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[LAND-USE ADAPTATION TO CLIMATE CHANGE IN THE WORLD'S LARGE RIVER BASINS]

Exploring the range of possible river basin reactions to climate change to aid the development of a universal adaptation approach

Contents

1 Abstract

Climate change threatens the hydrological and agricultural balance of large river basins, which have sustained civilization throughout history. Although in some instances, certain land-use practices can also pose a threat to river basins, this study highlights land-use changes as a major adaptive tool. Given the great range in system characteristics there will be significant differences in the reaction of differing basins to climate change. Currently, there is no universal approach to how these system changes should be dealt with in terms of adaptation strategy. Before an approach can be developed, the global range of climate change effects and adaptation options must be determined to understand what range of inputs a universal adaptation approach must address.

This study aims to illustrate how contrasting river basins will react differently to climate change, serving as a foundation for the construction of an adaptive approach framework. The study initially conducts a global scale analysis of the effects of climate change on variables such as agriculture, river basin hydrology, vegetation, and development. This results in an analysis of the global distribution of effects relevant to river basin systems. This information was then used as a background for seven river basin case studies representing the range of characteristics such as land-use, hydrology, development, climate, latitude, and geomorphology. Sub issues under the main titles of physical, societal, and future scenarios are investigated to create river basin profiles. A river basin profile is a compilation of predefined information relevant to land-use and climate change. The acquired information is used to determine what threats and adaptation options can be expected in certain regions and basins. In addition, barriers (obstacles preventing adaptation) which exist under those conditions are investigated. Results and conclusions are qualitative because of the small sample size.

Results indicate a variety of combinations and degrees of threat in different continents. Depending on the expected future constraints in physical conditions in combination with the

expected societal trends, adaptation barriers[1] were identified which also differed per continent. For example, in North America, the continental US faces large threats of reduction in water resources and agricultural productivity. In Eastern US, there are concerns of threats of increasing discharge and flood. The Mississippi River Basin is subjected to both concerns. There is a conflict in Eastern US between adaptation opportunities leading to identification of a clear barrier. An increase in cultivated land is needed to enhance productivity to counteract losses (in North-central and Eastern US) whereas land is also needed for rehabilitation of wetlands to buffer floods.

Floods are the major concern for the future of river basins throughout Asia. However, in the large areas of Russia that are predicted to experience an increase in agricultural productivity, conflict will raise with the space needed for natural flood buffers. There are also large areas where crop fraction has a profound influence on runoff (and hence discharge) increasing both the negative effects of agriculture in flood regime and the benefit and need for and efficiency of vegetation to buffer floods. Loss of vegetation predicted for large areas will exacerbate flood threats and the corresponding complications.

The threats, barriers, and adaptive opportunities have a large degree of spatial variation in South America and to a lesser degree, Africa as well. Southern Europe faces reductions in crop productivity and water supplies while Northern Europe will likely exhibit increases in both discharge and agricultural productivity. The Rhine River Basin the conflicting challenges of maintaining and improving regulation and navigability and improving ecological continuity simultaneously. This is likely to be a common challenge for most highly populated and regulated river basins. In Australia, reductions in agricultural productivity and water supply are the prevailing threats. In the Murray-Darling River Basin, competition for water is very high between agriculture and crucial wetlands, leading to an adaptation barrier.

In general, higher altitudes and latitudes are predicted to experience increases in both discharge and agricultural productivity upon climate change. Not only will the capitalization on increased productivity be limited by vegetation needed to buffer floods, but also new agricultural practices that minimize erosion will have to be explored. This is because permafrost melt and increased discharge will increase erosion concerns and limit new cultivation. Low latitudes, developing, and arid regions are generally threatened by reduction in water resources and crop productivity. This is often in conjunction with high levels of existing stress on river water resources creating competition for fresh water. Reactions to climate change vary from basin to basin.

The findings of the study indicate great variability of threats, adaptation options, and barriers. The results indicate irrigation efficiency improvement, agricultural shifts, natural flood buffers, and regulation that preserve ecological continuity as the major adaptation tools of the future. The major challenge to the future approach involves balancing compound reactions[2] of a basin often resulting in the conflict between two or more adaptation efforts/options. In addition, efforts are further limited by the allocation of competitive resources such as water needed for both ecosystems and populations. The most illustrative case is the land need for both natural flood

[1] A barrier is considered anything that prevents or challenges adaptation.

[2] Compound reaction refers to a reaction to climate change that calls for multiple courses of action that often conflict with each other, such as for instance increased agricultural cultivation and erosion control.

buffers and agricultural shifts in the North-Central US. While re-vegetation is likely to be advisable as for a future flood defense, nearby apicultural losses will induce incentives to cultivate the same land. Successful resolution of conflict will require the quantification of needs and adaptation limitations along with the ranking of priorities.

The future framework will have the task of balancing efforts and resource allocation in the face of adaptive limitations posed by conflicting opportunities and high levels of resource competition. Because adaptation efforts and resource allocation have a competitive nature, the limitations they face create a need to determine what actions and resource take precedence over others and to what extent. In the end, there will be a need for sacrifice in order to achieve sustainability. Based on the analysis, the future framework should focus the following principals; quantifying needs and limits, assessing risk, ranking priorities, innovating accordingly.

2 Introduction

Since the birth of civilization, populations have depended on the services provided by large river basins. As history unfolded, these river basins have become more developed and regulated, expanding the range of services beyond freshwater and agriculture to incorporate functions ranging from large scale transport to hydro-electricity. These functions, which support life and wealth, are dependent upon the intricate balance of hydrological, ecological and agricultural systems. As the ever-changing world progresses, climate change threatens the systems that support the crucial functions of large river basins.

One of the most prominent effects of global warming on river hydrology is the melting of mountain glaciers. Many of the upstream sources that nourish river waters are already shrinking and threaten to disappear entirely. This may result in an initial increase of fresh water availability, followed by a long-term loss of sustainable supplies. Shifting precipitation patterns will negatively affect the timing and quantity of downstream flows. Acute crises will become a greater threat to certain river adjacent communities and beyond as the temperatures rise. However, effects will vary regionally. While droughts will be a primary concern in some basins, floods will be the predominant threat to others. In some scenarios, both threats will be sincere concerns (Noah et al. 2008). To add to the spatially varying trend of threats, some areas will suffer great losses in agricultural productivity while in other region's yield will increase and areas once impossible to cultivate will become productive (Leemans et al. 1994).

The effects of climate change also induce social concerns for the dependents of these large fresh water sources. The impairment of food production will affect livelihoods and settlement patterns around the world especially in many developing regions. This is likely to occur simultaneously with an increase in demands for fresh water and food (Michel et al. 2007). As temperatures rise, evapotranspiration rates will increase and the need for irrigation will rise. In regions of predicted crop yield losses, this change may spark efforts to increase crop acreage, leading to greater irrigation needs. In addition, under changing conditions of water availability, agricultural infrastructures will have to recalibrate. Agricultural production will have to move to areas more suitable to meet their needs (Erikson et al. 2009). Concerns vary depending on the location, development and social fabric of the specific areas.

Past studies have shown that land-use and land cover can greatly affect river hydrology (Moussa et al. 2002; Leemans and Born, 1994; Doll et al. 2002; Hernandez et al. 2000; Fohrer et al. 2000; Klocking and Haberlandt, 2001). In some cases, land-use such as agricultural practices can have a more profound influence on fresh water resources than climate change (McCarthy, 2001). Land-use changes can be the greatest adaptation tools available to large river basins. This fact also reminds us that climate change effects must be considered in the context of specific land-use practices.

Past mitigation efforts have proved to be unsustainable. Due to influential site-specific intricacies, the balance of contrasting river basins will react differently to climate change. As a result, issues presented by climate change cannot be addressed with generic mitigation and adaptation strategies. Currently there is no existing framework for river basin adaptive planning that can incorporate the broad range of reactions to climate change (resulting from the influence of numerous site-specific intricacies on vulnerability and adaptive potential). Such a framework must exhibit global consistency and local applicability i.e. it there should be a universal approach that can be applied to the variety of scenarios.

The adaptive potential of large river basins exhibits comparable variability to threats and perhaps an even greater range because vulnerability to climate change depends on the specific land use, societal and hydrological basin characteristics. Flood concerns illustrate this point well. In cases of dense river adjacent settlements and intense agricultural productivity, floods can be a great concern in the future. In other river systems, the ecology could be highly adapted to and dependent on flood regimes/cycles. Barriers, which include anything that prohibits or challenges adaptation options, also vary greatly between different basins. In addition, each region has specific water needs/concerns and corresponding development plans. Adapting to the threats presented to these resources by the warming climate is an intricate task. Due to the large inconsistency between differing river basins, a dynamic framework must be developed.

In order to properly integrate land-use adaptation into a future framework, this study aims to illustrate the range of various possible reactions to climate change. In doing so, this thesis asks; how will contrasting river basins react differently to climate change in terms of land-use adaptive potential? Land-use adaptive potential depends on the threats, adaptive options and barriers of the specific basin/ region. Determining the range of reactions takes the initial stride in developing the discussed framework by outlining the inputs that it will need to address. In addition, the conclusions of this study will help outline future framework and research objectives. This will allow land use planners to better assess how land-use adaptation strategies should be used to counteract the impacts of climate change.

Before any adaptation planning can be done, the area's specific threats must be identified. The approach highlights areas of concern and discerns potential areas in which a river basin could expect a specific impact. It then provide specific examples of contrasting basin's adaptive capacity in these areas under the provided circumstances. In this process, the knowledge gaps and further research needed to continue developing the said framework become apparent. The outcome of this study aims to serve as a resource to aid planners to determine what may be necessary and advisable under specific conditions, what land-use changes are necessary and/or feasible and where. Policy makers need to know what the threats are and what options they have to mitigate and/or adapt to those threats.

In order to counteract and adapt to the negative impacts of climate change using land use strategies, specific areas of the world must be distinguished. This study compiles global data of relevant climate change, land use, and water information, in order to illustrate the present and possible future regional distribution of site-specific intricacies (land-use/ cover, climate, water use and resources) which river basins may exhibit. Global information relating to depictions of future scenarios will help gain insight on how these variables might look in the future. The study asks how contrasting river basins will react differently to threats and barriers in terms of land-use adaptive potential.

From the analysis of this information, specific regions of particular concerns, needs, vulnerabilities, and adaptive feasibilities become apparent. However, global information cannot depict all relevant attributes. Precise characteristics such as the specific hydrological systems and social concerns of specific river basins are not well analyzed or represented globally. In a large-scale analysis, smaller regions of anomalies within larger regions of seemingly consistency will be lost. To help resolve these issues, a series of case studies representing various regions are investigated in detail. Depicting specific cases within regions adds a finer detail to the study these and shows how specific basins may react and adapt in certain regions. These studies may also reinforce assumptions made by the global data and/or reveal inconsistencies

3 Methods

3.1 Compiling Global Spatial Data

A literature based impact-assessment of climate change and spatial land-use patterns was conducted on a global scale. Relevant maps, model results, and information pertaining to climate change, land-use and river hydrology on a global scale were collected, including maps of predicted climate changes, land-use/land-cover and maps depicting various trends around the world. These maps illustrate the global distribution of various major crop types and pastures, as well as various forms of natural vegetation and the influence of climate change on them. This data was collected by obtaining scholarly articles available to the Universiteit Utrecht Library, JSTOR, and Omega Google Scholar. Subjects investigated include future global climate changes, present and future water use and resources, present and future global land cover (cropland, pasture, and vegetation), current, future and potential agricultural distributions, future demands and agricultural production, and specific concerns and trends of the different continents.

After this information was obtained, an attempt to discern areas that can expect certain changes and challenges commenced. The predicted climate and hydrological changes indicate the challenges to water availability and highlight concerns such as floods and droughts depending on what is predicted in which regions. The current and future distribution of crops, cropland intensity, and agricultural productivity were used to give reference where land-use/ agricultural changes should and could be made to adapt to climate change. The vegetation of regions, and future shifts in such, show what regions may become unproductive agriculturally. It also shows where specific vegetation types are, and could be useful to buffer threats such as flooding. Using this approach, I assess:

1- Which physical properties are affected by climate change and to what extent?
    - This answer is presented in terms of climate, hydrological regime, and land-use/cover
2- What does this mean for
    - Vegetation
    - Crop production
    - People
3- What are the conflicts and constraints, where are they, and to what extent? The spatial distribution of conflicts and constraints illustrate where basins might expect a need for change and what change is needed.
    - What are the main problems?
    - Where will they arise?
    - What is the severity?
4- What can be done?
    - What are the adaptation and mitigation options and constraints and where are they?

3.2 The Case Study River Basins

Seven case study rivers were investigated to display the varying concerns, vulnerability and adaptive capacity to climate change. These included large contrasting river basins (at least 185,000 km^2) to represent the ranging conditions of the global river basins. The selected case-study rivers include the Amazon, Nile, Rhine, Mississippi, Brahmaputra, Mackenzie, and Murray-Darling River basins. These particular case studies where chosen to represent the major climate zones, continents, terrains, hydrological systems, and social fabrics.

The Amazon represents a relatively flat tropical basin in low latitudes. The Nile is a very large basin in an arid climate under water stress, is generally underdeveloped, and is situated in Africa. The Murray-Darling Basin is also subjected to an arid climate but involves large areas of irrigated agriculture and is situated in Australia with a very different social fabric. The Brahmaputra is a complex hydrological system fed in large part by monsoons and subjected to the unique terrain of the Himalayas. The unique social fabric of the Himalayan populations makes this a particularly interesting case study. Originally, the Ob was chosen to represent a high altitude river basin. However, as the relevant literature available was limited, the Mackenzie River Basin substituted. The Rhine was chosen because of its location in Europe and dense population.

