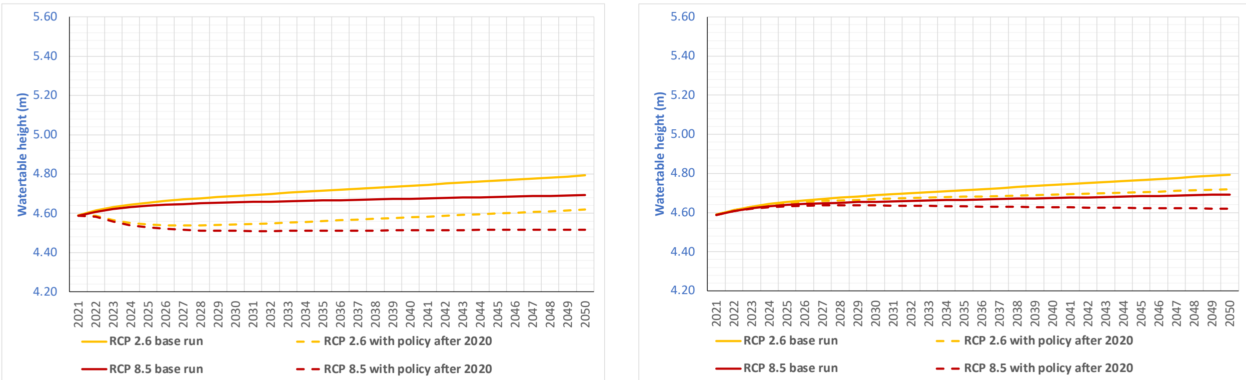


Figure 9.28. Change in groundwater table following the implementation of the two alternative policies that have a negative impact on this key variable compared to the base run scenarios: a) Policy #2: adoption of crops with PET that is 50 % less than the base run value; b) Policy #3: adoption of better soil conservation practices that result in a 50 % decrease in the P factor.

The driver behind the sudden decrease followed by an increase in groundwater table seen in Figure 9.28.a is the decrease in demand for irrigation water supply caused by switching to crops that have a smaller PET value (policy #2). With less water needed for irrigation, less water is applied and thus less of water percolates to the groundwater stock. Conversely, going for policy #3 that reduces the P factor (Figure 9.28.b) does not cause a sudden decline followed by a subsequent increase in this key variable. Instead, it leads to a steady, but slower increase in the watertable height. By reducing soil erosion, this policy favors better crop yields and contributes to reducing both land abandonment and reforestation efforts. That, in turn, leads to less bioproductive lands being available compared to the base run. Since infiltration on cultivated lands is less than on bioproductive lands, as more of the land is retained for agriculture, less of the precipitation water reaches the groundwater stock under both RCP scenarios.

These things considered, with reference to the alternative policies discussed in this section, it becomes evident that having more of the irrigated agriculture can lead to a more accelerated increase in the groundwater table, whereas using less water in agriculture leads to the opposite. Indeed, this is conditioned by the irrigation water being abstracted from surface water resources. At the same time, by ensuring better crop yields, soil conservation practices lead to bioproductive land that is more favorable for water retention and percolation to groundwater, being traded off for more productive agricultural land which, in turn, has a smaller infiltration fraction. All the while, policies #1 (adoption of crop varieties that are expected to yield 50 % more yield for the same PET value) and #5 (halting population decline from 2021 onwards) do not cause a visible change in the groundwater table compared to the base run.

9.3.3. Impact on Bioproductive Land Area

Although bioproductive land area continues to increase under all policies, it happens with various rates. Thus, two of the six policies are neutral, i.e., bioproductive land stock changes as it does in the base run. As a result of individually implementing each of the other four policies, the increase in this stock is slowed down. Therefore, they are to be considered as having a relatively negative impact on this third key variable of interest. Their comparative impacts are visually demonstrated in Figure 9.29, in order of their impact intensity (i.e., how much the increase is slowed down). Of the four, policy #3 - adoption of better soil conservation practices that result in a 50 % decrease in the P factor - has the biggest impact (Figure 9.29.a). It is followed by policy #4 - ensuring that 10-times more people work in agriculture (Figure 9.29.b), policy #2 - switching to crops that have a smaller PET value (Figure 9.29.c) and policy #6 - uptake of technologies that increase workforce efficiency (Figure 9.29.d). The performance of these policies is similar under both RCP climate scenarios.

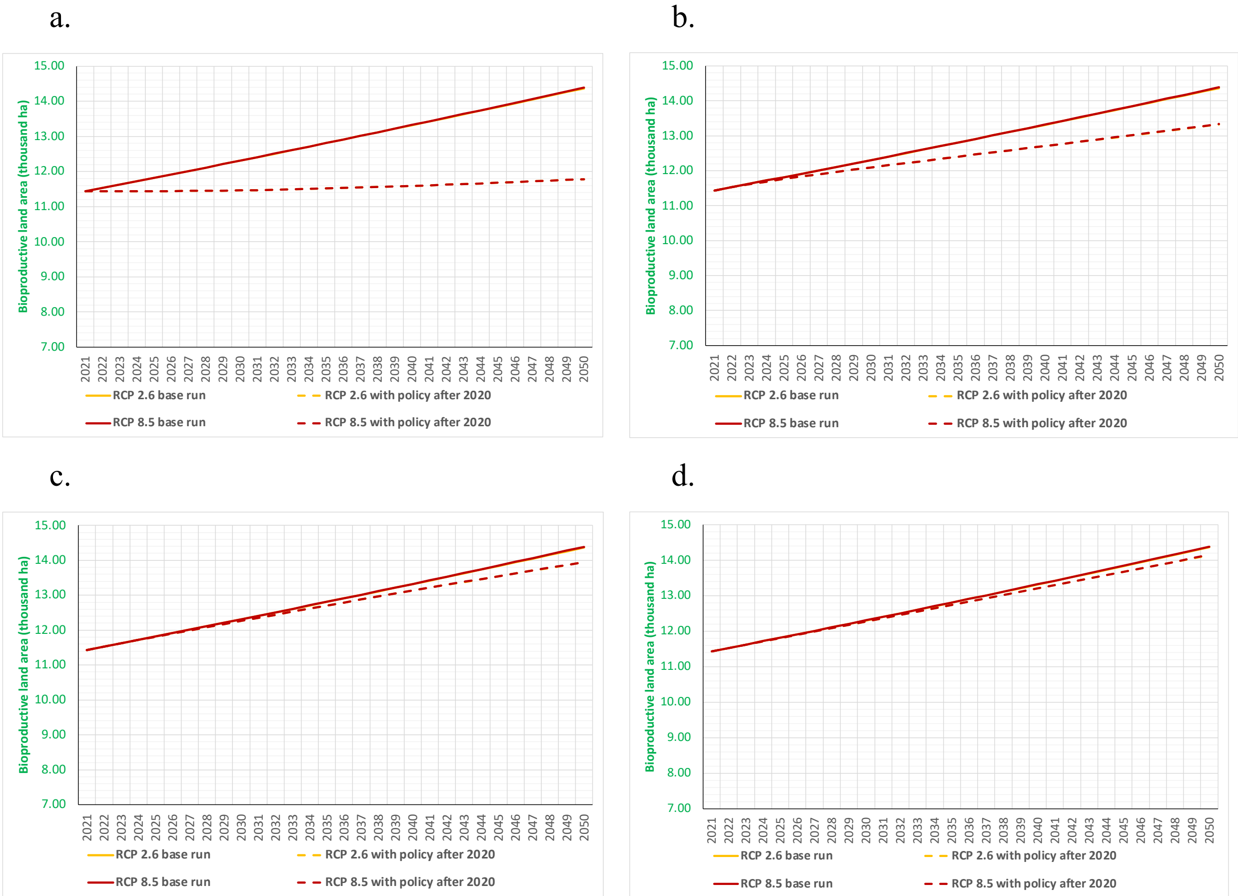


Figure 9.29. Performance of alternative policies #3 (a), #4 (b), #2 (c), and #6 (d), which have a negative impact on the rate of growth of bioproductive land area in Ikel SES. Their impact on the land stock is similar under RCP 2.6 and RCP 8.5. Hence, the red lines override the yellow lines.

In Figure 9.29.a, the impact of policy #3 is seen as it causes the strongest slowdown in the bioproductive land area increase. Similar to the impact on groundwater table, by implementing better soil conservation practices that result in a 50 % decrease in the P factor, crops produce better yields and farmers have a stronger incentive to keep the lands instead of abandoning them. Consequently, less abandoned lands are available for conversion – either natural or human-driven – into bioproductive lands.

Ensuring that 10-times more people work in agriculture than they currently do, i.e. that the fraction of the Ikel SES population engaged in agricultural activities is ten times larger compared to the base run (policy #4) has a similar impact, as it is visible in Figure 9.29.b. Compared to the previous policy, the rate of increase here is somewhat larger, leading to the bioproductive area being larger towards 2050 then it would be after implementing policy #3.

For different reasons, policies #2 and #6 have a much smaller impact (Figure 9.29.c and 9.29.d respectively). Cultivating crops with PET that is 50 % less than the current, base run value (policy #2) makes it less imperative for farmers to have access to additional water resources in order to achieve good results. Subsequently, less of the arable land is being abandoned and less land is available for (re)forestation, i.e., conversion to bioproductive land. A five-fold increase in workforce efficiency through the uptake of such technologies (policy #6) has an even smaller effect on the slowing down of bioproductive land stock increase, due to a very small effect on the relative increase of rainfed and irrigated cultivated lands.

To conclude with, none of the discussed alternative policies facilitates a larger increase in the bioproductive land stock compared to the base run. In fact, most of them have the opposite effect, while neither adopting crop varieties that are expected to yield more yield for the same PET value (policy #1), nor halting population decline, keeping it the 2021 level (policy #5) cause a visible change in this key variable compared to the base run.

9.3.4. Discussion on Alternative Policies

When discussing the alternative policies, several points should be recalled. First, the analysis of alternative policies is based on the same assumptions as in the case of policies proposed by GMB participants. Most notable of these are the somewhat over-optimistic assumptions, which also have a significant impact on key variables in general and on crop yields in particular. Additionally, the rankings and the amplitude of alternative policy impact – whether positive, neutral or relatively negative – are based on the specific values assigned to parameters (Table 9.5). These parameters take effect from 2021 until 2050, representing both successful policy adoption from year one of their implementation and their continuous application throughout this period.

Thus, the first observation that stands out from this analysis is that most of these policies – five out of six – are favorable for average crop yield values in terms of average yield per unit of area (kg/m^2) calculated for the entire Ikel SES area, while none of them provides any additional value for bioproductive land area increase. On the contrary, four of the six alternative policies lead to a slowing down of the increase in this stock. This highlights an important aspect of Ikel SES: *the land stock is limited, and there is an ongoing tradeoff between using the land for agriculture or using it for providing habitats and preserving and restoring biodiversity*. This observation gives rise to the imperative of understanding and deciding *how much is enough*:

- How much bioproductive land in Ikel SES is enough for the purposes of maintaining local biodiversity?
- How much land is enough for agricultural pusposes and how much of that is enough to be used for irrigated crops?
- How much yield is enough for farmers to be cultivating?

The second discussion point arises from the question of *how much is enough.* It is related to the focus on crop yield understood as quantity of crop per unit of cultivated area (e.g., kg/m2) and the question about how much crop production in Ikel SES overall is sufficient. This prompts an inquiry into the impact of alternative policies not only on crop yield, but also on the total crop production in Ikel SES. To this end, Figure 9.30 illustrates the comparative performance of the five alternative policies that have a positive impact on crop yield as they impact the total crop production in Ikel SES. The relative performance is demonstrated for the two RCP scenarios. As seen in previous sections, of the latter, RCP 2.6 is the most conducive for crop production, meaning that the yield under those climatic conditions is expected to be somewhat higher than under RCP 8.5 as a result of the same policy. In case of alternative policies #2, #1 and #4, the policy has a more significant impact of total crop production than the climate scenario (Figure 9.30).

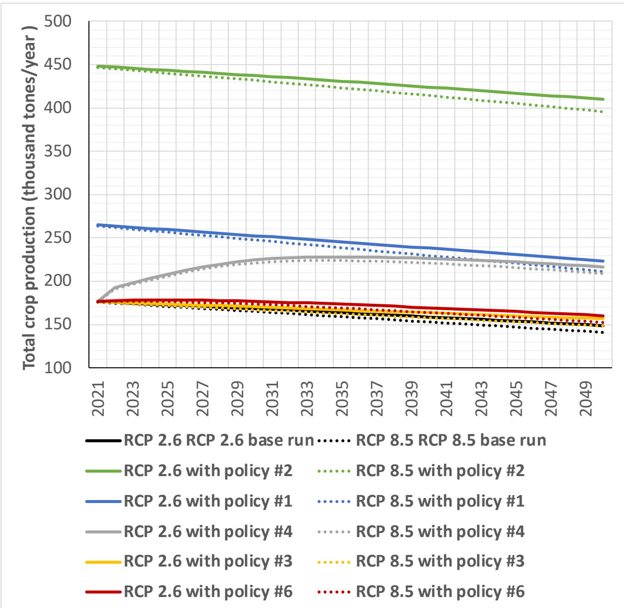


Figure 9.30. Performance of alternative policies on total crop production in Ikel SES under RCP 2.6 and RCP 8.5.