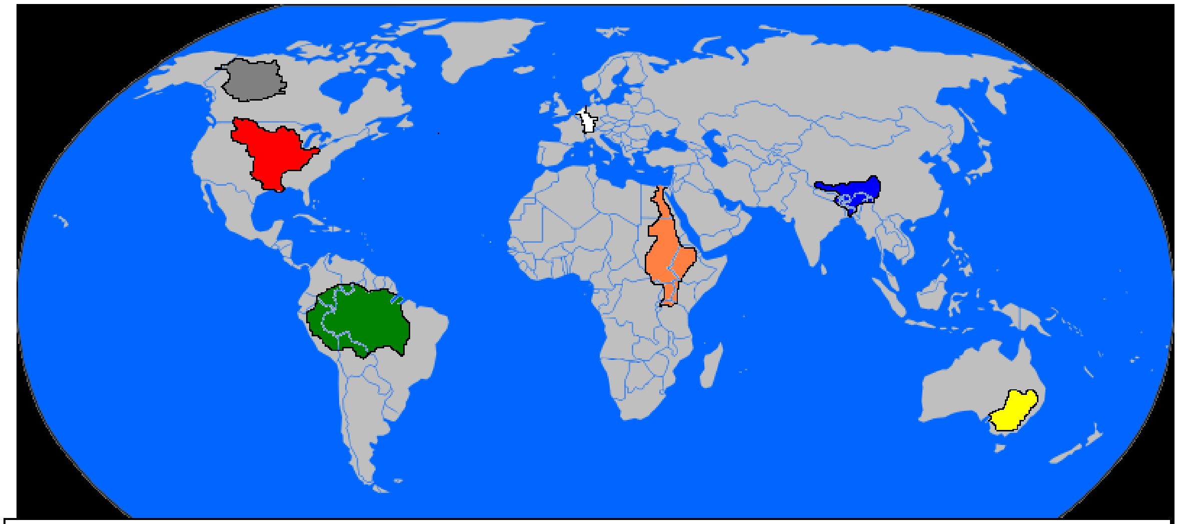


Figure 1- Global distribution of selected case study river basins. Grey= Mackenzie, Red= Mississippi, Green= Amazon, Orange= Nile, Blue= Brahmaputra, Yellow= Murray-Darling

For each specific basin a river a basin profile was created with information compiled based on physical, social, and future scenario attributes. These attributes were assessed to determine each river basin's specific vulnerabilities and adaptive capacity to the effects of climate change. The specific attribute subjects are listed in the table below. Each subject mentioned in table 1 has multiple sub-titles.

Physical	Social	Future
Length	Water Use	Development
Area	Development	Water Demand/Resources
Topography	Main Functions/Services	Predicted Climate Changes
Water Resources	Vulnerability to Climate Change	Predicted Climate Change Impacts (CCI)
Land-Use/Cover	Population	CCI on Agriculture
Climate		CCI on the Environment
Hydrology		CCI on Hydrology
Ecology		CCI on Societal Services

Table 1- Headings of subjects investigated for case study river basin profiles. It should be noted that these are only the main subjects and many sub-headings are not represented in this table.

3.3 Integrating the data

After the global spatial data was used to locate areas of concern and potential, hot spots of vulnerability and adaptive feasibility were located for each continent by examining and assessing the specific combination of current and future characteristics. Areas with increased precipitation/runoff, agricultural intensity, and land-cover associated with high runoff and erosion, and predicted shifts to land-covers with such were considered regions of flooding and erosion risks. Regions exhibiting or expecting high water stress, increasing water demands, decreases in runoff/discharge/precipitation, extreme increases of temperature (and hence evapotranspiration), water intensive crops, arid/semi arid climates, and/or or large decreases in agricultural productivity are considered regions of water shortage vulnerability and heightened drought concerns.

These factors were assed to determine what land use changes would be best to mitigate and adapt to the specific concerns. Background knowledge of the general effects of land use and land cover on river hydrology was reviewed to aid the assessment. Then these areas were further characterized with other relevant information to gain clearer view of the concerns and feasible adaptation changes. Present and future agricultural information (specific crops, agricultural land distribution and intensity, and present and future productivity and potential) was analyzed to determine what, if any shifts and changes in agriculture could be beneficial to the particular stresses expected.

The information from the river basin profiles was used to add precision to the estimates made by global scale studies. The basin profiles characterize the particular issues, concerns, adaptation efforts and feasibility within a smaller (and more precise) scale. These real world examples either add credibility to the assumptions made by the global data or highlight inconsistencies. The basin profiles also indicate what supplementary information is useful in conjunction the global information to make sound assumptions and suggestions. In the other direction, the global information were used to fill in the gaps of information not available for a particular basin. The global data and the river basin profiles reinforce each other to create a well-rounded idea of how regions will react to climate change. The two data sets were analyzed to illustrate the global variability of concerns and adaptive capacity.

The combined and reinforced data depicts the range and spatial distribution of climate change threats and the corresponding adaptive capacity of the large river basins around the world. This was used to identify the major barriers and facilitators of each river basins' adaptive capacity to climate change. Further, the global spatial distributions of such were illustrated in contrasting regions of the world. Based on the results, planners can determine what the threats, land-use adaptation barriers, and capabilities are for any given river basin in a world of highly variable situations. The study utilizes an approach that can be applied to any large river basin. Comparing the river basin profiles to the global information validate this approach or expose areas of incompetence. Based on this, suggestions were formulated on what further research and improvements should be made in order to develop an effective dynamic framework for determining the land-use adaptation options of large river basins.

4 Results

4.1 Global Analysis of Future Climate and Hydrology

Based on a synthesis of three of the most contemporary climate models, the International Panel on Climate Change (Bernstien et al. 2007) presented predicted surface temperatures for 2020-

2029 and 2090-2099. The models present somewhat similar results spatially, with some differences in intensity. However, the general trend is for the greatest increases in temperature to be in the higher latitudes and altitudes. For the decade 2020-2029 the highest predicted increase was predicted for North-Central Russia with an increase of 2-2.5^{o}C. Most areas of North America (excluding western Canada), North Africa, Eastern Europe, and Asia (excluding Southern India and Southern China) are predicted to show a temperature increase of 1-1.5^{o}C. One of the three models predicted the same warming for Central, South America, and Southern Africa. Australia, central and Southern Africa, Western Canada, and Southern India and China are generally expected to experience surface warming of 1-1.5^{o}C in the decade 2020-2029 (Bernstien et al. 2007).

In the decade 2090-2099, Northern Russia is expected to exhibit the greatest warming, with predicted increases ranging from 4-5^{o}C to 6-7^{o}C between the models. Southern and North-Western Africa, Central and Northeast North America (especially the central United States), most of Australia (especially the Northwest), the Andes and the Himalayas expect increases ranging from 2.5^{o}C-5^{o}C. Other regions expect a range of increases from 1.5^{o}C to 3^{o}C during this decade. The differences among the models are much greater in this decade than during the former (Bernstien et al. 2007).

Future changes in precipitation have great relevance to both land use and hydrology. Areas under predicted increased precipitation will have a significant influence on crops and irrigation needs. Agricultural losses due to excess soil moisture are expected to double by 2030. In areas of higher rainfall intensity, soil erosion is a concern (Easterling et al. 2007). The averages of multiple models projecting to 2090-2099 show that, for the month of December to February, Central America, Saharan Africa, and the Middle East show the greatest predicted declines in precipitation of up to 30%. Northern Canada, Russia, and East-Central Africa exhibit the greatest predicted increases of up to 30%. Large areas of South America and Northern Canada are also expected to increase in precipitation from 10-20%. For the months of July and August, North Africa, the Mediterranean area, southern Africa, and central South America show the greatest decreases of up to 30%. Northern North America, Russia, and Eastern Asia show predicted increases of 10-20%. The Himalayas are predicted to show large decreases during the winter and increases during the summer (Bernstien et al. 2007).

Changes in runoff can indicate how much water will be available to crops and ecosystems. Increases in runoff can exacerbate floods and soil erosion, especially in highly cultivated and or urbanized regions. Declines in runoff can render areas that are currently suitable for rain-fed agriculture infertile. This is a particularly great concern for the Mediterranean, Central America, and subtropical regions of Africa and Australia (Easterling et al. 2007). Nohara et al. (2006), created a model predicting the global distribution of annual mean runoff changes between the present (1981 to 2000) and 2100. The results can be seen below in Figure 1. Runoff changes presented by the IPCC's 2007 synthesis report generally agree with these results. The IPCC's 2007 synthesis report noticed some trends of high-altitude increases, decreases over some dry regions, and less reliable changes in monsoon areas.

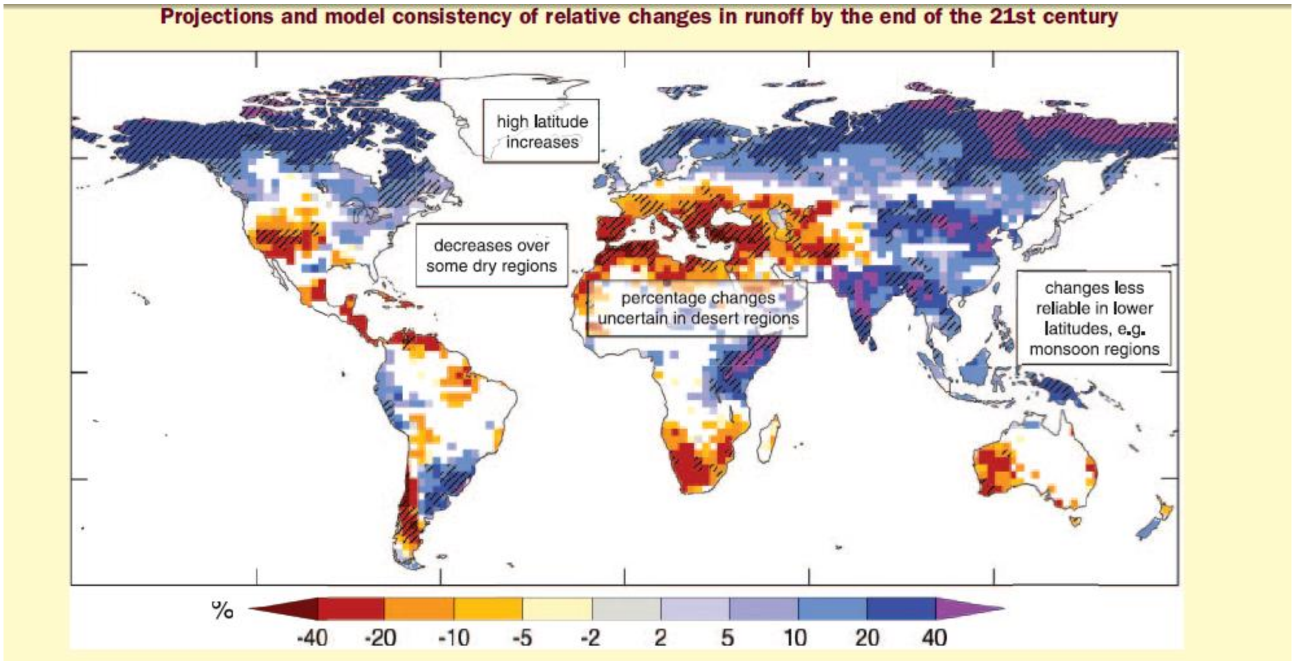


Figure 2- Large-scale relative changes in annual runoff (water availability in percent) for the period 2090-2099 relative to 1980-1999. The values represent the average of 12 models using the SRES A1B Scenario. White areas represent less then 66% agreement between the models (Easterling et al. 2007).

Foley et al. (2005) modeled trends in runoff due to several individual influences and to all factors combined. In North America, subjected to all factors, the model results indicated a general increase in runoff throughout the continent, with the exception of several small areas spotting the continent. Areas of decrease include the very southern and northern parts of the eastern United States and areas of Alaska and the Central U.S. When the influences on runoff are separated, it becomes apparent that this is generally a result of climate and precipitation changes. However, runoff changes due to land-use change (especially changes in the percent of land dominated by crops, "crop fraction") have significant influence on runoff decreases in the Eastern U.S. and increases in a large area of North-Central U.S./South-Central Canada.

In general, it seems that land-use change and crop fraction have not had as great an influence on global runoff patterns as climate and precipitation changes. This is evidenced by the combined influence map, reflecting climate and precipitation influences over he last century. However, it could still be true that land use and crop fraction have a major influence on runoff in smaller spatial scales such as river basins. This can be supported by the spotty and small fractioned pattern of land-use influences on runoff, while the influences of climate change and precipitation influence larger areas uniformly (Paio et al. 2007).

Based on model simulations of runoff based the changes in the past century, land-use-change influence on runoff decreases has been the greatest in the eastern half of the United States, South-central Canada, and South-East South America. This seems to diminish the influence of increasing precipitation and climate slightly in US. The increasing influence of land-use and crop fraction in the Asian islands seems to exacerbate the increasing effects of climate change and precipitation. There are strong influences of land-use and crop fraction on increasing runoff in Eastern Europe, Western Russia, North India, the southern tips of Australia, and South-East South America. However, the influences seem to be outweighed by the influences of climate change and precipitation on this particular scale. Foley et al. 2005 concludes that the major trends in runoff over the past 100 are a consequence of climate change and large-scale deforestation.

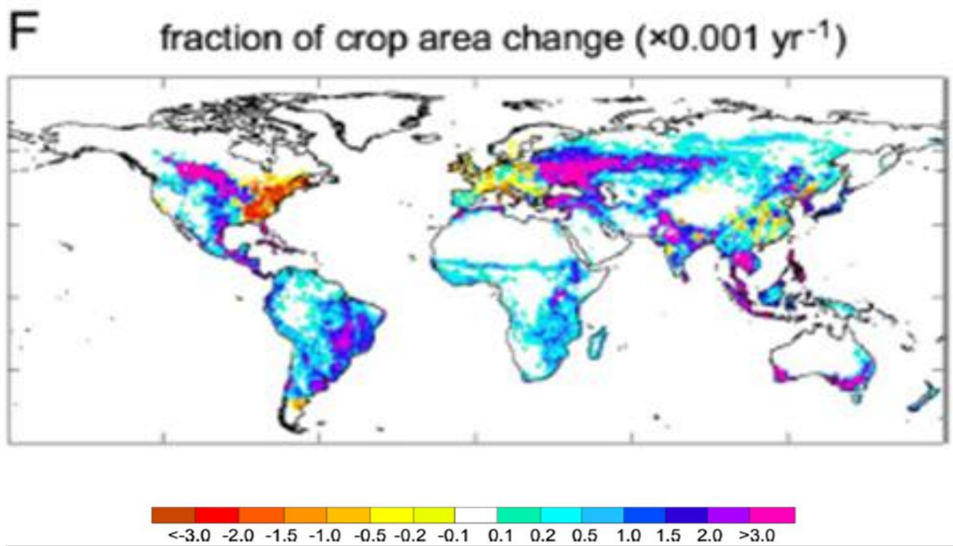


Figure 3- The influence agricultural intensity on runoff based on data over the last century (Paio et al. 2007).

Nijssen et al. (2001) performed a study on the future influences of climate change on river basins around the world. The general conclusions of this study are that: The greatest warming is in the winter in the high latitudes. The greatest hydrological changes occur in snow dominated river systems of mid to high latitudes. Generally, on a global scale, reductions in stream-flow are predicted for tropical to mid-latitudes and the opposite for higher latitudes. This is because most predicted precipitation increases are in the winter when available energy is insufficient to increase evapotranspiration significantly. Instead, water is stored as snow and increases stream-flow when it melts.

4.2 Contemporary and Future Water Resources and Demands

Vorossmarty et al. (2010) performed a study that mapped water stress on river surface water discharges throughout the world. The results depicted populations and withdrawals relative to river discharges. Although he warns to use the results with caution, due to various uncertainties, some trends become apparent. On a large scale, populations of East India, the Western US, the borders of the Sahara Desert, the Middle East, Central Asia, East Australia, The Southern Andes, and Southern Africa are putting great stress on their rivers with fresh water use at present time.

Other areas do not put as much stress on their rivers and could use more water and/or withstand discharge decreases with similar water use.

In general, the problem areas are highly populated, semi-arid regions. These results essentially mirror the general global water stress results presented by Kundzewitcz et al. IPCC, 2007. Kundzewitcz noted a few key vulnerabilities to climate change: There are multi-year droughts in the US and Southern Canada. Water supply is affected by shrinking glaciers in the Andes. Water supply is reduced by erosion and sedimentation in reservoirs in North-East Brazil. Due to flood disasters in Bangladesh, 70% of the country has been inundated. There is damage to ecosystems due to decreased stream flow of the Murray-Darling River Basin.

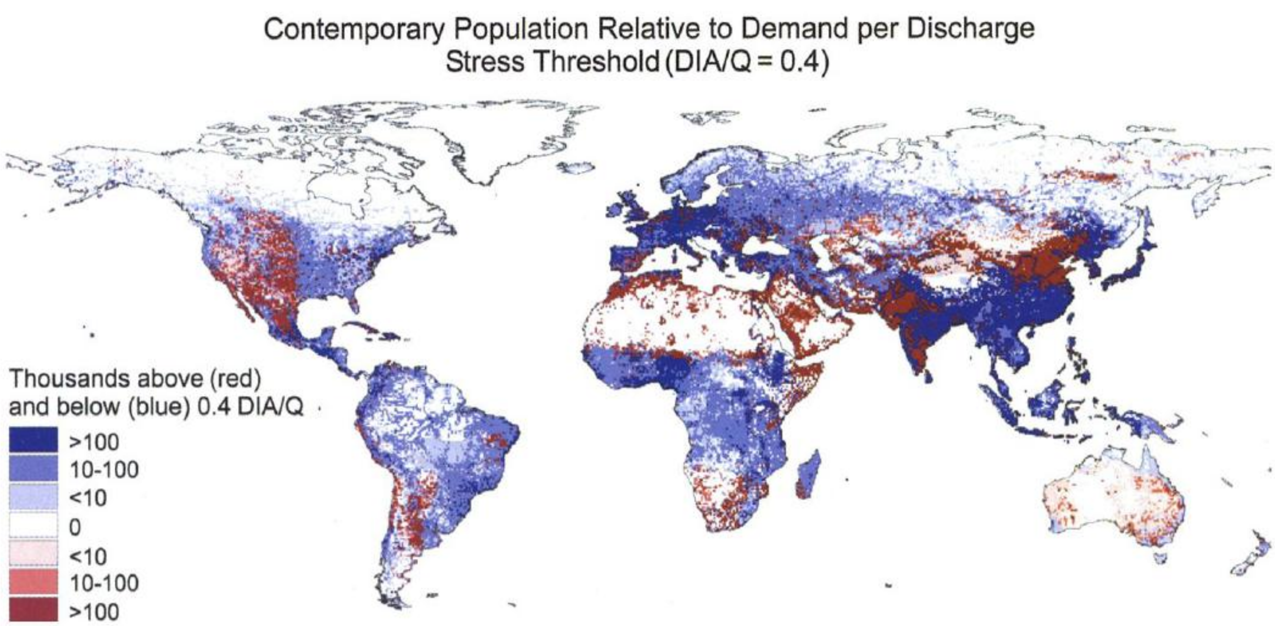


Figure 4- The global distribution of population with respect to water stress threshold DIA/Q=.4 indicating severe water stress. DIA represents Domestic, Industrial, and Agricultural water withdrawals. Q represents annual average discharge (Vorossmarty et al. 2010)

Later in Vorosmarty's study (2010) he predicts the future stress put on river discharges due to climate change, population change, and the combination of both. The results seem to indicate that due to the combination of both influences; almost all river basins will become greatly stressed in the future. However, when one examines the results of climate change and population change separately, it becomes apparent that population change is the dominant factor in this trend and the influences of climate change are much more varied throughout the globe. In the end, it seems that the western half of the United States and Northern Asia will exhibit the lowest increase in river discharge stress.

Doll and Siebert (2001) conducted a study that shows the irrigation requirements (IR) of the globe. In general, the largest irrigation requirements are in the Western and Central US, India, Most of China (other than the lowlands of the west) and Mediterranean Europe. Other strong trends exist but in too small of regions to be accurately depicted on a global scale. Doll et al. (2002) presented two GCM models from previous studies predicting future changes in IR using different strategies. Both studies highlight future increases in IR in the same areas. However, two models depict different change intensities. Areas expecting an increase or decrease generally agree between the two models. Increases in IR are expected for most of the Western and Central US (excluding some areas of the south), the very north section of China, and some patchy areas of Europe. There are some areas of India, Pakistan, South Vietnam, and Southern Indonesia that are projected to experience very large increases in the future IR. Certain areas of India are expected to experience IR increases of over 100%. Most of Eastern China is projected to exhibit decreases ranging from 5-15% in the South and 15-30% in the North. The two models do not agree in Northern China. Doll et al. 2002 organized a table of the projected changes in irrigation requirements in some large river basins.

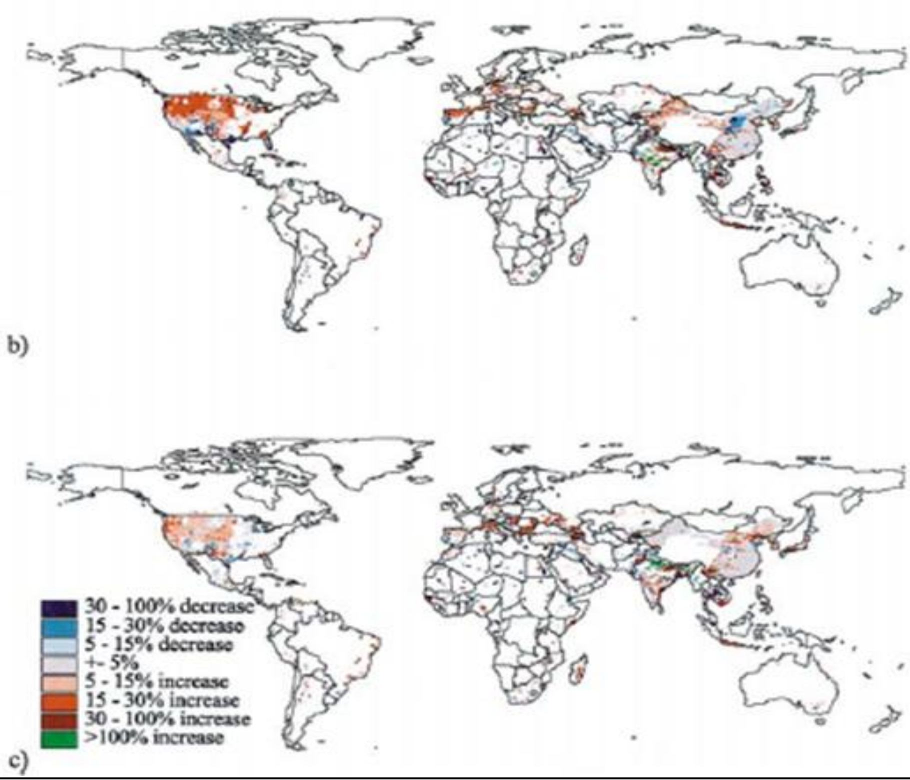


Figure 5- (B) Change in net irrigation requirements between baseline climatic conditions and those predicted for 2020 due to climate change by ECHAM4. (C) Like (b) but computed by HadCM3 (Doll et al. 2002)

4.3 Global Land Cover

In order to determine the present and future relationship between land cover climate change and river hydrology, the current and future land cover around the world must be illustrated and compared the general influence of climate change on land cover. Then future scenarios of vegetation cover can be used to help determine how certain areas might change in terms of land cover influence on hydrology and land-use adaptation options. Foley et al. 2005 created a global map that depicts the global distribution of current potential vegetation, pasture density and croplands (Figure 6). The modified Budyoko model presented by Monserud et al. (1993) also depicts potential global vegetation under current climate conditions. The two models correlate satisfactorily. Sitch et al. 2003 and Gerter et al. 2004 created simulation models to predict the future changes in vegetation cover, in light of future climate change in 2100 (Figure 7). Their two models have a loose spatial correlation but vary in extents of change.

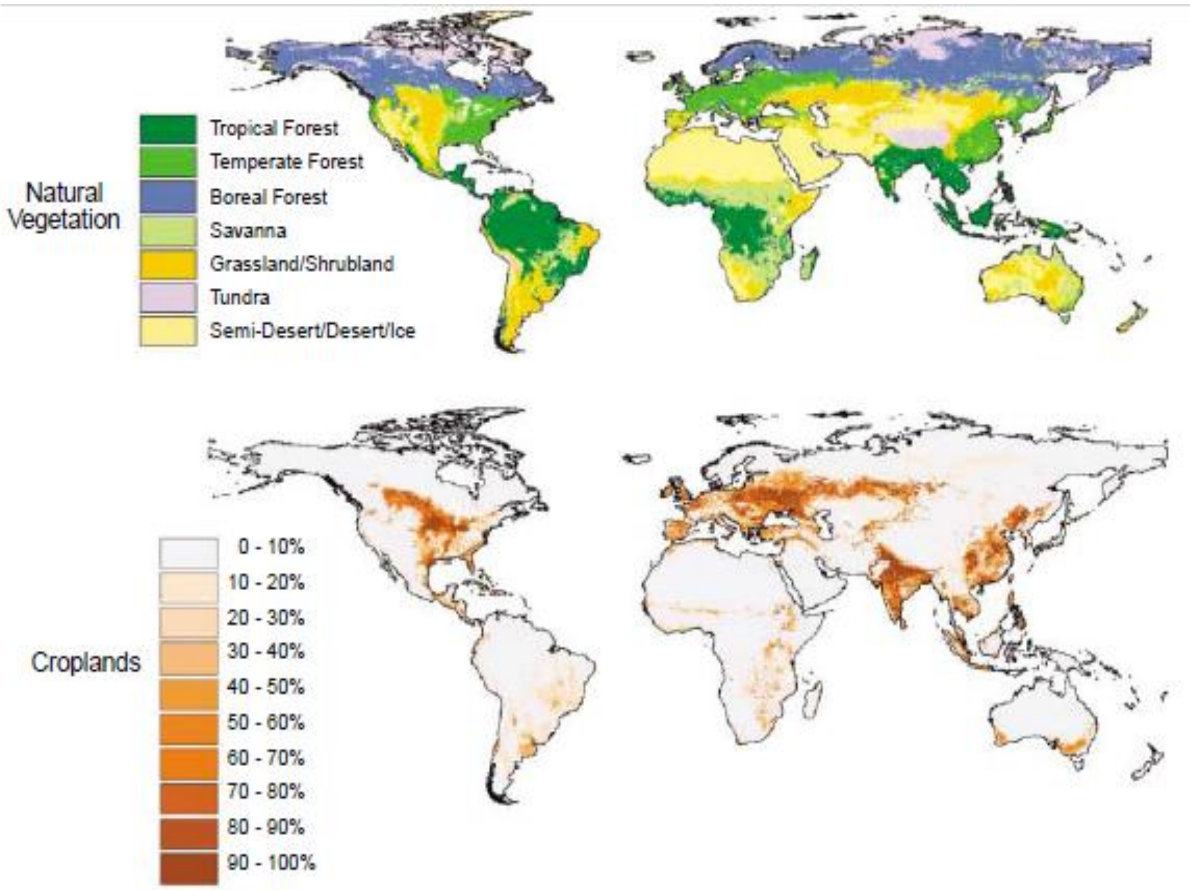


Figure 6- (Top)Worldwide vegetation potential (in the absence of human activity) and (Bottom) cropland intensity during the 1990s (Foley et al., 2005)