However, for alternative policies #3 and #6, their performance can be outweighed by the climate scenario (Figure 9.31). For example, although policy #6 tends to generally perform better than policy

#3, by 2050, under RCP 4.5, the uptake of technologies that require five times less workforce to cultivate crops (policy #6) would produce a weaker outcome than the adoption and constant implementation of better soil conservation practices (policy #3) under RCP 2.6 and RCP 8.5. This becomes particularly relevant if the main goal of the policy is a better performance on the long term: while from the short-term impact perspective, policy #6 may perform better, on a longer term – soil conservation is the better performing option between the two when it comes to total crop production in Ikel SES.

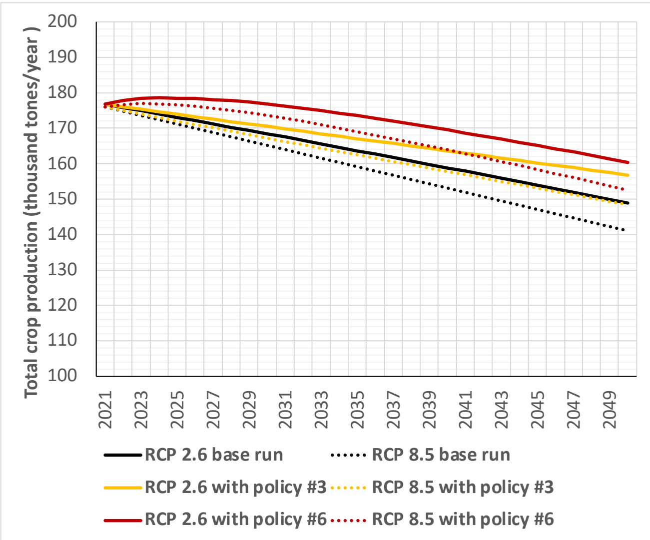


Figure 9.31. Comparative performance of policy #6 and policy #3 relative to the base run and to each other under climate conditions corresponding to RCP 2.6 and RCP 8.5.

The third discussion point refers to whether there is an alternative policy that has a positive impact across the three key variables. From the individual impact analysis, it could be seen that compared to the base run:

- Alternative policies #1, #2, #3, #4 and #6 have a positive impact on crop yield, and policy #5 is neutral.
- Policies #4 and #6 have a positive impact on groundwater table, policies #2 and #3 – a relatively negative impact on this key variable, while policies #1 and #5 are neutral.
- No policy has a positive impact on bioproductive land, policies #1 and #5 are neutral in relation to it, and policies #2, #3, #4 and #6 have a relatively negative impact on it.

This points to the fact that from the listed alternative policies, there is no single one that can provide additional increase to all three key variables simultaneously. However, there is one policy that can provide additional increase in average crop yield while not negatively affecting the base run increase in groundwater table and in bioproductive land. It is alternative policy #1: adoption of crop varieties that are expected to yield 50 % more yield for the same (current) PET value.

Further, considering the possibility to implement simultaneously several different policies, an important discussion point concerns the cumulated impact of policies. Based on the understanding that the policy focused on (re)forestation efforts proposed by GMB participants (GMB policy #1) performs well in relation to all three key variables and has very good results for groundwater table and bioproductive land, an inquiry is conducted into the impact of simultaneous implementation of this policy and those alternative policies that appear to have positive impacts on yields and relatively negative impact on groundwater and bioproductive land stocks.

Figures 9.32 – 9.34, for example, show how combined implementation of GMB policy #1 and of the alternative policy promoting the uptake of crops with PET that is 50 % less than the base run value (alternative policy #2) produces better results across the three key variables than the base run behavior of these variables. This is valid until 2050 in case of climate conditions of both RCP scenarios. Figure 9.32 illustrates the impact on average crop yield of the two policies combined relative to the same policies applied individually. The simultaneous implementation of the two policies results in crop yields that are higher than for any of the two policies implemented alone.

a. b.

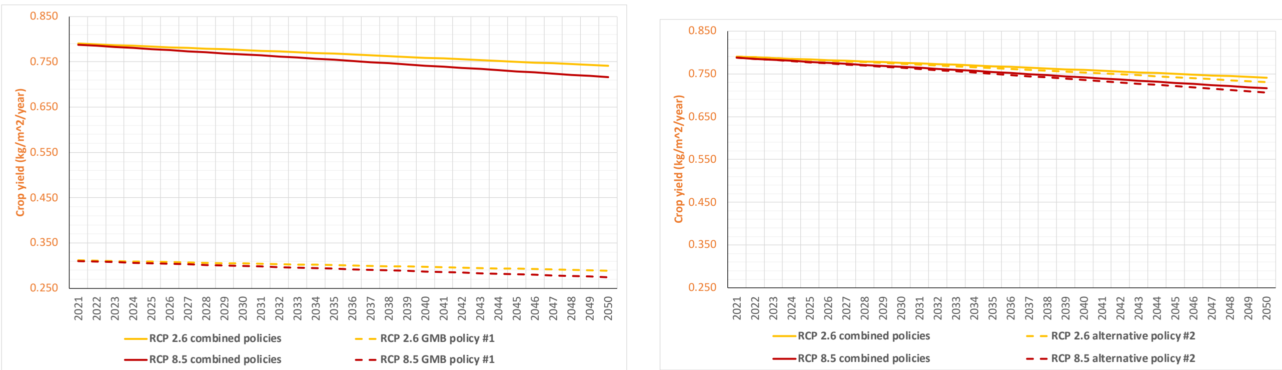


Figure 9.32. Performance against average crop yield under both RCP scenarios of GMB policy #1 and alternative policy #2 applied simultaneously compared to (a) GMB policy #1 alone and (b) alternative policy #2 alone.

The impact on groundwater table height of their joint implementation, even if somewhat less positive than if focusing on (re)forestation only, is also better than both the base run and the performance of only alternative policy #2, which replaces current crops with others that are 50 % less water demanding (Figure 9.33). In other words, by converting a larger fraction of abandoned land to bioproductive land, GMB policy #1 helps replenish the groundwater stock, compensating for what would otherwise be lost if only alternative policy #2 were to be implemented.

a. b.

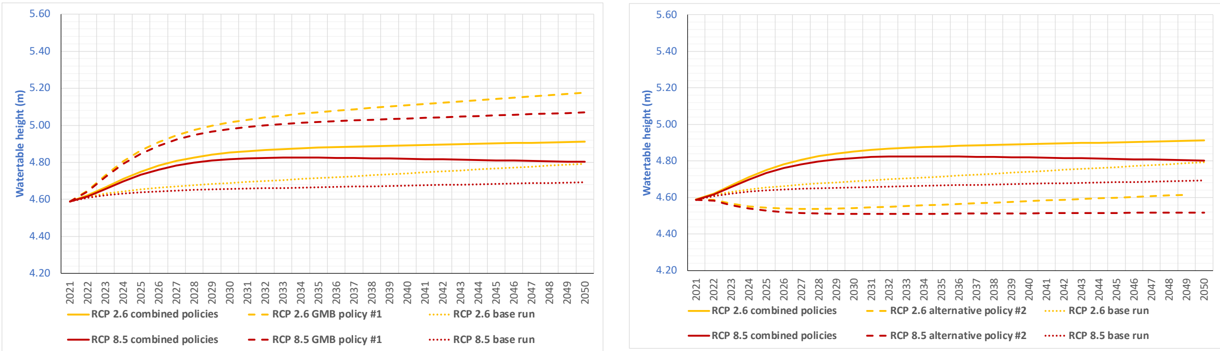


Figure 9.33. Performance against groundwater table height of GMB policy #1 and alternative policy #2 applied simultaneously compared to (a) GMB policy #1 only, and (b) alternative policy #2 only.

The impact on bioproductive land stock of simultaneously replacing crops with others that are 50 % less water demanding and increasing reforestation efforts 100-fold is also better than both that of the base run scenarios and of alternative policy #2 (Figure 9.34). Even if more of the abandoned land were reclaimed for agricultural purposes owing to better crop yields, doubling that policy with intensive (re)forestation of the other abandoned land would help provide the required habitat to restore biodiversity. Conditions of RCP scenarios do not make any significant difference

a. b.

Figure 9.34. Performance against bioproductive land area of GMB policy #1 and alternative policy #2 applied simultaneously compared to (a) GMB policy #1 only and (b) alternative policy #2 only.

In Figure 9.35, attention is drawn to the combined performance of both GMB policy #1 and alternative policies #2, #3, #4 and #6. As seen earlier, all of them positively impact average crop yields in Ikel SES (Figures 9.6 and 9.25). At the same time, alternative policies #4 and #6 have a positive impact on groundwater table height (Table 9.7) and a relatively negative one on bioproductive land stock, whereas alternative policies #2 and #3 have a relatively negative impact on both groundwater and bioproductive land. Should all these policies be implemented simultaneously, the outcomes on the longer term would be positive for all key variables. This indicates that intensive (re)forestation efforts would help compensate for a decrease in the height of groundwater table and in bioproductive land relative to the base runs under all RCP climate scenarios.

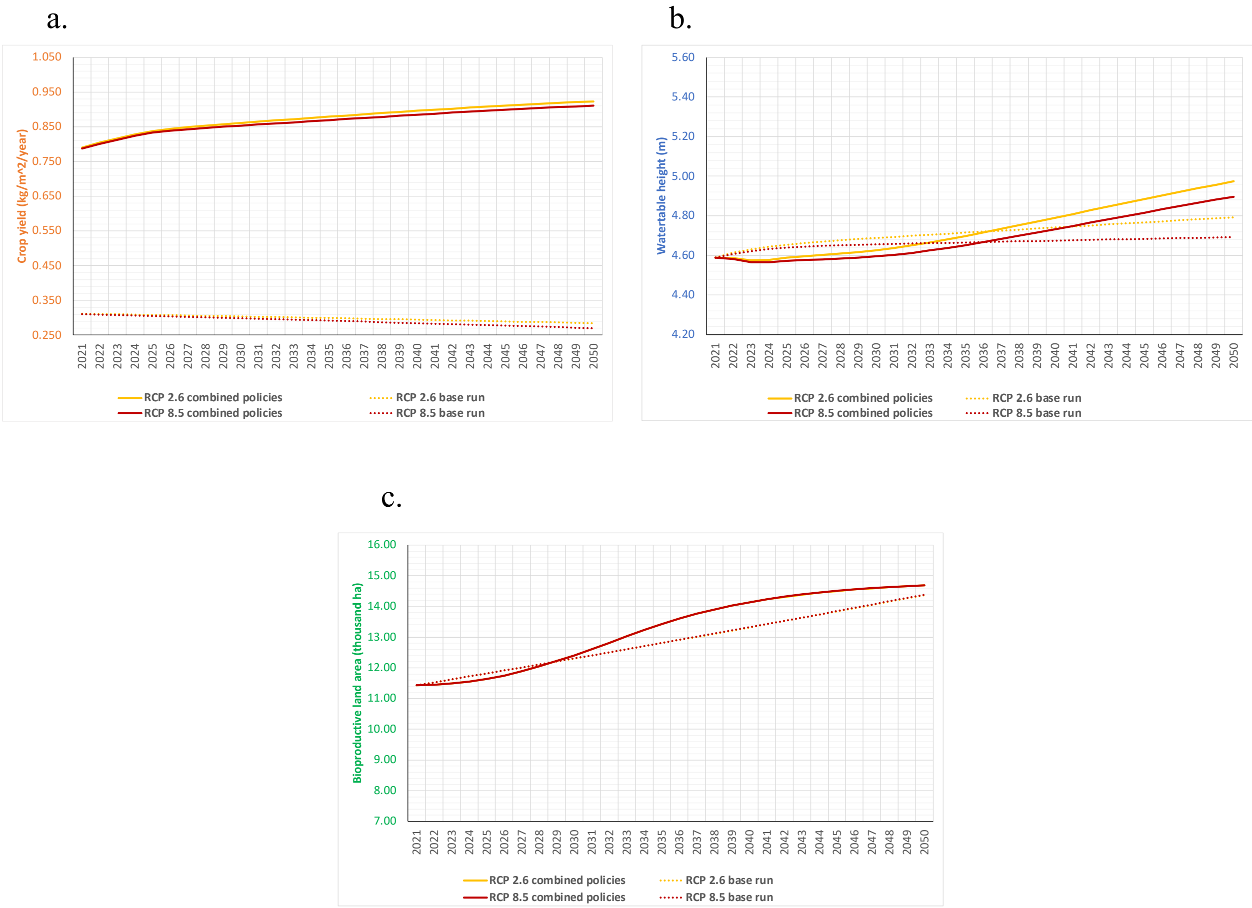


Figure 9.35. Performance of joint implementation of intensive reforestation policy proposed by GMB participants and alternative policies #2, #3, #4 and number #6 (Table 9.5) comparative to the base run, under all RCP climate scenarios for: (a) average crop yield in Ikel SES; (b) groundwater table height; (c) bioproductive land area.

Following combined policy implementation, average crop yield is significantly higher than the base run and increases continuously throughout the 2021-2050 period (Figure 9.35.a). The height of the groundwater table slightly declines initially compared to the base run but recovers the growth rate and increases faster than the base run towards the end of the period (Figure 9.35.b). The increase in bioproductive land initially slows down below the base run rate. Before long, it increases above that rate, and then continues to increase at a relatively slower rate. The total bioproductive area is above the base run level throughout nearly the entire period from the onset of policy implementation, including towards the end of the 2021-2050 period.

These things considered, what stands out from the analysis of listed alternative policies is that most of them positively impact the average crop yields, both individually and in various combinations. For groundwater, there are two alternative policies that help increase this stock. Regarding bioproductive land stock, the capacity to provide additional value is divided among the various alternative policies. While none of them is expected to reverse the projected increasing trends, some of them may reduce the speed of increase below the base run levels. However, in combination with the policy proposed by GMB participants that increases (re)forestation efforts 100-fold, these alternative policies still yield results that are above the base run levels.

9.4. Concluding Remarks on Policy Analysis

Formal model simulation has revealed that, within the set time frame, the change in the height of groundwater table and in the bioproductive land area is generally expected to be as desired by the GMB participants. The outcomes are contrary to their more pessimistic expectations (Figure 5.1).

The analysis of policies proposed by workshop participants of alternative policies has shown that there are multiple policies with the potential to produce outcomes that are even better than the base run situation under all RCP climate scenarios. Such outcomes are more aligned to what has been defined in the participatory process as ideal scenarios (Figure 5.1). This is favored by the potential increase in the annual precipitations under some RCP scenarios towards the middle of the 21st century. More precipitation contributes to the increase in yields and in the groundwater recharge. The decline in population allows for the abandoned arable lands to be directed towards providing habitats for biodiversity. The implementation of one, more or all these policies is a matter of priority and resources of local, regional and national policy-makers. It would result in a faster or slower change in these key variables.

Without doubt, these results arise following the development and analysis of Ikel CliRes within the boundaries of the discussed assumptions. That being the case, agricultural production, for example, is sensitive to the value and change in the runoff and infiltration coefficients on arable lands: the higher the coefficients, the lower the crop yields. Moreover, there is an unequivocal dependence of agricultural production on rainfall erosivity factor. If the latter exceeds certain values for a long time, it could lead to crop failure. Groundwater table, too, is sensitive to runoff and infiltration coefficients. As seen in the policy analysis above, land uses that have lower runoff and higher infiltration and percolation rates help groundwater stock recharge faster. Groundwater table height is also very sensitive to the equilibrium or piezometric level of the groundwater stock, and to its recharge time. On the other hand, bioproductive land area in this model is very sensitive to the rainfall erosivity factor and to land use conversion fractions.

A note of caution is due: the values attributed to these parameters are literature and expert opinion-based approximations that help understand the overall dynamics but might yield over-optimistic scenarios. Having a more precise estimation of such data-scarce parameters could provide deeper insights as to the effort need to be undertaken though policy interventions to achieve the desired outcomes. Of particular interest are the annual and seasonal variations in climate data, which are represented neither in detail, nor exhaustively in this model.

These things considered, a resilience assessment to such impacts is presented and discussed in the next chapter to provide a better insight into how the key variables might perform in case of climate change impacts that can be simulated by Ikel CliRes.

10. POLICY DESIGN FOR BUILDING RESILIENCE TO CLIMATE CHANGE IMPACTS

Resilience is the capacity of a system to absorb disruptive changes while keeping the same function, structure and feedbacks. Rather than optimizing Ikel SES for a narrow, isolated purpose such as agricultural production, enhancing the resilience of the system as a whole would ask for policies and actions that simultaneously improve the situation in multiple key variables. Policy analysis conducted in the previous chapter has pointed towards how that could be done. Yet, to enhance the resilience of Ikel SES to climate change impacts, it is important to understand not only the trends in climate scenarios, but also the way in which Ikel SES would react to specific shocks that come with changing climate conditions. Recognizing which properties of the complex system affect its capacity to avoid or facilitate changes can provide leverage points for well-placed and most cost-effective interventions.

In this chapter, the climate impacts are first described and operationalized. After that, the behavior of key variables is compared under base run conditions and climate-stressed conditions. For the key variables and the situations where the behavior following the impact is affected negatively, a range of policies are tested, based on the results of policy analysis presented in the previous chapter. At the end of this chapter, a number of reflections are set forth with the aim to provide insights into Ikel SES attributes that can help build its resilience and into leverage points that policy- and decision-makers can make use of to that end.

10.1. Selected Climate Change Impact Scenarios

RCP scenarios discussed above estimate an increase in temperature with an annual average of 1.2-6°C by 2100 compared to the average for the 1986-2005 baseline period (Figure 2.3). Conversely, scenarios regarding precipitation are more divergent, with some indicating decrease, and some indicating their increase in certain regions of the country by 2100. Until 2050, the RCP scenarios do not differ greatly in terms of temperature and precipitation. Data generated by MarkSim® DSSAT website (ILRI, 2021) suggests an increasing trend in average annual temperature for both scenarios over the next three decades (Figure 9.2). For precipitation trends, MarkSim® data-based projection for RCP 2.6 scenario indicates a slightly increasing trend, whereas for RCP 8.5 precipitation are expected to slightly decrease between 2021-2050 (Figure 9.1).

Besides average annual temperatures and annual precipitation values, other related characteristics are likely to have a significant impact, such as rainfall intensity, variations in extreme temperatures, and changes in seasonal patterns. Due to its time resolution (annual time step, i.e., low seasonal resolution), use of trends in climate data rather than exact annual predictions for annual precipitation and average annual temperature variables, and corresponding structural elements of the model, Ikel CliRes does not account for seasonal impacts like temperatures and precipitation at the onset of the crop germination and seedling establishment periods, seasonal precipitations or lack thereof and the duration of dry spells. Consequently, not all possible climate change impacts or "shocks" are discussed in this chapter. However, some relevant impacts are investigated and discussed in the matter of resilience building. To this end, the list of climate change impacts subjected to policy design for resilience building is detailed in Table 10.1 below.

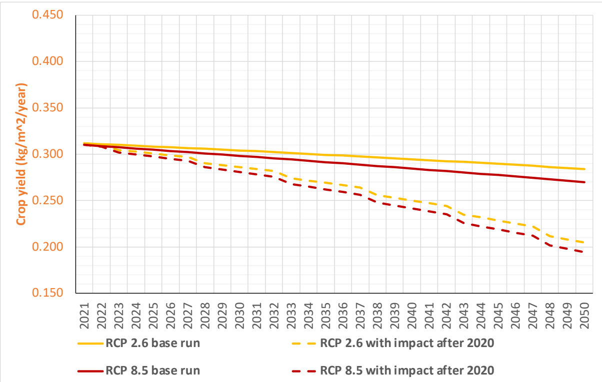
Table 10.1. Climate change impacts subjected to analysis for resilience building using Ikel CliRes model, and their operationalization.

Climate change impact scenarios	Operationalization for resilience analysis in Ikel CliRes model
Scenario #1: More intense precipitations. Climate change projections indicate that while towards mid-century, precipitations in central regions of R. Moldova might increase slightly, they are expected to change their patters: less frequent, but more intense rainfalls.	As rainfalls become more intense, the erosivity factor increases. This impact is simulated by increasing the rainfall erosivity factor (*R factor*) two-fold compared to its current value and including five-fold more intense storms every five years.
Scenario #2: Higher evaporation rates due to higher temperatures. Annual average temperatures are expected to increase, with more episodes of extremely hot temperatures in summer alongside warmer winters. With higher temperatures, the evaporation happens faster.	As water evaporates faster, a smaller fraction of the precipitation water infiltrates to the deeper layers to build up the base flow and to percolate to the confined aquifer. To simulate this impact, *infiltration coefficients* on all types of land use are reduced to half of their current value.
Scenario #3: More intense precipitations and higher evaporation rates due to higher temperatures.	This scenario incorporates both impacts described before. Thus, rainfall erosivity factor and infiltration coefficients are adjusted as mentioned above for scenarios #1 and #2.

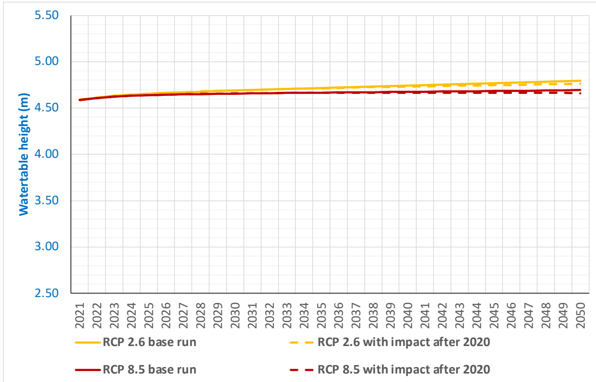
In Figures 10.1 – 10.3, each of the above impact scenarios is first presented as it affects the key variables compared to the base run. In the following sections, a range of policies are tested to identify those that help build resilience to the said impacts.

As a result of impact scenario #1 – more intense precipitations that lead to a higher rainfall erosivity factor – all three key variables are negatively affected (Figure 10.1). Thus, groundwater and bioproductive land stocks continue to increase, albeit at a smaller rate. This is still in line with the desired behavior of these variables as expressed by the stakeholder group participating in the model building. In contrast, crop yield is impacted significantly to the extent that the already declining trend in crop yields becomes even steeper due to precipitations being more intense and erosive (Figure 10.1.a).

a.



b.



c.

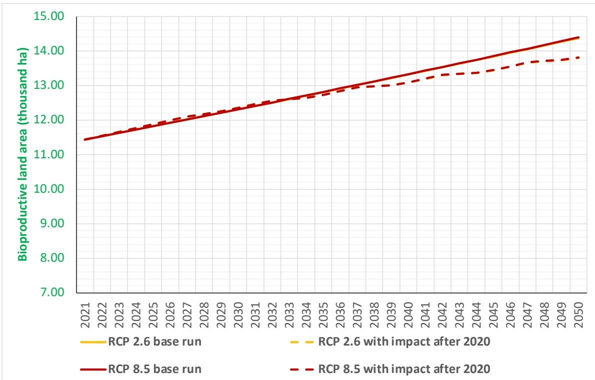


Figure 10.1. Impact of more intense precipitations (impact scenario #1) on: (a) average crop yields; (b) groundwater table height; (c) bioproductive land area under both RCP climate scenarios.

Scenario #2 – higher evaporation rates due to higher temperatures – has a mixed impact on the key variables (Figure 10.2). On the one hand, it favors higher crop yields in the beginning, as higher evaporation rates combined with enough water in the rootzone are favorable for the yields (Figure 10.2.a). On the other hand, it causes a somewhat slower increase in bioproductive land compared to the base run, but more importantly - a drop in the level of groundwater table (Figure 10.2.b). This is caused by water spending less time in the soil before evaporating, and, consequently, not managing to percolate to the deeper layers and to replenish the groundwater stock.

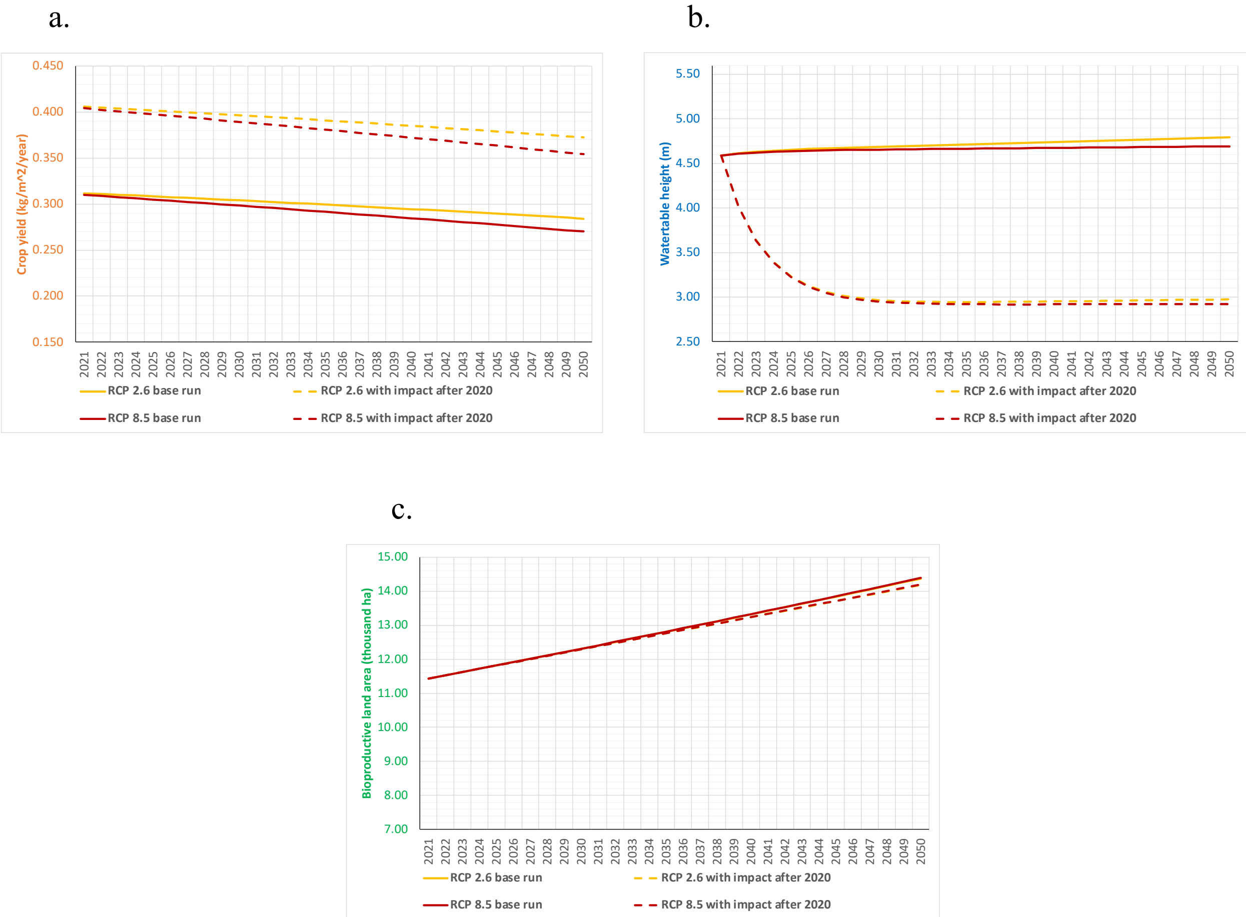
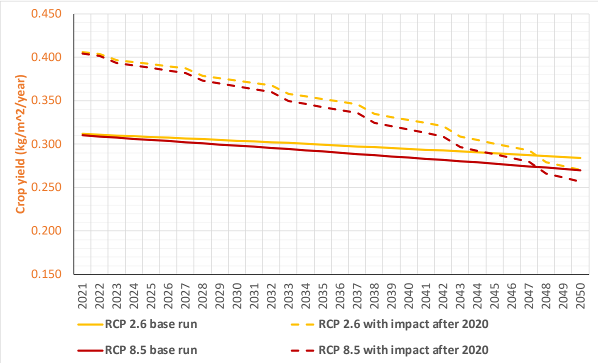