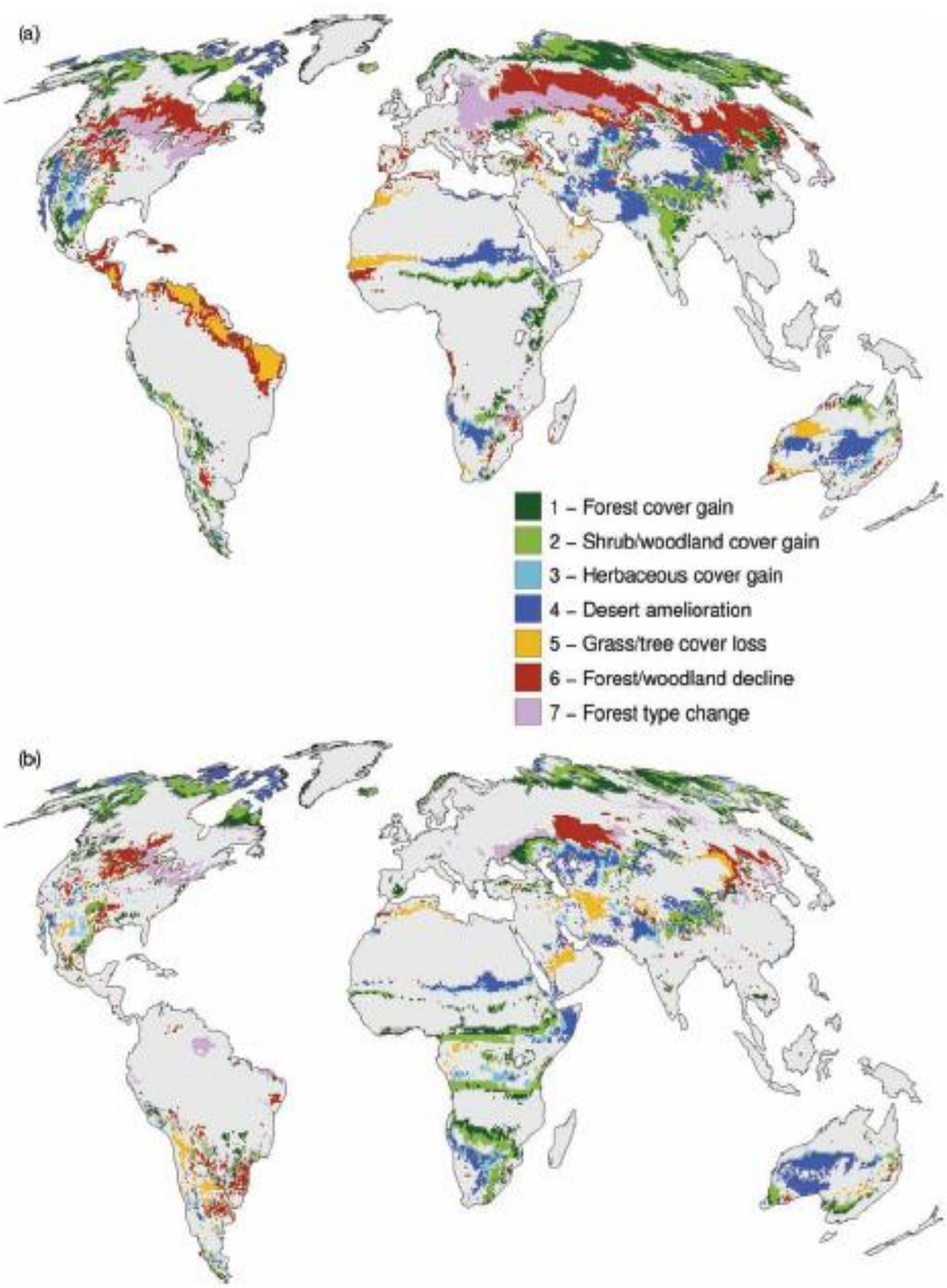


Figure 7- Predicted changes in terrestrial ecosystems by 2100 relative to 2000. Simulated by DGVM LPJ for two emission scenarios A2 and B1 (Sitch et al., 2003; Gerter et al., 2004)

Munserud et al. (1993) compared the results of four models in order to predict future vegetation. This study concluded with strong statistical confidence that all four models, although presenting different scenarios, conclude consistent results for the future of stable areas. The most stable areas are predicted to be desert, and Ice/polar desert regions. The locations will not change significantly, but the Ice/polar desert areas (excluding Antarctica) are projected to shrink by approximately 25%. The location of tropic rainforests is predicted to be stable, although size is predicted to increase 2-3 times. There is a consensus among all the models that tundra and tropical savanna is likely to sustain only moderate changes under global warming conditions. All Boreal zones are projected to shrink. Tundra may shrink as much as 50%. All vegetation zones in the subtropics are expected to expand, subtropical forest by 40-60% and subtropical steppe by 65-110%.

Global desert areas are not predicted to change significantly except in Africa where tropical areas are predicted to shrink as deserts expand. The OSU and the GISS predict expansion of seasonal forests on all continents, replacing savanna. Savanna is predicted to expand at the expense of desert in Australia. In the warmer UKMO scenario, savanna was predicted to expand at the expense of tropical rain forest. This is especially true for Indochina. In Africa, savanna is expected to shrink due to the expansion of the desert. Temperate steppe is projected to replace temperate boreal forests in much of Alaska, Canada, Germany, Scandinavia, and Eastern Siberia. Subtropical vegetation is projected to displace more moisture, demanding vegetation in the Western US, Mexico, Northeast China, the Mediterranean, East Brazil and South Africa. The opposite response is predicted in Australia where savanna is forecasted to expand at the expense of one third of the desert. All four models predicted shifts of 350-1000 km for Tundra (W/NW), Taiga (N/E), temperate forest (N/E), and steppe (N).

4.4 Global Agriculture

In order to determine land-use adaptation options/capacity and land cover influence on hydrology, it is important to have a well-rounded view of the land-use of various regions of the world, in developing countries, 70% of rural populations depend on agriculture for their livelihoods (Easterling, et al. IPCC, 2007). This may limit options for restoration, at the expense of agriculture in these areas

Easterling et al. 2007, described relevant facts about crops under the effects of climate change. The beneficial effects of CO_2 on crops increase up to a certain threshold temperature. In addition, the effect of CO_2 on crops is the greatest in areas under moisture stress. Models predict yield losses in the tropics under mild warming scenarios. In the Mid-high latitudes, crops will increase in yield with a threshold at 2^oC. The major vulnerabilities are in developing countries and lower latitudes.

Ramankutty and Foley (1998), compiled global agriculture data to create a representation of the distribution of cropland intensity with “reasonable accuracy”. The results highlighted in the most agriculturally intensive areas are the Northeast and Central US, (upper Mississippi River Basin), Eastern Europe, Western Russia, India and East China with crop fraction (fraction of land used for crop cultivation) up to .9-1 in some areas. The only areas with no croplands appear to be desert and Ice desert regions. These results correlate well with the results that Foley et al. (2005) established for the influence of crop fractions on runoff. In Foley’s map, areas of Indonesia, S/E South America, the southern tips of Australia, show that crops have an equally significant influence on runoff increase as the major agricultural hot spots. However, in Ramunkutty’s maps these areas have a rage of only .2-.5 crop fraction. Perhaps this says something about the runoff sensitivity to croplands in these areas.

The biomes with the highest cropland percentage are tropical deciduous forest, evergreen forest, temperate deciduous forest, grassland and dense shrub-lands with percentages ranging from 17.2-30%. Very low percentages are found in desert, tundra, and boreal areas (Ramenkutty et al. 2000). Parry et al. (2007) compiled agricultural data to compare global yields production and are of the major crops.

4.4.1 Current, Future and Potential Agricultural Distributions

Among the key factors determining the optimal distribution of crops and agriculture are yield changes, the corresponding need to expand (Leemans et al. 1994). When presented with potential land-use changes, there is a need to understand where there will be a need to expand and where potential new croplands lie spatially. Before that can be done it should be determined what crops are grown, and where. Leff et al. (2004) illustrated the regional distribution of crops around the world (Figure 3).

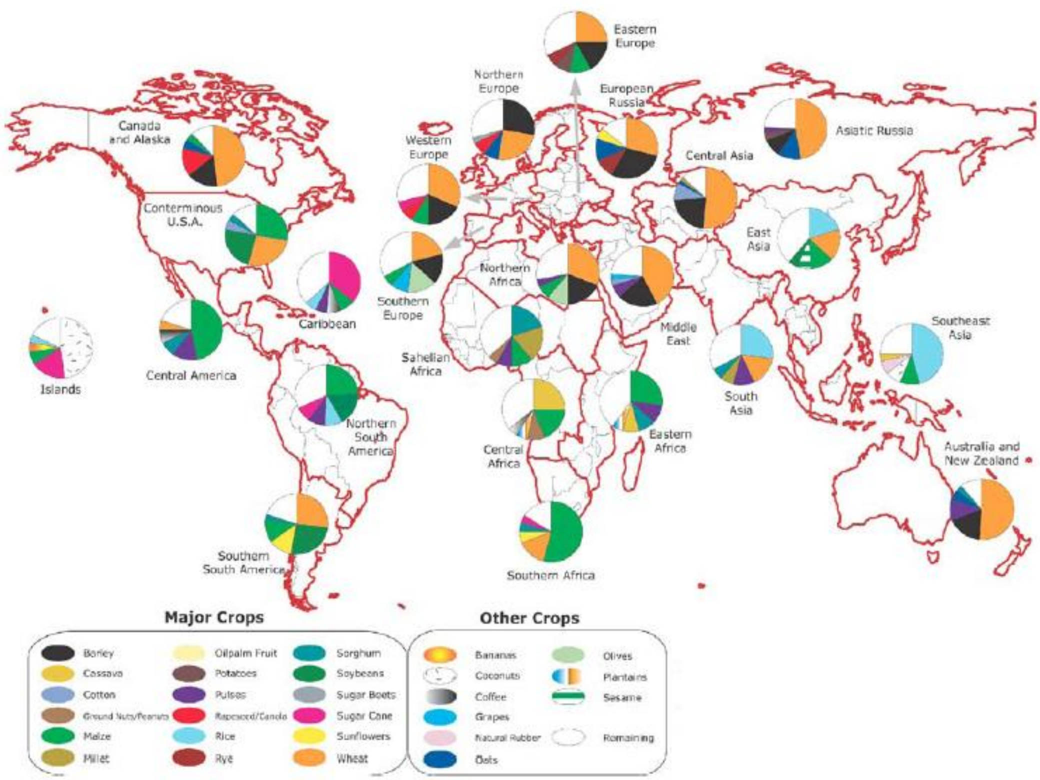


Figure 8- Regional distribution of major crops of the world divided into 24 agriculturally distinct regions. For each region, a pie chart represents the tom five most common commodities cultivated in the region (Leff et al., 2004).

In the same study, Leff et al. (2004), presented a global view of crop diversification based on the Agricultural Commodity Diversification Index (ACDI). There is very low crop diversification in North America, Brazil, Russia, the Middle East, Mongolia, the very southern tips of Australia, Sudan, Angola, Namibia and much of the Asian Islands. The areas of high diversity are India, East China, Venezuela, Columbia, Ecuador, Peru, Bolivia, Uruguay, Nigeria, Tanzania, and Ukraine.

Simulation models predict that the distribution of maize cultivation will expand drastically in much of South Canada by the year 2050. Maize is also projected to expand far into the east from Europe into Russia. However, the model results show these areas are expected to continue mediocre production rates of 10-15 t/ha dry weight. The North-Central US shows a contracting pattern, leaving large areas no longer productive. Sugar crops show the same pattern, including the odd results for the Northern US compared to nearby Southern Canada (Leemans et al. 1994).

The same study determined the global distribution of unused but potential agricultural lands showing great potentials in almost all of South America, Africa below the Sahara, South East Asia and the Asian islands, and northern parts of Australia. Fischer et al. (2002), mapped the global distribution of lands suitable for rain-fed agriculture based on a Suitability Index. The main regions of moderate to very high suitability are the eastern half of the US, Southern South America excluding South Argentina, most of Africa, excluding the Sahara, Europe, India, East China, the areas of Australia remote to the coast, Vietnam and Indonesia.

4.4.2 Future Agricultural Productivity and Demands

Agricultural demands are predicted to decline in the future. In addition, the FAO predicts an increase of 55% in crop productivity by 2030 and 80% by 2080. However, this will require a 19% increase in rain-fed agricultural lands and a 30% increase in irrigated lands. Most of the demand increases are expected in developing areas, mainly Sub-Saharan Africa and South America. The FAO predicts an increase in cereal yield of 1.1t/ha by 2050 in developing regions. However, this is in direct contradiction with the model results of Parry et al. (2004) (FAO, 2005). Easterling et al. (2007), presented the global distribution of climate change impacts on predicted cereal, livestock and forestry productivity by 2050 (figure 9). The predictions were based on literary research and expert judgment.

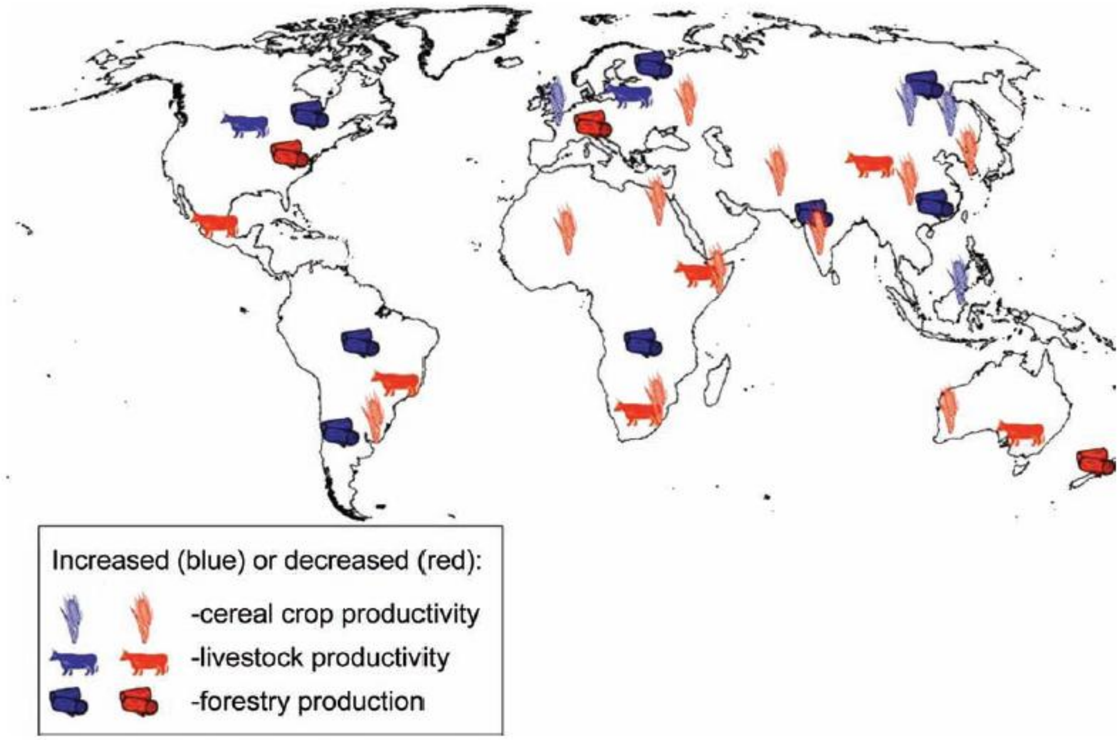


Figure 9- Major impacts of climate change on crop and livestock yields, and forestry production by 2050 based on literature review and expert judgment (Easterling et al., 2007).