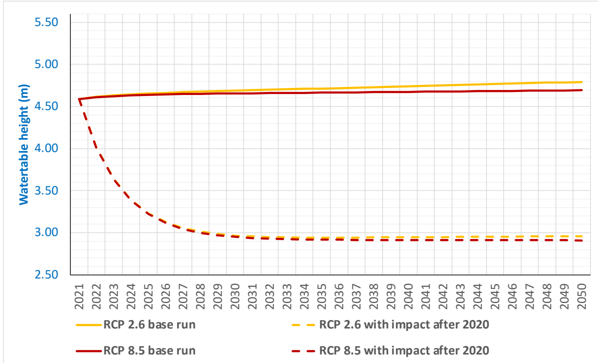
Figure 10.2. Impact of higher evaporation rates due to higher temperatures (impact scenario #2) on: (a) average crop yields in Ikel SES; (b) groundwater table height; (c) bioproductive land area under all three RCP climate scenarios.

The combined impact of higher rainfall erosivity and higher evaporation rates (impact scenario #3) because of increasing temperatures and more intense precipitations – the most expected scenario under both RCPs – negatively affects all key variables (Figure 10.3). While higher evaporation rates provide an initial boost to crop yields, this positive effect is quickly deterred by the dramatic impact of rainfall erosivity. As a result, by the end of the analyzed period, the average crop yields are below the base run levels (Figure 10.3.a). The level of groundwater table decreases much below the base run level and remains this way throughout the 2021-2050 period (Figure 10.3.b). Bioproductive land area continues to increase at a slower rate compared to the base run (Figure 10.3.c). It should be noted, however, that the quality of the vegetation cover on the bioproductive land is likely to be altered because of declining soil thickness.

a.



b.



c.

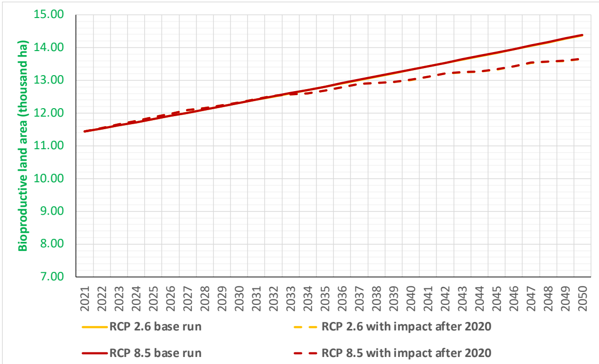


Figure 10.3. Cumulated impact of more intense precipitations and higher evaporation rates (impact scenario #3) on: (a) average crop yields in Ikel SES; (b) groundwater table height; (c) bioproductive land area under all three RCP climate scenarios.

To sum up, the selected impacts provide a glimpse into how (much) the climate change impacts might affect the three key variables of interest in Ikel SES. While the list is not exhaustive, the most notable is the effect on crop yields and groundwater stock of the most likely impact scenario: increasing temperatures and more intense precipitations lead to dramatic changes in both key variables. This calls for policy interventions that could prevent or at least smoothen the decline.

As detailed in the chapter on methodological approach, a resilience perspective either allows for undesirable states to be transformed into desirable ones or help buffer disturbance and generate adaptive capacity in order to cope with the stresses caused by climate change impacts (Boyd et al., 2008). In the next section, a scrutiny of policies is carried out to identify the ones which can help achieve the objective of building the desirable resilience of the three key variables to increasing rainfall erosivity and higher evaporation rates in Ikel SES.

10.2. Resilience Assessment to Climate Change Impacts

In this section, the focus is on how the stakeholders can build the desirable resilience of the three key variables to climate change impacts that were enumerated and described in the previous section. In the first part, policies are proposed that help reduce the decline in crop yields caused by increased rainfall erosivity (impact scenario #1) without causing an undesirable regime shift in the behavior of the other two key variables. Then, the same approach is undertaken to reverse the decline in groundwater table following the increased evaporation rate (impact scenario #2). Lastly, a set of policies are presented and proposed to help reverse the negative consequences for the key variables following the cumulated impact of more intense rainfalls and high evaporation rates (impact scenario #3). These policies are arguably the most helpful for building the resilience of Ikel SES to these specific climate change impacts. To help with the analysis, the policies are compared against a set of resilience features.

10.2.1. Resilience of Average Crop Yield to Increased Rainfall Erosivity

Impact scenario #1 has shown that increased rainfall erosivity may lead to a significant and constant decline of crop yields in Ikel SES (Figure 10.1), while reducing the speed of increase in the groundwater table and bioproductive land stock. At the same time, policy analysis has pointed to several policies that are conducive for better crop yields, namely (in order of policy performance):

1. **Alternative policy #2:** Adoption of crops with PET that is 50 % less than the base run value.
2. **Alternative policy #1:** Adoption of crop varieties that are expected to yield 50 % more yield for the same (current) PET value.
3. **Alternative policy #4:** Ensuring that 10-times more people among Ikel SES population work in agriculture.
4. **Alternative policy #3:** Ensuring constant implementation of better soil conservation practices that result in a 50 % decrease in the P factor.
5. **GMB policy #1:** Increasing 100-fold and sustain (re)forestation efforts.
6. **Alternative policy #6:** Supporting the uptake of technologies that require five times less workforce to cultivate crops.

Out of considerations for brevity and higher relevance, these policies are demonstrated on average crop yield under RCP 8.5 climate scenario, which is the least favorable of the two RCP scenarios (highest temperatures, least precipitation).

Figure 10.4 illustrates the extent to which the above policies are helpful for ensuring better crops with policy than without a policy. While all these policies result in better yields compared to impact scenario #1, none of them successfully reverses the declining trend in the behavior of agricultural productivity. In this situation, the objective of building the resilience of crop yields translates into buffering the disturbance and allowing more time for the system to generate adaptive capacity and cope with the stresses caused by climate change impacts, such as, for example, identifying alternative sources of income and/or securing alternative sources of food. To this end, four policies stand out among all, namely alternative policies #1, #2, #3 and #4.

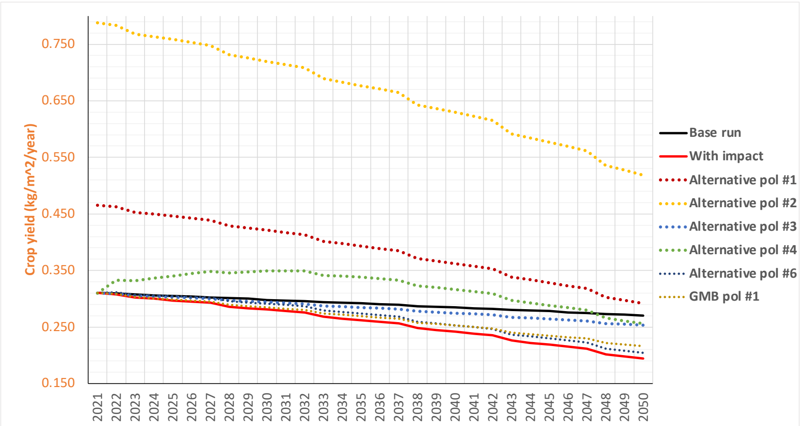


Figure 10.4. Performance of various policies in relation to the declining trend in average crop yield compared to the base run behavior and to the behavior following the increased rainfall erosivity after 2020.

Alternative policies #1 and #2, which imply the use of less water intensive crops, provide significantly better yields, compared to the impact scenario alone. Alternative policy #3 focusing on better soil conservation is successful in slowing down the rate of decline in crop yields due to soil erosion. Implementation of Alternative policy #4 that injects additional workforce, helps change the trajectory of trend in crop yields, albeit for a limited period, and is the only policy that manages to achieve that.

Figure 10.5 illustrates the fact that not even the simultaneous implementation of three of the four alternative policies can reverse the declining trend in crop yields fueled by the declining annual precipitation and increased soil loss that depletes the topsoil (Figure 10.6). Alternative policy #1 is omitted, since its impact is similar but smaller than the impact of policy #2.

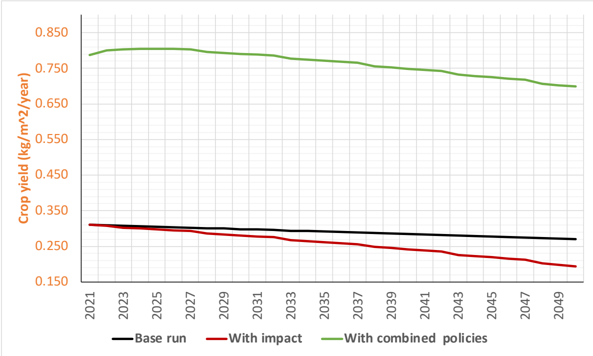


Figure 10.5. Crop yield with the combined implementation of Alternative policies #2, #3 and #4.

a. b.

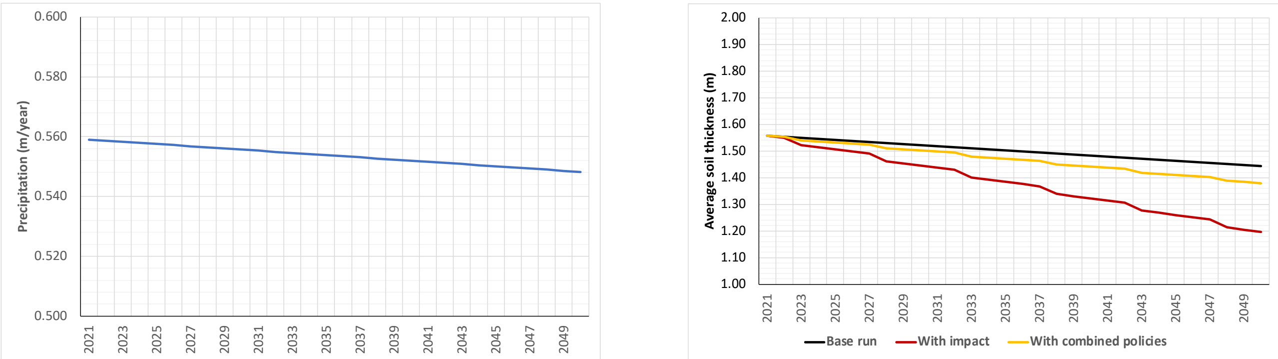


Figure 10.6. Change in (a) annual precipitation and (b) average soil thickness in Ikel SES, associated with the impact of increased rainfall erosivity under RCP 8.5 climate scenario.

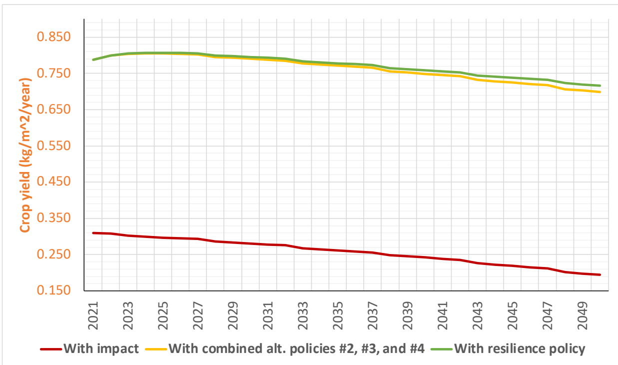
Besides failing to reverse the negative impact of climate change on crop yields, joint implementation of the three alternative policies does not lead to a desirable regime shift in the behavior pattern of the groundwater stock, while also reducing the speed of increase in the bioproductive land area (Figure 10.7).

a. b.

Figure 10.7. Impact on (a) groundwater table and (b) bioproductive land area of joint implementation of Alternative policies #2, #3 and #4.

However, when cultivating less water intensive crops, significantly improving soil conservation practices and ensuring availability of additional workforce are also combined with GMB policy #1, i.e., increasing 100-fold and sustaining these (re)forestation efforts, the situation looks different. On its own, increasing (re)forestation efforts does not excel in buffering the impact of increased rainfall erosivity on crop yields (Figure 10.4); in combination with Alternative policies #2, #3 and #4, it doesn't bring a notable improvement on crop yields either. Yet, the combination of these four policies does help increase the resilience of agricultural productivity to rainfall erosivity while also increasing the resilience of the other two key variables. That is because bioproductive land is increased directly, which in turn helps retain water from precipitation by reducing runoff and facilitating infiltration. Such positive outcomes render this combination of GMB and Alternative policies into a Resilience policy. The relative impact on the three key variables of the combined implementation of Alternative policies #2, #3 and #4 and of this Resilience policy #1 is illustrated in Figure 10.8 below.

a.



b.

c.

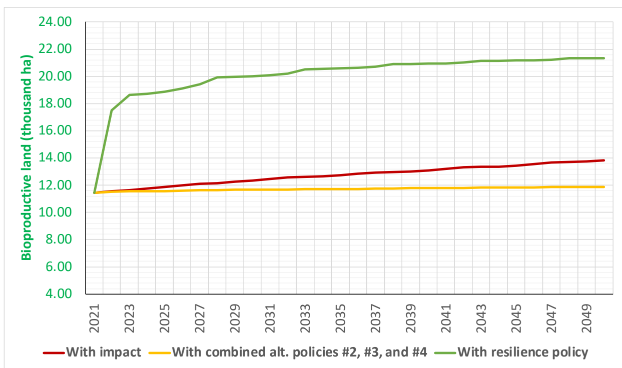


Figure 10.8. Performance of Resilience policy #1 in relation to (a) average crop yield, (b) groundwater table, and (c) bioproductive land, compared to the effects of combined alternative policies #2, #3 and #4 and to those of impact scenario #2 (increased rainfall erosivity).

Based on the above, it becomes evident then that a resilience policy for Ikel SES requires a set of leverage points to be acted upon so as to help build the resilience of average crop yield to increased rainfall erosivity while also enhancing the resilience of the system as a whole rather than optimizing it for a single purpose. Therefore, it can be considered that combining the adoption of crops with PET that is 50 % less than the base run value with constant implementation of better soil conservation practices that result in a 50 % decrease in the P factor and ensuring that 10-times more people among Ikel SES population work in agriculture, while also increasing 100-fold the (re)forestation efforts and sustaining them throughout the 30 year period is what would constitute a resilience policy consistent with the objective of enhancing the resilience of Ikel SES to impact scenario #1.

10.2.2. Resilience of Groundwater Table to Higher Evaporation Rates

Impact scenario #2 shows how higher evaporation rates due to higher temperatures may lead to a steep decline in groundwater table height in Ikel SES that does not manage to recover by 2050 to its pre-disturbance levels within the analyzed time frame (Figure 10.2.b). On the other hand, this impact scenario only slightly reduces the speed of increase in bioproductive land (Figure 10.2.c), while also leading to an increase in the average crop yield (Figure 10.2.a). Policy analysis conducted previously suggests that some policies can provide additional increase in groundwater table height compared to what is considered the base run under RCP 8.5 climate scenario. These policies are (in order of policy performance):

1. **Alternative policy #4:** Ensure that 10-times more people among Ikel SES population work in agriculture.
2. **GMB policy #1:** Increase 100-fold and sustain (re)forestation efforts
3. **Alternative policy #6:** Ensure the uptake of technologies that require five times less workforce to cultivate crops.

The relative success of the above policies in addressing the decline of groundwater table under the least favorable RCP 8.5 climate scenario is illustrated in Figure 10.9.

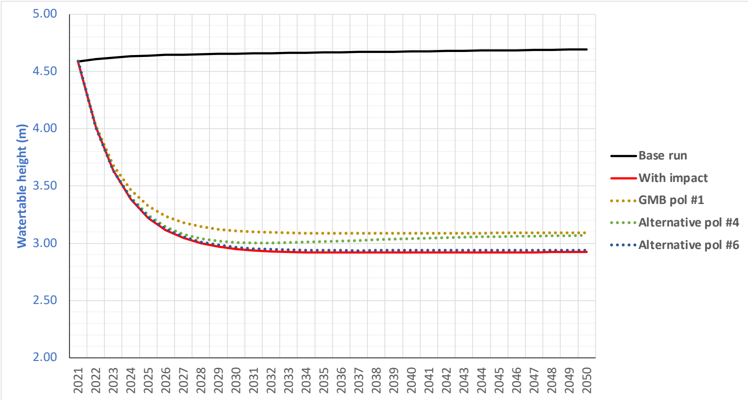


Figure 10.9. Performance of various policies in relation to the decline of groundwater table height compared to the behavior of this key variable following the sudden increase in evaporation rates due to higher temperatures after 2020 (impact scenario #2) and to the base run behavior.

All three policies provide some improvement compared to this particular impact scenario, with GMB policy #1 being the most effective of the three. However, none of them manages to restore the water table height to its previous levels be it individually (Figure 10.9) or implemented together (Figure 10.10).

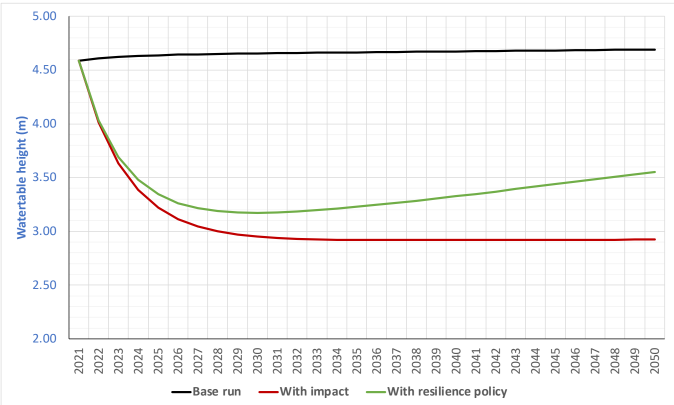


Figure 10.10. Performance in relation to the decline of groundwater of all three policies implemented together.

The implementation of all three policies combined has a positive impact, nonetheless. Firstly, even if by 2050 groundwater table does not manage to fully recover, when applied together, these policies help reduce the magnitude of disturbance. Secondly, they help increase the speed of recovery which would otherwise be rather slow after the impact. Since this combination helps positively alter the behavior of groundwater after the impact, it can be considered a resilience policy.

In addition to the positive impact on groundwater table, this policy can also lead to a positive impact on both the average crop yield and on the bioproductive land area (Figure 10.11). In both cases, the behavior of these two key variable with Resilience policy #2 implemented outperforms both the base run behavior and the behavior following climate change impacts in the 2021-2050 time frame.

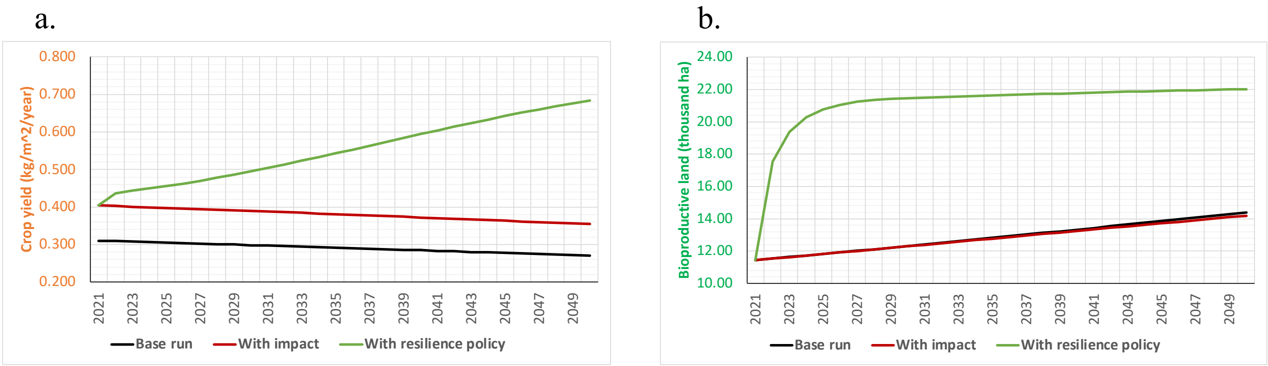


Figure 10.11. Impact of Resilience policy #2 on the other two key variables: (a) average crop yield and (b) bioproductive land area.

The increase in bioproductive land stock (Figure 10.11.b) is a direct consequence of intensive (re)forestation. The increase in average crop yield figures for Ikel SES, on the other hand, is a result of the increase in workforce and workforce efficiency in agriculture and the subsequent increased share of irrigated arable lands in the total, albeit decreasing, arable land area (Figure 10.12).

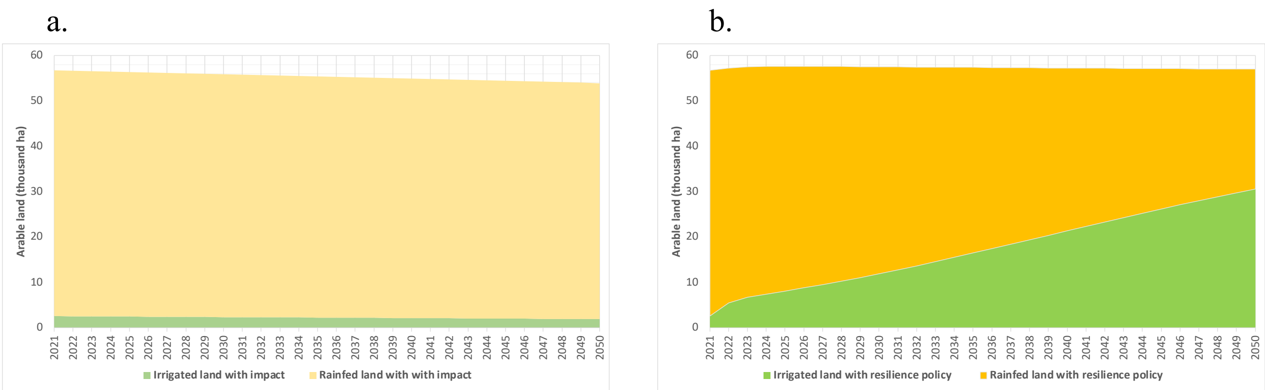


Figure 10.12. Share of irrigated and rainfed arable lands in the total arable land area (a) without Resilience policy #2, and (b) with Resilience policy #2.

To further aid the recovery and resilience of groundwater table to higher evaporation rates, an addition to the Resilience policy #2 is tested: *increasing the percolation rate of precipitation to the confined aquifer*. Percolation fraction is one of the data-scarce parameters. Therefore, it is likely that having a more accurate estimate of this value alone will help better assess and build the resilience of the groundwater table to impact scenario #2. At the same time, this intervention can be undertaken within the boundaries of Ikel SES by its stakeholders. Figure 10.13.a shows how increasing the percolation rate by 50 % in addition to implementation of GMB policy #1 and alternative policies #4 and #6 can help reduce the magnitude of disturbance, increase the speed of recovery and ensure the recovery of the behavior for this variable by 2050. This would also preserve the better performance of the other two key variables compared to impact scenario #2 (Figures 10.13.b and 10.13.c), rendering the combination of four interventions as what could be called Resilience policy #3.