Forestry is predicted to undergo significant changes throughout the globe due to climate change. Studies predict global shift from natural forest to plantation harvests, 20% in 2000, 40% in 2030, and 75% in 2070 (Easterling et al. 2007). Model results from various studies predict that by 2045 there will be a 29-38% reduction in forestry production in North America and Russia. South America and Oceana regions expect an increase. Forestry production is expected to increase in Western Europe and decrease in Eastern Europe. Harvest increases of 2-10% have been predicted for the Western US and 10-13% in South America and New Zealand. Harvest decreases are projected for Canada (Sohngen et al. 2001, Sohgen and Sedjo, 2005, Solberg et al. 2003, Perez Garcia et al , 2002). Supplies are predicted to shift from temperate to tropical zones and northern to southern hemisphere (Easterling et al. 2007).

Easterling et al. (2007), presented the sensitivity of crop yield to climate change for maize, wheat and rice, as derived from the results of 69 published studies at multiple simulation sites and scenarios. Responses include cases without adaptation and with adaptation. Adaptations represented in these studies include changes in planting, changes in cultivar, and shifts from rain-fed to irrigated conditions. In the results, climate change is measured by temperature but other factors were also measured.

Maize in mid-high latitudes seems relatively unaffected by climate change but seem to have the potential to increase yields by about 5% with adaptation. Maize in low latitudes can see yield losses of 17% with a 3^{o}C increase and up to 45% with a 5^{o}C increase. Adaptation could neutralize almost all of these losses at 3°C and reduce losses from 45% to 18% in the 5°C scenario. With low latitude maize, the influence of adaptation increases with temperature. Wheat yields initially increase in mid-high latitudes up to 3°C and then see reductions up to 21% at 5°C. Adaptation can neutralize the reduction of loss at 5°C in many cases. Wheat in low latitudes sees reductions of 20% at 3°C and up to 45% at 5°C. The reductions can be negated by land-use adaptation at 3°C but can only reduce losses from 45-33%. Rice in mid-high latitudes does not show significant reduction until 4°C and reductions of 20% can be neutralized by adaptation in many cases. In low latitudes, rice yields reduce 10% at a 3°C increase, and 20% at 5°C increase. Adaptation can negate yield losses from 7-17% as temperature increases.

Leemans et al. (1994) projected the global distribution of future wheat and maize productivity, expansion ad contraction by 2050. The results show large areas of increases and expansion in Canada, Russia, and East China. There is a large area of the North/Central US where the productivity of both crops are predicted to reduce significantly. Crop production is currently very high in this region. However increases are predicted for a large strip to the south east of that area.

4.5 Concerns in Specific Regions

Europe's sensitivity to a changing climate can be illustrated the great heat wave in the summer of 2003. During this time temperatures rose up to 6°C above averages and precipitation deficits up to 300mm. A record 36% drop in corn yield in the Italian Po Valley, in France, the corn grain crop yields reduced 30% and fruits and vegetables dropped 20% compared to 2002. Winter (wheat) crops almost reached maturity by the time the heat wave hit and still yields dropped 21% in France compared to 2002. EU agricultural losses were 16 billion Euro, 4 billion of which was from France alone (Easterling et al. 2007).

In Asia, a 2°C increase in temperature could reduce rice yields by .75 tones/ha in India and reduce rain-fed rice yields by 5-12% in China. Additionally, areas suitable for growing wheat could decrease in large portions of South Asia and the southern part of East Asia. Wheat production in India and china is predicted to increase 7-25% by 2050. An increased risk of crop losses in Bangladesh results from increased flood frequency under climate change scenarios (Easterling et al. 2007).

In Africa, yields of grain and other crops are threatened by increasing droughts. Some crops, such as maize, could be terminated in certain areas. Livestock production would suffer as usable rangeland becomes unproductive shrub land or desert in South Africa, Sudan, Nigeria and Mexico.. This exhibits how vulnerability to food insecurity is common in semi-arid areas where marginal groups rely on rain-fed agriculture. Farmers in such areas are reluctant to adopt new agricultural technology because of high costs and low consumption values (Adger et al. 2003, Easterling et al. 2007).

4.6 River Basin Case Studies

Table 2- Summery of the major attributes of the river basin case studies.

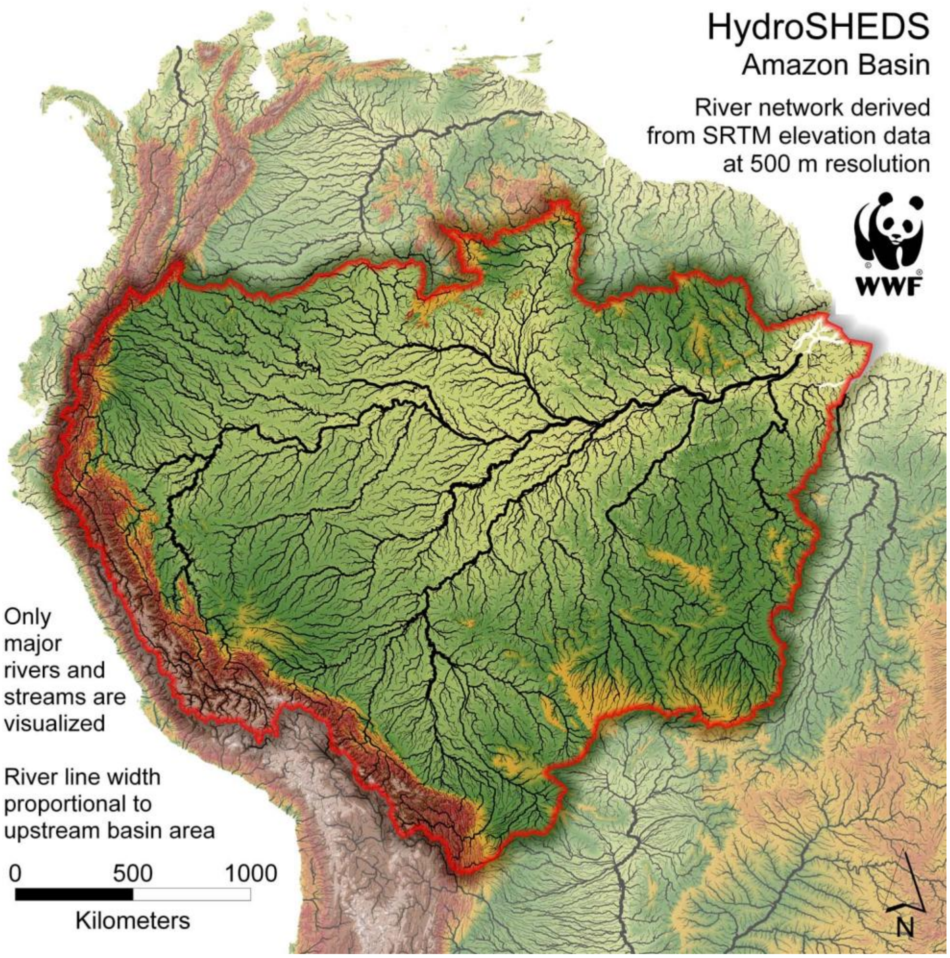
River Basin	Length	Area	Average Discharge	Climate	Population	Hydrological Regime	Socio-economic status	Water resources/use	Predicted Climate Changes
Amazon	7,100km[1]	6,100,000km^2[1]	209,000m^3/s[1]	Tropical	-Approx 10 million[6] -Growth rates range from 5.2%-7.2%[6] -Mostly concentrated in urban areas along the river[6]	Precipitation regulates inter-annual and inter-decadal fluctuations. The Amazon Rainforest also plays a critical role[2]	Subject to large social and economic pressure which leads to large scale deforestation[3]	-Abundant[4] -Moderate use[4] - Low irrigation[4]	-Strong Drying in the second half of the year by 2050[5] -Rainfall reductions by 2050[5] -Results vary[5]
Murray-Darling	Darling 2,740 km- Murray 2,530 km- Murrumbidgee 1,690 km[7]	1,059,000 km^2	767 m^3/s[8]	Rainforests east uplands, Temperate southeast, Subtropical northeast, Semiarid and arid west[9]	2,004,560[7]	Variability in precipitation results in variability in flow[8]	85% of the basin is owned by large agricultural businesses[7]	-Low and stressed[9] -83% of consumed water was for agriculture[9]	- Highly Uncertian[10]
Brahmaputra	2,906[11]	651,335[11]	21,261m3/s[11]	Subtropical, Subject to a summer monsoon	118,543,000[12]	-Fed by ancient reservoirs formed by glaciers[12] -12% of flow is glacier melt[12] -Discharge responds directly to rainfall with a one month lag[13]	-Poverty[11] -Strong economic growth and poverty reduction[11]	-Highly dependent on shrinking groundwater resources (reduced recharge)[14/15]	-Floods and flood area are predicted to increase 20-50% with a 6°C increase in temperature[16] -Most models predict an increase in precipitation[13/16]
Mississippi	3,766km[17]	3,200,000km^2[18]	18,300m^3/s[19]	Wide Range	Approx 70 million[18]	-Precipitation dominated hydrological system -land-use and land-cover changes have a large influence[18]	-Highly developed -Rapidly Industrialized agriculturally[20]	-Large resources[21] -Affluent irrigation and water use[22]	-Model Results Conflict for basin as a whole - However, generally they predict increases in precipitation for the upper east basin, decreases in the lower west.
Nile	6,825 km[23]	Approx 3 million km^2	2,800 m^3/s[23]	Mostly arid/semiarid in Egypt and Sudan, Tropical Climates in the East African lake regions and Southwestern Ethiopia[24]	- Estimated at over 250,000,000[25] -3% growth rate[25]	Two main sources subjected to heavy rainfall[25] -Equatorial Plateau -Ethiopian Highlands	Drought and famine are a feature of life[26]	-Low water resources [21,26,27] -Extremely stressed [21,26,27]	-Model results are too variable to reliably predict runoff and precipitation changes

Rhine	1320 km[28]	185,000 km²[28]	2200 m³/s[28]	-Temperate[28] -Alpine [28]	Approx 50 million[30] -low growth rates (5-.8%)	The alpine region- Snowmelt regime, max. discharge in summer Lowland- Summer min. discharge is attributed to evapo. Peaks in growing season[29]	-Highly developed -Agriculture not the major economic contributor [28]	Currently stable[31]	-Predicted increased winter precipitation of 20% by 2100 (increased discharge up to 40%)[28] -Predicted decreased summer discharge of 15% (evapo. Increases, winter storage decreases)[28]
Mackenzie	1,738 km[31]	1,800,000 km²[31]	15,500 m³/s[31]	Varies with region[31] -Cold temperate -Mountain -Subarctic -Arctic	397,000[32]	The annual spring break up effects water availability, ecosystems, and river geomorphology greatly[32]	Relatively pristine	-Plentiful resources[34] Extremely moderate use[34]	-GCM models predict a ranging of 3-7% decrease in runoff[32] -GCM models agree that precipitation is likely to increase but hydrological effects are offset by increase in evaporation[32] -Spring runoff increases and break up are predicted to occur earlier

Sources

(1) Organization of American States 2005, (2)WWF, (3) Marango et al. 1994, (4) Coe et al. 2009, (5) Nijssen et al. 2001, (6) Organization of American States 2005, (7) Australian Bureau of statistics, (8) Beare et al. 2002, (9) Bryan et al. 2004, (10) CSIRO, (11) Dimbock et al. 2003, (12) Erikson 2008, (13) Immerzeel et al. 2008 (14) IOP, conference 2009, (15) Mondal et al. 2000, (16) Mirza et al. 2003, (17) http://ga.water.usgs.gov/edu/riversofworld.html, (17) Foley et al. 2004, (18) Grimes 1991 (19) Sparks 2010 (20), Earth trends (21), Sun et al. 2008 (22), Awulachew 2008 (book) (23), Onway and Hulme 1996 (24) Karyabwite 2000, (25) Conway 2005 (26) Abu Zeid & Hefny 1992, (27) International Secretariat of the Dialogue on Water and Climate 2003, (29) Asselman et al. 2000, (30), Dammen et al. 1997, (31) Abdul at al. 2005, (32) Cohen et al. 1997, (33) Burn et al. 2008, (34) Yin 1999.

4.6.1 The Amazon



The Amazon River Basin is the largest source of fresh water in the world, responsible for 1/6 of global freshwater resources (Junk et al. 2007). The river basin houses one of the world's most diverse aquatic ecosystems. In addition to being a vast freshwater source and a global biodiversity hot spot, the river provides a broad range of social and ecological services, as well as effecting climate regulation. It is essential to investigate the threats, vulnerabilities and adaptation capabilities of such a significant global asset, as global climate change presents itself.

Although the basin is home to world's largest freshwater resource, very little of its water is used for irrigation. In the Brazilian savanna areas (Cerrados) of the center-west region, as well as North Brazil, the potential for irrigation has expanded substantially in recent years, following recent advances in soil management and irrigation techniques applicable in that region (FAO(20). Statistics show that the Brazil uses only a tiny fraction of its total freshwater resources (Earthtrends). Research shows that irrigated lands have nearly twice the yield as rain-fed lands for several major crops in the region (Kundel, FAO, 2008)

With a mean annual discharge of 210,000 m/sec, the river flow of the Amazon exceeds that of the nine other largest rivers combined (Organization of American States, 2005). Several climate models have confirmed that approximately 50% of its river flow originates from water recycled in the Rain Forest (Case, 2010). Much of the flow originates from, in, and adjacent to the Northern Andes (Organization of American States, 2005). The Amazon Rainforest plays a key role in the water balance of the river. Extensive studies have shown that increased deforestation affects the frequency of floods of rivers in the western Amazon from Peru. Over 60% of the water level variability can be explained by abundant rainfall over the Rio Solimoes and the Rio Negro catchments (Marango et al. 1994).