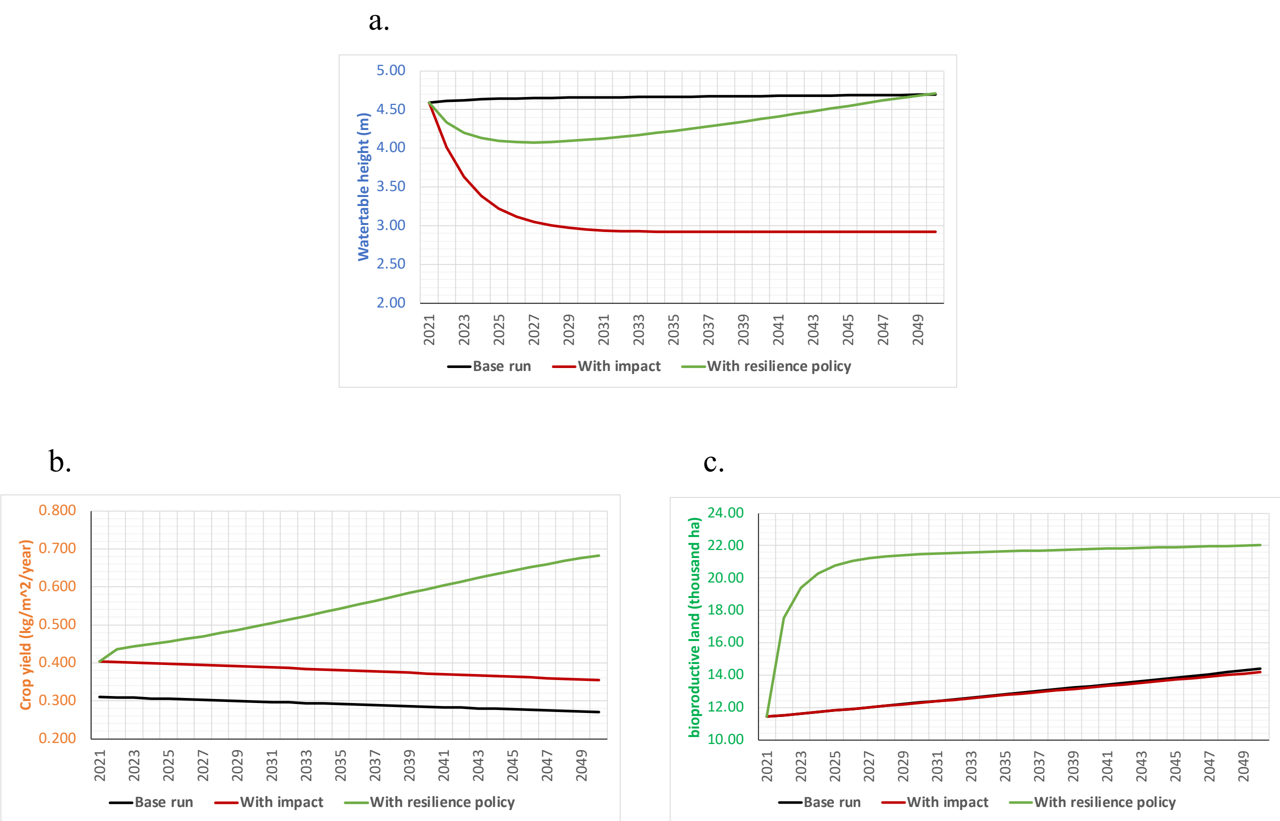


Figure 10.13. Impact of resilience policy that increases the percolation rate in addition to Resilience policy #2 on (a) groundwater table height; (b) average crop yield; and (c) bioproductive land area.

These things considered, it becomes clear that although some of the policies discussed in the previous sections can help improve certain resilience characteristics of groundwater table to higher evaporation rates, additional efforts are needed to ensure the full recovery of this key variable. In this context, facilitating a higher percolation rate can be such an additional policy.

10.2.3. Resilience of Average Crop Yield and Groundwater Table to Increased Rainfall Erosivity and Higher Evaporation Rates

Impact scenario #3 demonstrated that the cumulated impact of more intense precipitations and higher evaporation rates leads to a dramatic decrease in average crop yield and in groundwater table compared to the base run, and a slowing down in the increase of bioproductive land stock (Figure 10.3). Namely, average crop yields in Ikel SES decline continuously, like in impact scenario #1, but with a smaller magnitude of disturbance. At the same time, almost identically to impact scenario #2, groundwater table declines sharply and does not manage to recover throughout the entire period in focus. Of the two RCP climate scenarios, the situation is worse in case of RCP 8.5 temperature and precipitation conditions.

Based on the previous analysis, the following set of resilience-building policies are expected to provide the best results for average crop yield and groundwater table behavior:

1. **Resilience policy #1:** Joint implementation of GMB policy #1 and alternative policies #2, #3 and #4, i.e., increasing 100-fold and sustaining (re)forestation efforts, adoption of crops with PET that is 50 % less than the base run value, ensuring constant implementation of better soil conservation practices that result in a 50 % decrease in the P factor and ensuring that 10-times more people among Ikel SES population work in agriculture.
2. **Resilience policy #2:** Joint implementation of GMB policy #1 and alternative policies #4 and #6, i.e., increased and sustained (re)forestation efforts, ensuring that 10-times more people among Ikel SES population work in agriculture, and ensuring the uptake of technologies that require five times less workforce to cultivate crops.
3. **Resilience policy #3:** Joint implementation of resilience policy #2 and increasing the percolation rate of precipitation to the confined aquifer by 50 %.

Figures 10.14 and 10.15 illustrate how the above policies contribute to building the resilience to climate impacts of average crop yield in Ikel SES and of groundwater table respectively, while Figure 10.16 show the response of bioproductive land stock to these policies.

For average crop yield in Ikel SES, all three policies provide conditions for building its desired resilience to the extent that by the end of the period in question, average yields do not decline below the base run. However, the way resilience is built varies (Figure 10.14).

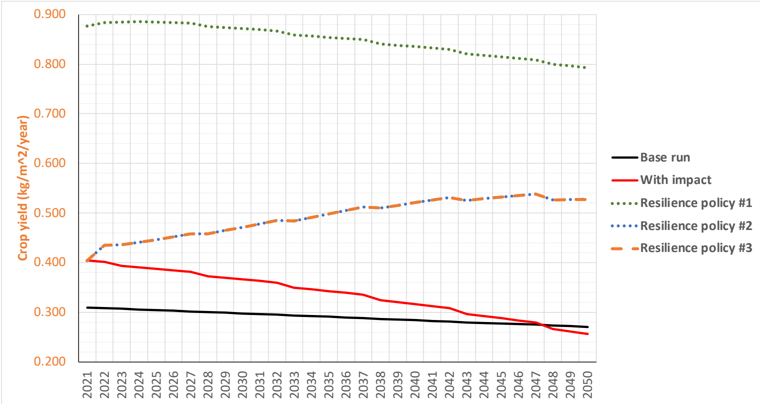


Figure 10.14. Performance of resilience policies in relation to the decline of average crop yield compared to the base run behavior and to the behavior in case of impact scenario #3.

There are two main findings from testing the three resilience policies against the behavior of average crop yield in Ikel SES. One is that Resilience policies #2 and #3 perform identically. The second finding is that the way policy #1 and policy #2 (and #3) build this key variable's resilience is rather different.

From an engineering resilience perspective, all policies enhance the system's *hardness* and *robustness* – its ability to withstand this climatic disturbance without a negative change in the performance of the outcome and without significant loss of performance respectively. In all three situations, the yield would be higher than with impact and no resilience policies over the entire period. From this perspective, policy #1 is the best performing one.

From an ecological resilience perspective, policy #1 enhances this system's *elasticity* and *index of resilience* – its ability to withstand the disturbance without changing to a different steady state and the probability of keeping the current regime respectively (Herrera, 2017). In more concrete terms, the regime shift does not happen, and the behavior pattern of this key variable remains a decreasing one. This, according to resilience objectives stated by the stakeholders, is not a desirable outcome. In contrast, policies #2 and #3 prompt a regime shift, meaning that the declining trajectory of average crop yields for this period is changed to an increasing one – an outcome aligned with the desired outcome.

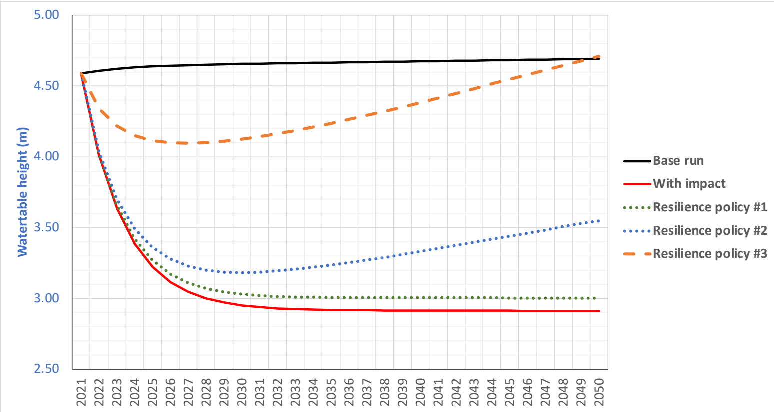


Figure 10.15. Performance of resilience policies in relation to the decline of groundwater table height compared to the base run behavior and to the behavior in case of impact scenario #3.

Similar to crop yield, in relation to groundwater table the results of the three resilience policies are better than no resilience policy at all. Nevertheless, only policy #3 is successful in restoring the level of the groundwater to what would be its initial state (Figure 10.15).

From an engineering resilience perspective, resilience policy #3 is the most helpful in increasing the system's *hardness*, followed by policy #2. In case of policy #1, it does not start recovering in the given period; it is therefore unclear if the system recovers at all with this policy alone in place. In terms of *robustness*, the hierarchy is the same. The situation is similar for *recover rapidity*, as well, i.e., the average rate at which the system returns to equilibrium after a disturbance.

From the point of view of ecological resilience, policy #1 conserves the *elasticity* and *resilience index* of the system, whereby the behavior of the groundwater table would maintain a slightly declining trajectory. However, this outcome is not desirable. A desirable one would be to have a regime shift, and to see the level of groundwater increasing. To that end, resilience policy #3 is the most effective, followed by policy #2.

Based on the above, it follows that to achieve the best possible desirable outcomes, the most conducive of the resilience policies is policy #3. It is both supportive of a trajectory that is more likely to preserve the equilibrium of average crop yield behavior and is the only one that is successful in restoring the level of the groundwater within the period in focus, while also providing maximum additional growth to the bioproductive land area (Figure 10.16).

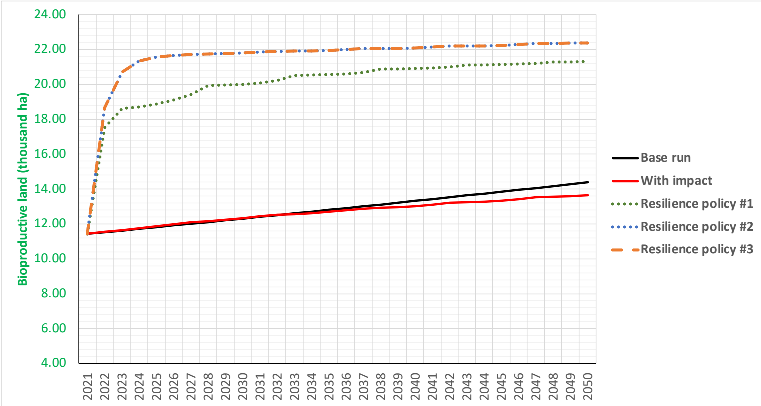


Figure 10.16. Performance of the three resilience policies in relation to the bioproductive land area.

10.3. Concluding Remarks on Policy Design for Building Resilience

In this chapter I have considered several possible climate change impacts that can affect Ikel SES and can be simulated by Ikel CliRes model. Then, the specific impact on the key variables was analyzed and best performing of the alternative policies and of those proposed by GMB participants were tested to check the extent to which they can help increase the resilience of average crop yield, groundwater table and bioproductive land to the specified impacts.

The results of this resilience assessment point to the fact that Ikel SES is characterized by several resilience features that are undesirable and misaligned to the needs of the stakeholders involved in this resilience assessment exercise. It has also been shown that resilience policies are more complex than any of the individual policies discussed in the policy analysis chapter, and that their success is tightly connected to clarifying the desired performance of the outcome function (i.e., resilience objective). That is because, the resilience policies put forward in this chapter work best for some of the variables in some ways under certain climate change impact.

According to the reference modes put forward by GMB participants (Figure 5.1), the resilience policy that performs best across the key variables for all three climate impact scenarios discussed in this chapter is the one referred to as Resilience policy #3. It includes simultaneously an ambitious increase and sustaining of (re)forestation efforts, ensuring that significantly more people work in agriculture throughout the 30-year period, ensuring the uptake of technologies that require significantly less workforce to cultivate crops and increasing the percolation rate of precipitation to the groundwater table. Naturally, this should be regarded within the limitations of the model architecture and of the assumptions underlying both the model and the analysis.

11. CONCLUSIONS AND RECOMMENDATIONS

The ultimate purpose of this research effort is to support the development and effective implementation of policies for climate change adaptation in developing countries. I propose that through a formal systemic approach, we can arrive at effective policy conclusions that can yield better performance patterns for several issues of major regional concern. To support the development of such policies, the approach would integrate in a coherent process a set of concepts, tools, techniques and processes from SES and resilience framework and system dynamics modeling. Ultimately, the process would:

- Help policymakers, decisionmakers and other stakeholders better understand the socio-ecological system under focus, and what builds or erodes its resilience to climate-change impacts.
- Give policy- and decisionmakers a reliable tool to experiment long-term impact decisions in a consequence-free environment.
- Foster the commitment of stakeholders to the implementation of policies aimed at building the system's resilience to climate change impacts.

Thus, I design, build and implement a client-based process under data scarcity conditions in a network governance setting within a developing country. The process involves making an extensive analysis of a complex socio-ecological problem to single out policies that are helpful in meeting a set of development objectives: improving crop yields, preserving groundwater resources and securing habitats for biodiversity conservation – all this while facing the uncertainty of anticipated climate change impacts.

To this end, first a computer simulation model – Ikel CliRes – has been developed using a participatory approach. This approach combined several methods, techniques and tools from two related fields: system dynamics and resilience of socio-ecological systems. The two have many things in common, but prior to this research, they have not been combined much in the literature, and are not known to have been combined in practice. I have merged them in ways that yielded better results for the purpose of this research than either of them used separately.

Following this, the model has been used to analyze several policies, and to design a set of policy interventions that would increase the desirable resilience of a socio-ecological system within the boundaries of Ikel watershed to some of the known climate change impacts: increasing temperatures, decreasing annual precipitation and increasing rainfall intensity. Policies have been discussed with decision makers and their implementation is now underway pointing to the effectiveness of this approach. Main findings of this research are presented in the following sections.

11.1. Findings

As the relationship between science, policy, and practice changes, the demand increases on research to engage more productively with stakeholders and end users to ensure positive outcomes for all parties. Consistent with previous findings, mapping and engaging key actors has helped identify and articulate the current social and environmental issues in a way that ensured the relevance of the developed model. It has also helped make sure that the resulting policy recommendations address real problems, not merely an intellectually engaging challenge. In addition, the design of the engagement process has contributed to empowering each individual participant in the GMB process to partake in building the model and finding the solutions without externally imposing them.

SEI has been especially useful for initiating the participatory approach in a network governance setting. It has helped with identifying the problem and defining the dynamic hypothesis and informing the GMB process. In particular, it has proven helpful in providing guidance on how to engage relevant stakeholders and how to build a stakeholder group when there is no single lead institution or executive, and when the problem at stake goes beyond the responsibilities of one single organization or institution. Likewise, GMB process and scripts have provided a clear structure, tools, and the vocabulary that help resilience practitioners that use SEI:

- Have a common language when discussing and analyzing the process, challenges, success, and outcomes of facilitated events, including the conceptual model.
- Conduct workshops in which participants build the conceptual model themselves, with the support of the facilitator, making the conceptual model more comprehensible for participants.
- Provide a transparent, informed, and facilitated process, where participants build a shared mental model of the system and develop ownership of the outcomes.
- Acquire a conceptual model that is accurate enough to constitute the basis for a formal computer simulation model that could potentially help measure resilience.

All in all, coupled use of SEI and GMB has provided for a frictionless transition from stakeholder led development of a conceptual model toward a formal SD model. The qualitative model developed through GMB workshops and interaction with stakeholders allowed participants to propose policies that they believed would increase the resilience of Ikel watershed to climate change impacts.

Scenario analyses of the conceptual model did not allow stakeholders to understand how various policies would impact the system on a long term. However, it did allow them to gain insights, to develop a common mental model of the system, and to prioritize actions for Ikel watershed, increasing consensus, feeling of ownership of the outcomes, and commitment that prompts action. Indeed, one of the notable results in the earlier stages of this research was the adoption and implementation of a local climate change adaptation plan for Ikel watershed.

Even if qualitative conceptual models alone are insufficient for testing various policy options in consequence-free environments, the insights gained by GMB participants made it possible for them to come up with interventions that were later confirmed to be effective adaptation policies and enhance the effectiveness of resilience policies. Following are approximates of the quotes from some of the people who participated in the interviews: “perhaps we could keep the productivity, but we would need to switch to less water intensive and weather sensitive crops,” and “if we stopped cutting trees, we would have more biodiversity and less erosion of arable land.”

Stakeholder process has proposed average crop yield, height of groundwater table, and the area of bioproductive land to be the key variables to define Ikel watershed as a socio-ecological system for the scope of this research. GMB participants have expressed that the objective for Ikel SES in the face of looming climate change impacts is at least the conservation and at best the increase in all key variables between 2016 and 2050. For the central region of R. Moldova, where Ikel watershed is located, the climate projections suggest a clear increase in temperatures by 2050 and beyond, and a less certain change in annual amount of precipitation. The least favorable projection is the decrease in annual precipitation at least by 2050, as anticipated by RCP 8.5. Building the resilience of Ikel SES to climate change is more impact-focused compared to adaptation to climate change. Besides, rather than optimizing Ikel SES for a narrow, isolated purpose such as agricultural production, enhancing the resilience of the system as a whole require policies that improve the situation in multiple key variables simultaneously. In this context:

- an *adaptation policy* seeks to implement measures that help achieve the said objective under projected temperature and precipitation trends of RCP climate scenarios.
- a *resilience-building* policy involves doing the same under specific impact circumstances accompanying future climate trends: more frequent storms, higher evaporation rates or both.

Recognizing which properties of the complex system affect its capacity to avoid or facilitate changes has provided leverage points for better-placed and more effective interventions. In the given circumstances, some of the most helpful policies for building the resilience of Ikel SES to selected climate change impacts are the ones detailed below. To provide an insight into how the stakeholders can build the desirable resilience of the three key variables to such climate change impacts, these resilience policies are focused on three impact scenarios:

- decline in crop yields caused by increased rainfall erosivity.
- decline in groundwater table following the increased evaporation rate.
- decline in groundwater and crop yields following the cumulated impact of more intense rainfalls and high evaporation rates.

Resilience policy #1 requires the adoption of crops with PET that is less than the base run value with constant implementation of better soil conservation practices and ensuring that significantly more people among Ikel SES population work in agriculture, while also drastically increasing the (re)forestation efforts and sustaining them throughout the 30-year period.

Resilience policy #2 calls for drastically increasing the (re)forestation efforts and sustaining them throughout the 30-year period, ensuring that significantly more people among Ikel SES population work in agriculture and securing the uptake of technologies that require much less workforce to cultivate crops.

Resilience policy #3 simultaneously includes an ambitious increase and sustaining of (re)forestation efforts, ensuring that significantly more people work in agriculture throughout the 30-year period, ensuring the uptake of technologies that require significantly less workforce to cultivate crops and increasing the percolation rate of precipitation to the groundwater table.

We compared their relative success in enhancing the system's ability to withstand cumulated impact of more intense rainfalls and high evaporation rates:

– without a negative change in the behavior of all key variables (*hardness* attribute).
– without significant loss of performance in all key variables (*robustness* attribute).
– helping increase the rate at which the key variables return to equilibrium after a disturbance (*recover rapidity* attribute).
– helping produce a desirable regime shift in the behavior of all key variables and avoid an undesirable one (*elasticity* attribute).
– helping produce a desirable change in the probability of all key variables keeping the current regime (*resilience index* attribute).

In all impact scenarios, the performance of the three key variables with resilience policies in place is better than without policies. However, the most conducive of these is resilience policy #3. This finding is based on comparative analysis against a set of resilience features of these policies' performance. Resilience policy #3 has been found to be both supportive of a trajectory that is more likely to preserve the equilibrium of average crop yield behavior, and to be the only one that is successful in restoring the level of the groundwater within the period in focus, while also providing maximum additional growth to the bioproductive land area – an outcome aligned with the desired outcome as expressed by the stakeholder group.

As expected, data scarcity has prevented a thorough measurement of Ikel watershed's resilience attributes. However, Ikel CliRes simulations have allowed for comparisons between policy performances based on these attributes, facilitating the selection of those policies that are most conducive for achieving stated resilience objective.

11.2. Adaptation to Other Contexts

The process developed and implemented in this research facilitates policy design for resilience-building in a developing country and can be adapted to other contexts. The adaptation can happen on two levels: adaptation of Ikel CliRes simulation model and adaptation of the participatory process itself.

Ikel CliRes simulation model has been elaborated as part of a localized process in a SES that is geographically defined by the limits of Ikel watershed. However, this simulation model can be adapted and used in other watersheds. One condition for this is that the key variables of interest for analysis are the same when using it in other watershed SESs as in the case of Ikel SES, i.e. agricultural productivity, groundwater table height and bioproductive land area. If that is the case, then a further adaptation would require defining the model parameters and initial stock variables according to the local conditions (e.g. land use area, infiltration and runoff fractions, etc.). Special attention needs to be paid to the relief and hydrogeological structure of the watershed. The assumption in case of Ikel SES is that groundwater stocks are interconnected and replenished from groundwater stocks that are located outside of Ikel watershed boundary. In case of a different structure in water budget, *Water Recourses* sector would require adequate structural alterations.

More importantly, the participatory process that was designed and carried out in this research can be replicated for other watershed SESs or, indeed, for SESs that have different geographical boundaries. Different communities have different values and priorities. Ikel CliRes has put agricultural productivity, groundwater table height and bioproductive land area at the center of resilience analysis. Implementing the steps in this participatory process can helped engage with other communities and their specific values, identify other key variables, build the computer simulation model, and then identify, test and improve resilience policies around those specific key variables.

11.3. Lessons Learned, Research Limitations and Further Work

It is generally perceived that resilience has a positive valence and that building resilience is always good. Policy evaluation and design has brought to the forefront of resilience discourse the need of defining resilience in more specific terms. If the result is to be a specific one when talking about building or assessing the resilience, one must be very specific about "the resilience of what to what" and about measuring the "what". Model simulations have pointed more visibly to the phenomenon of undesirable resilience of Ikel SES structure to some of the climate change impacts, thus informing the discussion around the need for eroding the undesirable resilience of certain model components or variables. Also, Ikel CliRes has proved useful in addressing both valences of resilience.

As far as data scarcity is concerned, faced with limited and, at times, unreliable data, I have relied greatly on the stakeholder engagement in the model development process. Stakeholders from within the GMB participants group, from the SEI application process, from local interest groups and scientific community, from local and national institutions have contributed extensively to the initiation of a participatory process, defining higher-resolution vulnerabilities to climate change, building the conceptual model, identifying go-to adaptation policy interventions and less-known data sources. Notably, stakeholder role has been pivotal for structure and behavior validation of the formal simulation model, establishing sufficient confidence in Ikel CliRes model to progress toward policy evaluation and design. Carried out in data scarce conditions by design, the process developed in this research has proved to be helpful for understanding what builds or erodes the resilience of a SES to climate-change impacts, as well as for engaging and informing policymakers, decisionmakers and other stakeholders. Implementing this process in different geographical contexts would allow for an assessment of this its success based on broader evidence. Furthermore, extending the research beyond policy proposal and into assessment of policy implementation could indicate whether the expectations related to such policies are confirmed. Future work should focus on generating reliable data so as to provide the possibility of comparing stakeholder assumptions to data-based evidence.

Due to lack of precise data, the values attributed to model parameters during calibration are literature and expert opinion-based approximations that help understand the overall dynamics but might yield over-optimistic scenarios. Having a more precise estimation of such data-scarce parameters could provide deeper insights as to the effort needed to be undertaken though policy interventions in order to achieve the desired outcomes. Of particular interest are the annual and seasonal variations in climate data, which are represented neither in detail, nor exhaustively in this model. As a follow-up to this study, another version of this model could be developed that is based on a higher temporal resolution (e.g., seasonal, monthly or daily time step) to better understand the seasonal climate change impacts, in particular the impact on crop yield.

In addition, to conduct policy design and evaluation, values used for operationalization of policies proposed by GMB participants, of alternative and of resilience policies were mere assumptions intended to test and illustrate a possible alternative scenario and the direction of change they produce. Availability of better real-life data and more extensive testing and analysis with larger data sets for each of the model parameters could further inform the model end-users and help them arrive at an extended list of learnings about the resilience of Ikel SES to climate change impacts.

Throughout the research period, there has been an increase in awareness that as scientists, we need to be able to communicate actionable results to non-technical audience, such as policy makers. In view of that, it has been challenging to find the both accurate, easily understandable and actionable graphs and figures, as well as most appropriate time step. Downscaled projected weather data for 2010 to 2050 was downloaded from MarkSim® daily weather generator, aggregated into annual series, and treated for bias and fluctuation correction. Trends based on the method of least squares rather than actual yearly data were used for policy analysis and design. I have considered that using smoothed instead of fluctuating weather could prevent wrong assumptions by the layperson, who may risk interpreting fluctuations in simulated weather data as point predictions. On the one hand, it has provided simulation results that could be assessed against these attributes, making it possible to design resilience policies that enhance the desirable attributes. On the other hand, this has rendered the endeavor of measuring resilience attributes impractical and prompted the decision to leave aside a meticulous analysis of the said resilience attributes. Future work may focus on the tradeoffs between using trend data and using realistic annual or seasonal variations when carrying out resilience assessment and communicating science to the lay person.

Of the 20 initial GMB participants, two were part of every step of the model building and policy analysis process that span over 5 years. For the most part of the research, they were representing an

NGO very active in the area. Research completion coincided with one of them becoming a Member of the Moldovan Parliament and vicechair of the Environmental Committee (Parliament of R. Moldova, 2021), and the other one becoming Minister of Environment. On that occasion, the MP has expressed the interest to adapt Ikel CliRes to the context of other watersheds in the country. At the same time, one of the priorities for the Ministry of Environment is to increase the area of forested lands as a means to reduce climate change impacts, prevent soil erosion and increase biodiversity (PAS, 2021) and to encourage less water-intensive crops (Europa Liberă, 2021). Furthermore, the President of R. Moldova has stated her support for an intensive tree-planting plan on multiple occasions in the recent months, saying that "Afforestation must become a major goal of our country in the medium and long term […] There is unanimous agreement that a national afforestation program would benefit citizens from several perspectives: creating jobs in rural areas, improving agricultural productivity and reducing soil erosion, regulating local climate, purifying air and protecting waters." (Ecopresa, 2021). While it is tendentious to attribute this solely to their participation in GMB process, both people confirmed that taking active part in this research has influenced their view on policy making and has been informing their mental models on climate change adaptation. Indeed, this rather fortunate circumstance indicates that the successful uptake of research findings depends on multiple external circumstances that are often independent of the researcher. However, it is equally an indication that when the circumstances are favorable for policy makers to appeal to science-based arguments, the science must be prepared to deliver.

Similar to the two GMB participants referenced above, the majority of GMB participants have changed their roles within the initial organization or have all together changed the organization they represent. This leaves a limited number of GMB participants in their original roles to implement the findings from this research. Nevertheless, the broad contribution of stakeholders to this research has brought it to a wider attention of policy and decision makers in RM. Maintaining continuity in the institutional arrangements and the connectivity between institutions has been and will continue to be a challenge due to the nature of institutional politics. It is a matter of future work to continuously communicate and promote research findings, and to assist local and national decision makers with the implementation of resilience policies.