Tropical deforestation reduces evaporation and increases stream-flow. Global and meso-scale climate models indicate that once deforestation in the Amazon occurs on a very large scale (>100,000 km^2), atmospheric feedbacks my significantly reduce precipitation. Other studies have confirmed this notion, showing that significant reduction in precipitation will only occur if more then 40% of the Amazon rainforest is deforested (Coe et al. 2009).

The Amazon River not only plays a key role in the water cycle and balance in much of South America, but it is also a key driver in climate (Case, 2010). Not only is the surrounding rainforest a great sink, but the river also plays a key role in the ocean's sequestering of CO_2. By delivering a tremendous amount of nutrients into the ocean it increases the NPP of oceanic plumes. N_2 - fixation far from the mouth of the Amazon contributes to atmospheric sequestering of carbon in the Western Tropical North Atlantic (Subramaniam et al. 2008).

Cattle ranching is the leading source of deforestation in the Amazon, accounting for about 75% (Coe et al. 2009). Numerous studies have shown that deforestation tends to correlate with population density and can be a somewhat reliable indicator of deforestation. Deforestation is greatest in areas of high cattle counts and non-urban regions of high and growing population density. In Brazil, the heaviest deforestation takes place in the frontier and old frontier lands at proportions of 20-30% of land deforested (Perz et al. 2003). Deforestation rates are driven by a global demand for soybean and beef.

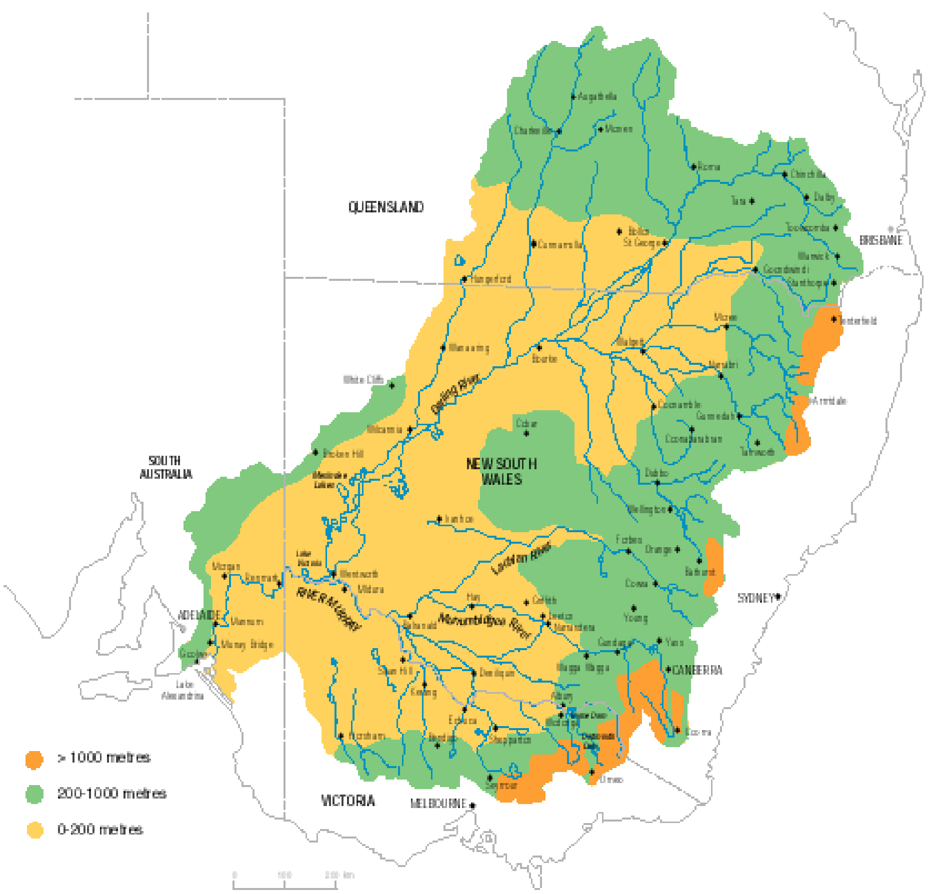
The services of the Amazon River include providing drinking water, livelihood, and protein for the majority of the population of the Amazon. In addition, it provides nearly all domestic and commercial transportation in the region (Coe at al, 2009). Although agriculture in the basin is crucial, little water is used for irrigation (Mclain et al. 2001). Commerce, agriculture, and transportation are intricately related to the annual flood cycle (Marango, et al. 2009). Besides internal needs, the basin provides the world a range of commodity and non commodity products such as wood, iron, steel, tin, and gold many of which (wood, gold, tin) have growing global demand (Organization of American States, 2005). Fearnside et al. (1999) predicted that plantation area would have to increase 38% in order to meet future demand.

Although model projections for the Amazon vary, they all generally agree that the region will experience a reduction in rainfall. Percentages from all possible scenarios in the Amazon range between 5, 10, 25, and 50% by 2050. As a result, silviculture area is will need to increase meet the current demand (Fearnside et al. 1999). For the basin specifically a 9.8% decrease in precipitation volume is projected. Two models predict a runoff increase and one projects a slight decrease (Nijssen et al. 2001). GCM models predict a basin wide temperature increase of 2-3^{o}C by 2050 (Mitchell et al. 1995; Kattenberg et al. 1996).

Decreased precipitation raises concerns of longer and more severe droughts and great changes in seasonality. When this is coupled with current land-use trends, increased erosion loss of ecologically and agriculturally valuable soils, loss of biodiversity, and decreased agricultural yields become major concerns (Case, 2010). GCM models predict that evergreen forests are to be succeeded by savanna and grassland in Eastern Amazonia and savanna will expand into parts of Western Amazonia (Cramer et al. 2004). Other modeling experiments project an expansion of savanna, grasslands and desert ecosystems into Northeastern Amazonia (White et al. 1999).

The IPCC (2001), predicts that subsistence farming in the Amazon will be hit hard by climate change. Northeastern Brazil has suffered some of the most severe yield impacts in the world. This area is home to over 45 million people, and highly vulnerable to droughts and famine in the absence of expected climate change (Case, 2010). Predicted agricultural yield decreases may be underestimated because the likely increase in pest infestation has not been incorporated into the model simulations.

4.6.2 The Murray-Darling Basin



The Murray-Darling Basin (MDB) is actually a river system composed of three main rivers, the Murray, the Darling, and the Murrumbidgee. These are Australia's three largest rivers in one basin, covering over 1 million km^2 and encompassing much of Southeast Australia. The Murray-Darling Basin contains a great range of climate conditions and vegetation ranging from rain-forests in the cool humid East Uplands temperate Mallee County of the southeast, subtropical areas of the northeast, and semiarid and arid plains of the far west. The basin also exhibits great temporal variation in climate and rainfall, abruptly shifting from drought dominated before 1948, to flood dominated until the present (Beare et al. 2002). The rainfall regime of the basin is highly stratified ranging from over a yearly average of over 1000 mm in some southern coastal areas to less then 300 mm/year in the southwest basin (Kundel, 2010).

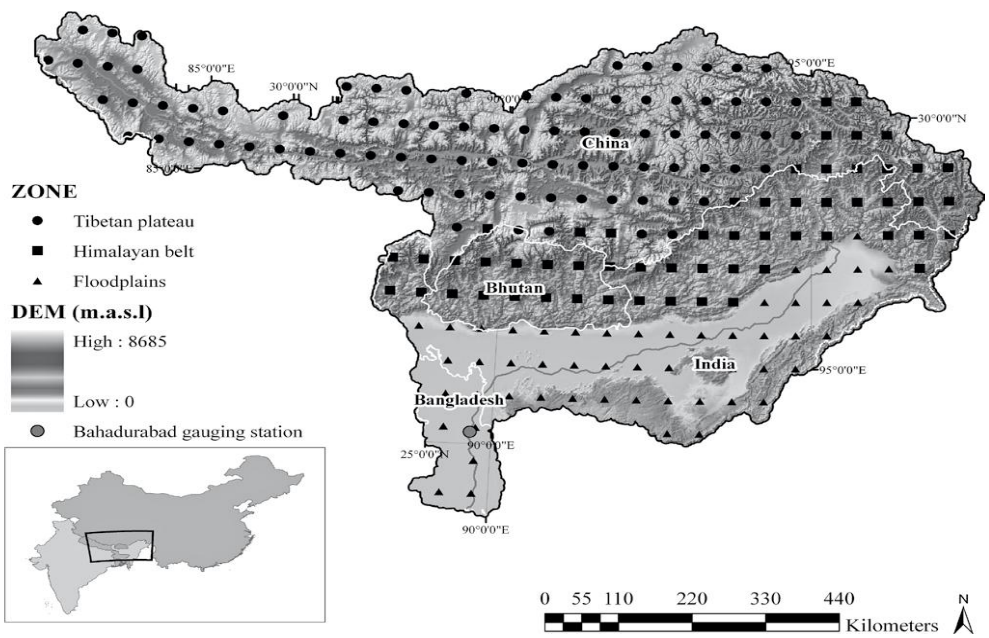
Despite the size of the Murray-Darling Basin, the surface water runoff is disproportionately small. Only about 10% if the basin contributes to river system runoff except in time of flooding (Beare et al. 2002). In this river basin, most of the runoff is created in the headwater catchments (Macquarie catchment) and flows into the Burrendong Dam. Reforestation may actually pose a threat to the river discharge in the Murray-Darling River Basin. Model results indicate that river flow would decrease 7-15% with only a 2-10% increase in reforested lands in the Macquarie Catchment. It has been said that this has broader implications applicable to the entire basin (CSIRO, 2002).

The Murray-Darling Basin consists of 67% agricultural lands amounting to a total of 89 million hectares and consuming 70% of Australia's water use (Australian Bureau of statistics, Bryan et al. 2004, Crab et al. 1996). The basin's agricultural composition is 95% sheep, beef cattle and cereal crops. There have been large trends of sheep pasture converting to other uses, mainly cattle, due to the recovery of beef prices. In addition there has been wide spread conversions from rain-fed to irrigated pastures, estimated at 22% from 1996-2001 (Bryan et al. 2004, Young and McColl, 2003). During the same period, there has been a 90,000 hectares expansion of cereal croplands and a 118,000 hectare reduction in sheep pasture. Beef pasture, rice and grapes have expanded in rages from 23,000-30,000 ha (Bryan et al. 2004).

Competition for water is high between supply to towns, irrigation, essential and endangered wetlands, and streamflow (CSIRO, 2002). The water requirement for ecology is an especially competitive need in this particular basin. For instance, the Macquiree Marshes are an important refuge and breeding area for water birds and other natural wildlife. It is listed under the RAMSAR Convention of Wetlands of International Importance and is very sensitive to flow regime changes. 50 GL of high security water and 75 GL of general security water have been allocated to the Marshes to ensure their ecological sustainability (Kingsford, 2000, CSIRO, 2002).

The Murray-Darling Basin has a high vulnerability to climate change impacts as the already limited flows and high water usage are further threatened by rising temperatures, decreased precipitation and changes in land-use trends. Future reforestation is likely but has not been quantified or estimated. Models project that flows into the Burrendong Dam will reduce +1- (-30) percentage by 2030 and +6-(-55) percentage by 2070 Projected precipitation changes are estimated to decrease in winter and spring by 2030. Predictions are highly uncertain for the summer and fall. An increase in discharge is highly unlikely (CSIRO, 2002).

4.6.3 The Brahmaputra



The Brahmaputra makes for a good case study due to its distinctive attributes. Most notably, it is subjected to an orographic summer monsoon of great climatic variability. The monsoon penetrates northward along the Brahmaputra in to the Southwest Tibetan Plateau (Erikson et al. 2008). In addition to the climatic variability, the basin is separated into three distinct topographies; the Tibetan Plateau in the North, the floodplains in the south, separated by the Himalayan Belt (Immerzeel et al. 2008). The Brahmaputra is fed by unique water reservoirs fed by glaciers 16,000 years ago (Erikson et al. 2008). Such a unique basin highlights the need to downscale to the basin level where imprecise global view cannot acutely analyze regions subjected to some of the world's more unique complications.

Satisfying the needs of rare ecosystems and human uses of the Brahmaputra River Basin will be a delicate balance. Due to frequent changes in the hydrologic patterns, zonation forms five distinct fish habitat types. Flood pulse is probably the most influential determinate of faunal distribution. In addition, fish migration is intimately related to flood regimes. However, deforestation due to population growth increases erosion in the upper basin, making the areas extremely sensitive to severe floods even after just a few days of continuous rain (Buruah and Biswas, 2002, IOP conference, 2009). To complicate adaptation measures, regulation of river flow with dams, barrages, and embankments seriously affects rare and endangered biodiversity of the Sundarban, the largest coastal wetland in the world. Further, it disrupts the natural flow regime patterns to which species are adapted (Gopel and Chauhan, 2006).

The land of the Brahmaputra River Basin consists of mixed shrublands and grasslands in the north and mostly agriculture grassland mosaic in the south. The southern mosaic is spotted with water bodies in the southwest and herbaceous wetlands in the southeast (Immerzeel et al. 2008). In the BFA (Brahmaputra Floodplain Area), agriculture is the mainstay of economic activity covering 67% of the area. However, only one third of the BFA depends on the river for irrigation, domestic and industrial needs. Although the area used to be highly dependent on groundwater, predictions of future impacts on groundwater has prompted governments to develop the use of Brahmaputra's water (Mondal et al. 2009, Buruah et al. 2002).

The many distinctive characteristics of the Brahmaputra give rise to a broad range of vulnerabilities to climate change. As glacial melt continues, it is likely that low-flow and water storage capacity will substantial decrease due to climate change. The impact on food production and economic growth will likely unfavorable. These shortages could arise abruptly. Some of the most densely populated areas on earth could be subjected to severe floods and water scarcity simultaneously. In addition to these vulnerabilities, large areas of permafrost at high altitudes will shrink, exacerbating erosion, stability and desertification (Erikson et al. 2008). The impacts of climate change are predicted to be more extreme the upper basin (Immerzeel et al. 2008).