Finally, results and recommendations should be treated as indicative rather than exhaustive, and as an invitation to better understand the systemic relationship between society and ecology before rushing to implement what would look like an appropriate climate adaptation or resilience policy. They are also an invitation to further explore the potential for Ikel CliRes model enhancement toward a better decision-support tool for resilience building in Ikel SES.

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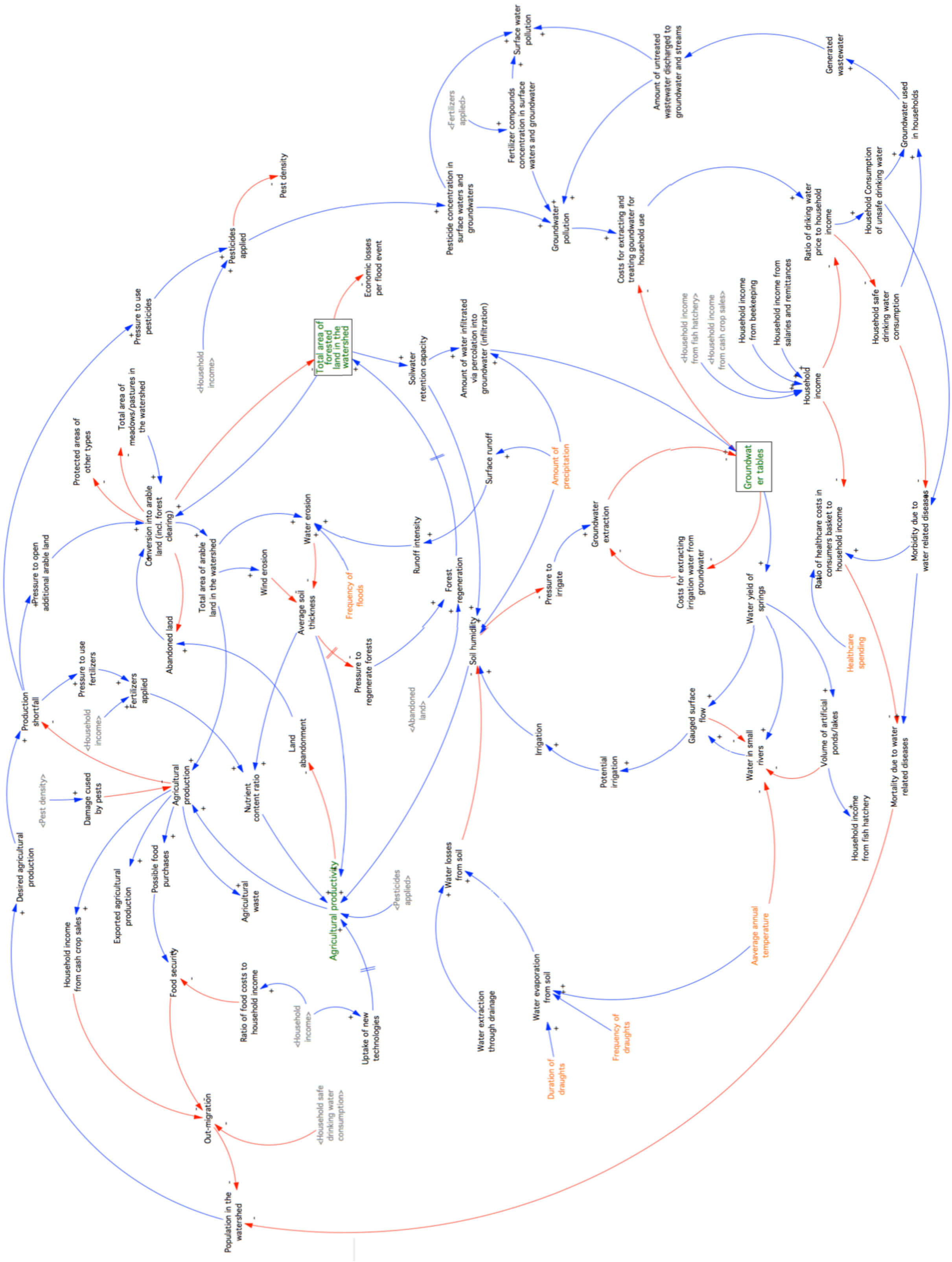
APPENDIX A: COMPREHENSIVE CONCEPTUAL MODEL INCORPORATING ALL VARIABLES THAT HAD BEEN PROPOSED BY GMB PARTICIPANTS



APPENDIX B: TABLES WITH ANNUAL CLIMATE DATA AND THE DERIVED LINE OF BEST FIT DATA USED IN IKEL CLIRES

Table B1. Annual climate data from MarkSim® daily weather generator, corrected for bias.

Year	**Average annual temperature** (°C) **RCP 2.6**	**Average annual temperature** (°C) **RCP 8.5**	**Annual precipitation** (m) **RCP 2.6**	**Annual precipitation** (m) **RCP 8.5**
2021	11.5	11.6	0.556	0.556
2022	11.6	11.7	0.556	0.556
2023	11.6	11.7	0.549	0.556
2024	11.6	11.8	0.565	0.557
2025	11.7	11.8	0.565	0.557
2026	11.7	11.9	0.565	0.557
2027	11.7	11.9	0.565	0.557
2028	11.7	11.9	0.565	0.557
2029	11.8	12.0	0.565	0.557
2030	11.8	12.0	0.565	0.557
2031	11.8	12.1	0.565	0.557
2032	11.8	12.1	0.565	0.557
2033	11.8	12.2	0.565	0.557
2034	11.9	12.2	0.565	0.555
2035	11.9	12.3	0.565	0.555
2036	11.9	12.3	0.565	0.555
2037	11.9	12.4	0.565	0.555
2038	11.9	12.4	0.565	0.552
2039	11.9	12.5	0.565	0.552
2040	12.0	12.5	0.565	0.551
2041	12.0	12.6	0.565	0.551
2042	12.0	12.7	0.565	0.551
2043	12.0	12.7	0.565	0.551
2044	12.0	12.8	0.565	0.550
2045	12.0	12.8	0.565	0.550
2046	12.0	12.9	0.565	0.549
2047	12.0	12.9	0.565	0.549
2048	12.0	13.0	0.565	0.548
2049	12.0	13.0	0.565	0.548
2050	12.0	13.1	0.566	0.547

Table B2. Line of best fit data derived from annual climate data and used for policy evaluation.

Year	**Average annual temperature** (°C) **RCP 2.6**	**Average annual temperature** (°C) **RCP 8.5**	**Annual precipitation** (m) **RCP 2.6**	**Annual precipitation** (m) **RCP 8.5**
2021	11.6	11.6	0.561	0.559
2022	11.6	11.6	0.561	0.559
2023	11.6	11.7	0.561	0.558
2024	11.7	11.7	0.562	0.558
2025	11.7	11.8	0.562	0.558
2026	11.7	11.8	0.562	0.557
2027	11.7	11.9	0.562	0.557
2028	11.7	11.9	0.562	0.556
2029	11.7	12.0	0.563	0.556
2030	11.8	12.0	0.563	0.556
2031	11.8	12.1	0.563	0.555
2032	11.8	12.2	0.563	0.555
2033	11.8	12.2	0.564	0.555
2034	11.8	12.3	0.564	0.554
2035	11.8	12.3	0.564	0.554
2036	11.9	12.4	0.564	0.553
2037	11.9	12.4	0.564	0.553
2038	11.9	12.5	0.565	0.553
2039	11.9	12.5	0.565	0.552
2040	11.9	12.6	0.565	0.552
2041	11.9	12.6	0.565	0.552
2042	12.0	12.7	0.565	0.551
2043	12.0	12.7	0.566	0.551
2044	12.0	12.8	0.566	0.550
2045	12.0	12.8	0.566	0.550
2046	12.0	12.9	0.566	0.550
2047	12.0	12.9	0.567	0.549
2048	12.1	13.0	0.567	0.549
2049	12.1	13.0	0.567	0.549
2050	12.1	13.1	0.567	0.548

APPENDIX C: STAKEHOLDERS ENGAGED IN VARIOUS STAGES OF THE RESEARCH

Table C1. List of stakeholders engaged in individual SEI interviews.

No.	**Organization**	**Type of organization**	**Stakeholder's role in the organization**
1	National Institute of Economic Research	Academic Institution	Head of the Department of Agri-food Economics and Rural Development
2	National Institute of Economic Research	Academic Institution	Researcher
3	Institute of Ecology and Geography	Academic Institution	Researcher
4	International Fund for Agricultural Development	International organization	Climate change resilience expert
5	United Nations Development Programme in Moldova	International organization	Project manager for "Reducing Climatic Risks and Disasters"
6	Ministry of Environment	National Ministry	Public policy specialist
7	Department of Water Resource Management, „Moldovan Waters" Agency	National Agency	Lead expert
8	Straseni Rayon Council	Regional Institution	Deputy chair
9	Public Health Centre of Straseni Rayon	Regional Institution	Public health specialist
10	Călărași Ecological Inspection	Regional Institution	Inspector
11	Criuleni Rayon Council	Regional Institution	Vice-president
12	Criuleni town	Urban Mayorship	Mayor
13	Cricova town	Urban Mayorship	Mayor
14	Housing Department Cricova	Urban Mayorship	Director
15	Drasliceni commune	Rural Mayorship	Mayor
16	Romanesti village	Rural Mayorship	Mayor
17	Hirjauca commune	Rural Mayorship	Mayor
18	Millenium Training and Development Institute	NGO	Director
19	NGO EcoVisio	NGO	Executive director
20	NGO EcoVisio	NGO	Project manager
21	NGO National Environmental Centre	NGO	President
22	NGO National Environmental Centre	NGO	Environmental expert
23	NGO National Environmental Centre	NGO	Ecological agronomy expert
24	Moldovan Environmental Governance Academy	NGO	Director
25	Romanesti	Village	Citizen

Table C2. List of stakeholders engaged in GMB workshops.

No.	Organization	Type of organization	Stakeholder's role in the organization
1	Ministry of Environment	National Ministry	Institutional Expert
2	International Fund for Agricultural Development	International organization	Climate Change Resilience expert
3	Department of Water Resource Management, „Moldovan Waters" Agency	National Agency	Lead expert
4	Criuleni Rayon Council	Regional Institution	Vice-president
5	Agricultural Department of Călărași Rayon Council	Regional Institution	Expert
6	Public Health Centre of Straseni Rayon	Regional Institution	Public health specialist
7	Călărași Ecological Inspection	Regional Institution	Inspector
8	Cricova town	Urban Mayorship	Mayor
9	Drasliceni commune	Rural Mayorship	Mayor
10	Hirjauca commune	Rural Mayorship	Mayor
11	Romanesti village	Rural Mayorship	Mayor
12	Housing Department Cricova	Urban Mayorship	Director
13	Ichel Watershed Committee	Watershed committee	Secretary
14	NGO National Environmental Centre	NGO	President
15	NGO National Environmental Centre	NGO	Environmental expert
16	NGO EcoContact	NGO	Project manager
17	NGO EcoVisio	NGO	Project manager
18	NGO Society for Responsible Consumption	NGO	Researcher
19	Cricova	Town	Citizen
20	Vadul-lui-Voda	Town	Citizen

Table C3. List of stakeholders engaged in model validation.

No.	**Organization**	**Type of organization**	**Stakeholder's role in the organization**
1	National Institute of Economic Research	Academic Institution	Head of the Department of Agri-food Economics and Rural Development
2	Institute of Ecology and Geography	Academic Institution	Head of geography and landscape research laboratory
3	Institute of Ecology and Geography	Academic Institution	Researcher
4	State University of Agronomy	Academic Institution	Head of Environmental Engineering Department
5	Ministry of Environment	National Ministry	Institutional Expert
6	International Fund for Agricultural Development	International organization	Climate change resilience expert
7	Department of Water Resource Management, „Moldovan Waters" Agency	National Agency	Lead expert
8	Criuleni Rayon Council	Regional Institution	Vice-president
9	Agricultural Department of Călărași Rayon Council	Regional Institution	Expert
10	Public Health Centre of Straseni Rayon	Regional Institution	Public health specialist
11	Călărași Ecological Inspection	Regional Institution	Inspector
12	Chisinau municipality	Urban Mayorship	City council member and Expert in agronomy and economic policies
13	Cricova town	Urban Mayorship	Mayor
14	Drasliceni commune	Rural Mayorship	Mayor
15	Hirjauca commune	Rural Mayorship	Mayor
16	Romanesti village	Rural Mayorship	Mayor
17	Housing Department Cricova	Urban Mayorship	Director
18	Ichel Watershed Committee	Watershed committee	Secretary
19	NGO National Environmental Centre	NGO	President
20	NGO National Environmental Centre	NGO	Environmental expert
21	NGO EcoContact	NGO	Program manager for sustainable development projects
22	NGO EcoContact	NGO	Project manager
23	NGO EcoVisio	NGO	Project manager
24	NGO Eco-TIRAS	NGO	Researcher and Executive director
25	Cosernita	Village	Farmer
26	Vadul-lui-Voda	Town	Farmer