Exacerbating the situation, agricultural water demands are projected to increase 6-10% for every 1^{o}C temperature increase. Further, warming has been documented and predicted to be significantly higher then the global average (Erikson et al. 2008). The proposed construction of a barrage on the Brahmaputra River in Bangladesh for improved water use, may alleviate some of the scarcity pressures but it is limited by the flat terrain (Mondal et al. 2009). Artificially managing river flow while avoiding large-scale ecosystem disruptions will be challenging.

4.6.4 The Mississippi

The Mississippi River Basin is a good example of a large, highly regulated river basin subjected to intense agricultural and land-use changes. The Mississippi basin home to some of the most agriculturally productive regions in the world, supplying about 40% of the world's corn and soybean (USDA, 2003). The upper basin is highly regulated by flood control levees, 53% of which are between Rock Island and St. Louis, 83% south of St. Louis. Negative effects on ecosystems have recently been recognized (UMBRA). Although cropland only covers about 30% of the basin the land-use intensity in this region is extreme and has profound influence on the rest of the basin (Foley et al. 2004).

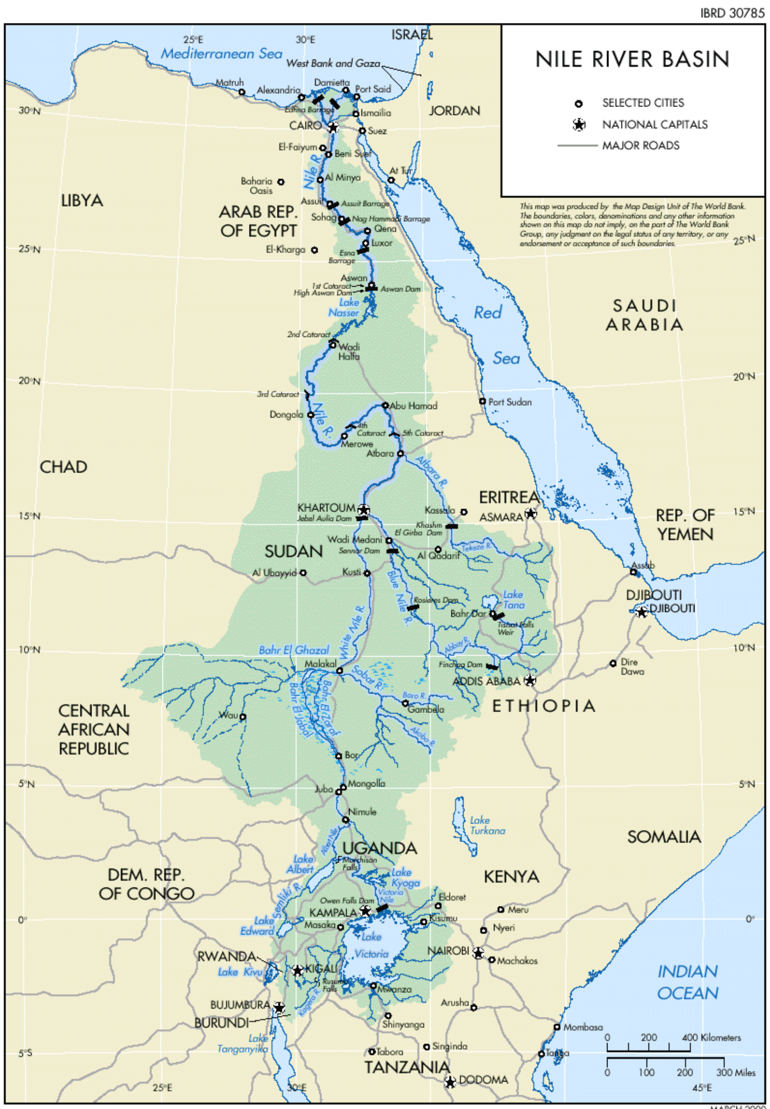
The land-use and land cover in the Mississippi River Basin ranges from mesic temperate forest in the east and irrigated agriculture in the west, and covers a variety of climate and ecological zones (Donner et al. 2003, Foley et al. 2004). In the east, where annual precipitation is significantly higher, the Basin is dominated by rain-fed crops (mainly corn and soybean), grasslands, pastures and forest. The west is dominated by rain-fed wheat, irrigated corn and soybean, grasslands, and shrublands. Agriculture is generally concentrated in the central upper basin with forest in the southeast (Foley et al. 2004).

Agricultural Industrialization (since the 1950s) has had profound effects on yields of the basin at the expense of natural habitats and soil erosion, despite a small decline in acreage. One of the most pronounced changes is the expansion of soybean from 3.5% of croplands in 1950 to over 22% today. Most of the change occurred in the Central US and the lower Mississippi Valley where soybean crops are now rotated with much more nitrogen demanding corn. Another notable shift during this time was the explosive increase in industrial fertilizer use, even unnecessarily (to an extent) over soybean croplands, as 64% of soybean lands do not require fertilization (Donner et al. 2003). As a result of agricultural industrialization and to a lesser extent climate change, US crop yields have increased significantly in the past century. A 20% increase in soybean yield/ hectare can be attributed to improved cultivars (genetics→high yield), increased fertilizer, higher planting densities, improved technology and increased reliance on irrigation. Maize average yields have increased from a range of 5-10 t/ha between 1990-2001 with the greatest increases in central regions (USDA, 2003).

The discharge of the Mississippi is highly influenced by the land-use of the basin. Floods have been increasing for the past 90 years and levees increase flood damage by increasing river stage and velocity. The rampant drainage of the wetlands has been blamed for many of today's water/water resource problems. The flood of 1993 and its damage to St. Louis highlighted the need for more wetlands. It has been estimated that strategically placing 13 million acres of wetlands on hydric soils could solve the basin's flooding problem in an ecologically sound manner by increasing base flow and decreasing floods (Hey et al. 1995). Schilling et al. (2004) showed that on a smaller scale, streamflow could be significantly influenced by the replacement of natural vegetation by row crops in Iowa. Process-based land-surface model of the entire Mississippi suggest that effects of land cover change on the water balance are strongly dependent on location and on the particular land cover transition. In the eastern basin, forest transition to summer crops increases flow. In the North Planes, grassland to summer crops decrease flow. Grassland transition to wheat has almost no net effect in the southern planes. The upper basin is most influenced by land-use changes (Foley et al. 2004).

The future of the Mississippi River Basin is uncertain, as future precipitation projection models conflict and water stress indexes have proved to be too difficult to predict, due to the competing influences of land-use and climate change and spatial variability (Sun et al. 2008). Further, there is large variability in future budget components and water yields (Jha et al. 2004). At present time water stress is marginal despite the fact that the US withdrawls over 25 percent of its total renewable freshwater resources each year (Earthtrends). Irrigation accounts for 74% of total water consumption. Over half of the withdrawal is from groundwater of the Mississippi valley, Western Texas and coastal regions (Sun et al. 2008).

4.6.5 The Nile



The Nile River Basin represents a region with serious water resource and societal vulnerabilities to climate change. Egypt and to a lesser extent, Sudan, are almost entirely dependent on waters from upstream riparian countries. Egypt's water consumption exceeded availability from 1981-1990 (Conway and Hulme, 1996). In fact, Egypt imports an estimated 15.3 km^3 of water annually. Upstream riparian countries are likely to demand more in the future. Although much more water originates in Sudan, it is only allocated 16.7-21.7 mk^3 (wet versus dry scenarios) compared to the 50.1-64.7 km^3 allocated to Egypt under the Nile Waters Agreement (Conway, 2005). Ethiopia is subjected to high water and food scarcity and only withdraws 2.2 km^2 annually (Earthtrends).

Although water demand is likely to increase and availability may decrease in the future, there is much room for improvement in water use efficiency. Per capita water supply is expected to decrease from 922 m^3 (in 1990) to 337 m^3 in 2025 (Conway and Hulme, 1996). Large population growth rates (3%/year) and Egypt's engagements in huge expansion policy for irrigated agricultural lands in the Western Desert and Sunai reduce resource and exacerbate threats of water scarcity (Karyabwite, 2000, Conway, 1995). Water demand for desert reclamation is estimated to increase total water demand by 9.1 km^3/year by 2025.

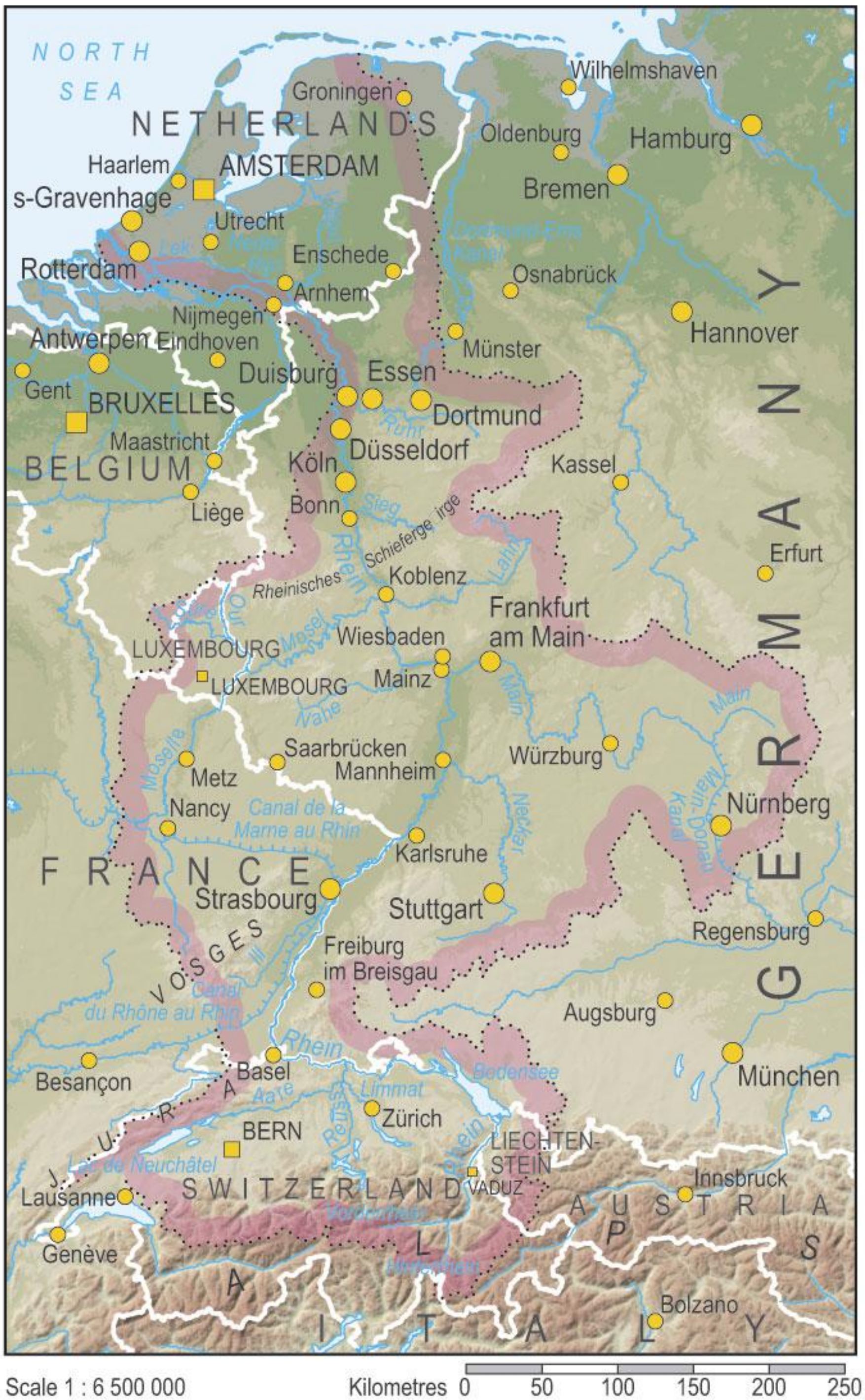
It appears that much of these water losses are unnecessary. Firs, there are large losses due to seepage and evaporation, especially in the Bahr el Ghazal and the Sobat sub-basins. Second, over 80% of water use in the basin is used for agriculture and the resource is not used efficiently. Research is being conducted on how to make new irrigation systems more affordable (Abu Zeid & Hefny, 1992). Future water demands can be reduced significantly by increasing the reuse of agricultural drainage water and improved water transport and distribution. There is also a large potential to improve irrigation and potable water use efficiency (Abu Zeid & Hefny, 1992).

Despite being the main consumer of water resources in the basin, the area cover of croplands is relatively small in the Nile River Basin. The upper Nile basin is predominately barren with dense urban and industrial concentration along the river in much of Egypt and croplands in the delta. There is a strip of grassland below the barren region in central Sudan and croplands/vegetation mosaic below that. The lower half of the basin is mostly savanna with large water bodies and croplands in the deep South (Awulachew, 2008).

The agricultural land-use in the Nile River Basin is often inappropriate. Rice and sugarcane production is high in Egypt, which is ill-advised due to the low yield/water ratio. The Nile Basin Initiative expresses interest in developing cotton production in Egypt and Hydropower in Ethiopia. In addition, Egypt's surface flooding irrigation system is only 50% efficient (Karyabwite, 2000).

The future of the Nile River Basin is highly uncertain. Drought and food security are the major concerns. Due to the high natural climate variability of the region, model results for precipitation and streamflow are unreliable (Conway, 1995, Conway and Hulme, 1996). However, model projections for future temperatures are more consistent with predictions averaging 1.4^oC by 2050 and 2.4^oC by the end of the 21st century. The evaporation implications of this are likely to have a negative effect on crop yield and water use efficiency (Agrawala, OECD, 2005). While water demands are expected to increase in the region, estimated future water availability and demands indicate a slight surplus in 2025. However, this is not the case if the additional water needed for desert reclamation is incorporated (Conway and Hulme, 1996). The future of the basin will involve a careful balance of food, water, and efficiency.

4.6.6 The Rhine



The Rhine River Basin is an example of a highly populated and regulated river. In contrast to most river basin communities, agriculture is not the dominant component of the economy. Although almost half of the basin is used for agriculture, the region is characterized by a historical transition from the former agro-based economy to the large-scale resource based industrial economy seen today. (The basin is 49% agriculture, 33% forest, 11% urban areas, and 7% surface runoff) Recently, there has been a shift towards small-medium sized enterprise and service sectors. Agriculture is still a major land-use activity but only makes a comparatively modest contribution to the economy (International Secretariat of the Dialogue on Water and Climate, 2003).

Because of flood control issues and the river's navigational significance as the busiest river in Europe, there are many fabricated provisions to the river, regulating the flow. Branches of the lower Rhine are protected from flooding by embankments. Three weirs in the lower Rhine control water flow to divert sufficient water to Lake Ijsselmeer during low discharge. In the lowland area, excess water in the polders is drained by pumping stations and drainage canals into storage reservoirs (boezems). In the summer, fresh water from Lake Ijsselmeer is pumped into the polders to control the levels and prevent salt-water intrusion. A considerable amount of water is diverted from the Rhine into navigation canals (Asselman et al. 2000).

The discharge of the Rhine is determined by the amount and timing of precipitation, snow storage and melt in the Alps, evapotranspiration surplus in the summer, groundwater/ soil storage. The alpine region is governed by snowmelt regime and exhibits a pronounced maximum discharge in the summer. Retention of water in alpine lakes smoothes discharge fluctuations. In the Mosel Confluence the discharge is at its maximum in winter although there is considerable discharge from the Alps in the summer months. In the central and lowlands areas, the summer discharge is at a minimum due to evapotranspiration during the growing season, despite maximum precipitation in the summer (Asselman et al. 2000).

Agricultural activity and water use is most concentrated in the Netherlands and Lowlands. Although land used for agriculture ranges from 51-67% (except the Landquart catchment where it is 13%), in Switzerland, only 4% of surface water withdrawals are for agriculture. In contrast, in Germany the value is at 20% and 34% in the Netherlands (Daamen et al. 1997, Earthtrends)

The Ecology of the Rhine is becoming more and more of a high priority. In the Rhine, aquatic habitats must be interconnected to maintain ecological continuity. The "Rhine 2020" sets specific goals for reestablishing habitat patch connectivity. The implementation requires restoring river dynamics, change to more extensive agriculture in the floodplains, and reconnection of old river branches and torrents. This will improve migration and recolonization after extreme events. Various river structures may interfere with this goal. The ecological state of the Rhine has improved greatly after the "Program for the Sustainable Development of the Rhine" was implemented in 1995 (ICPR).

In the future, floods and navigation will likely be major concerns due to the predicted effects of climate change and the probable substantial growth in navigation (Asselman et al. 2000). The discharge of the Rhine is projected to increase in terms of both frequency and magnitude of peak flow (Middelkoop et al. 2001). The discharge regime is expected to shift from a snow fall/melt to a rainfall regime. Winter discharges are expected to increase because of expected increase in snowmelt, projected increase in precipitation, and discharge regime shift, especially in the Alps (up to 40%). Due to regime shift, temperature increases, and increase evapotranspiration, the summer discharge is expected to decrease approximately 15%. By the end of the 21st century temperature in the basin is expected to increase 2-4^{o}C and precipitation is projected to increase about 20% (International Secretariat of the Dialogue on Water and Climate, 2003, Middelkoop et al. 2001).

Because of the above-mentioned predictions and projections, flood protection is a concern, especially in the winter. Summer floods are predicted to decrease slightly (Daamen et al. 1997). This increase in flood frequency will stop inland navigation more often (Middelkoop et al. 2001). According to the WOFOST model, crop production is projected to increase in the basin due to climate change. However, the land-use implications are said to be minor. Regardless of climate change, build-up area is predicted to increase at the expense of agricultural lands. This could open possibilities for natural development and forestation (Daamen et al. 1997). Lower summer discharges may hinder navigation, decreasing the load capacity and days of possible navigation. Water demand for agriculture is expected to increase due to higher temperature and evaporation. Germany, Rotterdam, and Lobith are major areas of navigational concerns in light of predicted climate changes (International Secretariat of the Dialogue on Water and Climate, 2003, Middelkoop et al. 2001). High temperatures threaten to cause permafrost degradation and rockslides/ movement in large areas (Middelkoop et al. 2001).

4.6.7 The Mackenzie

The Mackenzie River Basin of Canada is a high latitude river basin with a unique competitor for land-use. Aboriginal Peoples harvest wildlife for subsistence and are beginning to own more land. Currently, agriculture is restricted to the lower basin. Although warming temperatures imply that agriculture will soon be able to expand north, the upper basin is used for forestry and wildlife, which is important for native communities who rely on wildlife for animals, food, and fur. Upstream developments of the forestry industry are beginning to arouse concerns of downstream implications (Cohen et al. 1997).

The Mackenzie is a natural resource based economy (Yin et al. 1999). Although water use is comparatively modest, instream flow requirements are crucial for fish, birds and other wildlife. The Peace-Athabasca delta has reached new water level lows and wildlife habitat viability is a growing concern. Experiments have been conducted to induce flooding of ecosystems by artificial dams (Cohen et al. 1997). In addition to its use to sustain the rich agricultural land and crucial wildlife, the Mackenzie River Basin is vital for plentiful water supplies, navigation routes, and is a major energy supplier for all of Canada (Yin et al. 1999). In addition, Nonrenewable resources such as fossil fuels are being mined throughout the region (Cohen et al. 1997)

The annual spring break-up is the most significant hydrological event. Changes in the timing of this event could significantly influence water availability, river geomorphology, and river ecosystems. In the future, an earlier onset of spring runoff can be expected because of increasing spring temperatures (Burn et al. 2008). Although an increase in runoff was expected, all but one model scenario (composite analogue) showed a decrease (Cohen et al. 1997). Current noteworthy trends in discharge include strong increasing trends in winter flow and minimum annual flow. Weak decreasing trends have been detected for annual mean flow and early summer/late fall discharges (Abdul et al. 2005). Studies have shown that there is an observed trend in the spring freshet to arrive earlier (Burn et al. 2008).

The basin consists of 75% continuous and discontinuous permafrost zones and crosses a variety of terrains. The basin crosses several climate zones including, cold temperate, mountain, sub-arctic, and arctic (Abdul et al. 2005). The Mackenzie consists of three main sub-basins, the Liard, the Peace, and the Athabasca. The Liard River runs from headwater locations through terrains of boreal forests, wetlands, high alpine tundra, and sub-arctic forest. The Peace River originates in the rocky mountains of British Columbia. The Athabasca (southern basin) originates in the Columbia Ice Field and is regulated by the Bennett Dam. The Athabasca River basin has three main regions, the Rocky Mountains, the Interior planes, and the Canadian Shield (Burn et al. 2008).

Due to the unique features of the basin there are unique concerns and vulnerabilities to climate change. The major areas of concern include, environmental quality, natural resources, and native lifestyles. Agriculture and forestry are of growing concern in Canada and especially the Mackenzie Basin (Yin et al. 1999). Accelerated erosion and landslides due to permafrost melt and extreme events (storm, fire, etc) arouse concerns effecting transportation, mining, buildings and other engineering structures. For example, the "winter road season" will be threatened in a warmer climate and land transportation on roads built on stable snow/ice in the winter will be threatened. Insulation and expansion of all season roads could be used to adapt here. Another prominent threat is communities vulnerable to spring flood risks. Further, sloping terrain and the Beauford Sea Coastal zone are especially vulnerable to erosion and landslides. Other conflicting predicted impacts of climate change on the basin are increased fire hazard and the invasion of new pests and diseases from warmer regions. Perhaps most conflicting are potential land-use demands as agriculture could expand north to utilize newly cultivatable soils. GISS model scenario predicts a significant increase in soil erosion in the basin (Cohen et al. 1997, Yin et al. 1999).

Although there is a broad range of concerns when faced with climate change, the Mackenzie River Basin is also expecting some potentially beneficial effects of warmer temperatures. A warming scenario could allow small grains to be cultivated further north, increasing cultivatable land by 10 million ha (Cohen et al. 1997). It is estimated that warming climate could ease thermal constraints to agriculture in this region as well as extend the frost-free growing season and area. Declining crop and forestry yields will likely result in an increase of grain cultivating land. However, an increase in cultivated land for crops will result in a further dramatic increase in soil erosion in the basin and will affect wildlife habitat (Yin et al. 1999).

5 Discussion

The impacts of global climate change on river basin hydrology are numerous and diverse. As no two regions are exactly alike, no similar change will have the same result in any two areas. Predicted impacts will have a drastically different outcome depending on the river basin and its attributes. After comparing the global trends to the specifics of the case study basins, patterns emerge on what the concerns and possibilities are across a range of basin characteristics and possible futures. In the following section the major threats, adaptation opportunities and barriers of each continent (excluding Antartica) are discussed. Barriers are regarded as anything that will prohibit or challenge an adaptation effort. Then, the relevance of the river basin case study if the corresponding continent is described. Based on the exhibited information, adaptation priorities for the basin are suggested.

5.1 Africa

5.1.1 Predicted Threats, Adaptation Opportunities, and Barriers; where are they?

Multi-model averages highlight the threat of significant predicted decreases in precipitation and runoff for large areas of northern and southern areas of Africa. This is likely to hinder the ability of these regions to cope with the increase in irrigation needs. In addition, it is expected that decreases in precipitation and runoff will affect areas that are currently suitable for rain-fed agriculture in sub-tropical areas. Subsections of these regions are already putting tremendous stress on the discharge of their rivers as a result of fresh water exploitation. This water stress will be a barrier to the adaptation to reduced precipitation and river discharge. However, currently there are large areas of cultivation of crops in North and Southern Africa, which is ill-advised for water stressed regions. This indicates that there is significant room for land-use improvement as the climate changes. Crop shifts could be a useful adaptation opportunity in these regions.

In Northern Africa, the primary crops grown are wheat and barley (Leff et al. 2004). If rainfall and discharge reduce significantly in this area it would be advisable to switch to more drought resistant crops such as sorghum, millet, and groundnuts to improve food and water security. Maize is currently the dominant crop of South Africa (Leff et al. 2004). Maize is the least drought resistant crop, especially in this region (Wahaj et al. 2007). Further, Maize is highly sensitive to climate change in low latitudes, even with land-use adaptation efforts (Easterling, IPCC, 2007). If climate change influences the area as predicted, a large-scale shift to drought resistant crops may be desirable.

Threats of increasing discharge and floods are highlighted by mult-model averages for East/Central Africa (Easterling et al. IPCC, 2007, IPCC synthesis report, 2007). Nearing et al. (2004) predicted an increase in soil erosion risks for areas of predicted increase in precipitation and runoff. If croplands are to expand in Central Africa, it should be in conjunction with soil conservation practices to help avoid increases in erosion. The lower half of this region is conveniently located in Central Africa were natural vegetation (tropical forest/tropical savanna) is thicker and hence more capable of soothing the effects of stronger discharges (Monserud et al. 1993, FAO (2, land-use e.o. hydrology). Moserud et al. (1993) predicted that tropical rainforests are relatively stable and will significantly increase in size in the future. Tropical savanna is predicted to undergo only moderate change. This may help sustain some of the future discharge increases. Natural vegetation buffers are an adaptive opportunity in this region.

In East/Central Africa, it may be useful to increase the amount of maize in place of the predominant soybean as the predicted increase in rainfall and runoff my significantly increase maize yields here. Maize yields have shown a high yield reaction to increased water (Wahaj et al. 2007). This may be a potential land-use adaptive option to the predicted threat reducing agricultural yields in this same area.

5.1.2 Lessons for the Nile

Much of implications of the global data are reflected in the future implications for the Nile River Basin. This basin is characterized my high water stress, low food security, and a high likelihood for climate change to exacerbate both. Further, future crop production yield losses, and water demand increases are apparent in both the global scale and basin scale data. Both global and basin perspectives highlight a possible need for crop shifts. In particular, high rice, and sugarcane production, together with the potential increase in cotton production in Egypt is more highly ill-advised and not well represented in global data. There are vital considerations that should be incorporated into land-use adaptation strategies that are not made evident by global data. Global data would suggest that the capability to increase water use efficiency is low, as the ability for low income rural farmers to adopt new technologies is limited. However, Abu Zeid & Hefny (1992) and Karyabwite et al. (2000) showed that the specific irrigation and water use of the Nile River Basin has great potentials to increase water use efficiency. Although the global perspective predicts a large decrease in runoff, the hydrology of the basin is too complex to predict accurately.

5.1.3 Future Land-use Adaptive Priorities of the Nile

Based on the available data on future scenarios of the Nile River Basin, the current specific crop acreage is not advisable land use. Due to a likely decrease in water availability, crop production, increase in evaporation and water demands, water inefficient crops such as rice, sugarcane and cotton may not be a feasible option in the future. However, economic incentives of such land-uses have not been incorporated into this study. The potential for a large shift towards drought resistant crops (sorghum, millet, and groundnuts) should be further investigated. Expansion of cotton production in Egypt appears to be a potentially highly problematic endeavor. The threat of poor food security and desert expansion indicates a need to increase and relocate crop acreage. Although the planned expansion of irrigated land in the Western Desert and Sunai may alleviate some concerns of future food security, the irrigation toll is tremendous. There is an abundance of potential agricultural lands throughout Africa, many of which have rain-fed potential. Alternative areas for agricultural land expansion should be considered before any large investments are made. Food security is often a problem of distribution rather then supply. Although there are some constraints, there is a large potential for water-use efficiency improvements. The dense urban concentration along the Nile in Egypt makes the area vulnerable to floods. However, as future discharges of the Nile are uncertain, precautionary actions are limited.

5.2 Europe

5.2.1 Predicted Threats, Adaptation Opportunities, and Barriers; where are they?

Large reductions in runoff are predicted for almost all of South. Multi-model averages for future runoff give a higher spatial resolution, showing that greater reductions are expected the further south one goes (Bernstien et al. 2007). By the decade of 2090-2099, most of Europe is expected to exhibit large decreases in precipitation in he second half of the year. By this time, the majority of areas in Western Europe are predicted to decrease by 20% but predicted decreases are milder in the eastern regions. The prominent threat of precipitation and discharge reductions for the southern half of Europe could have drastic effects on agriculture and hinder the lands currently suitable for rain-fed agriculture in the Mediterranean (Easterling, IPCC, 2007).

To complicate the issue, there is a large subsection of Southern Europe where irrigation requirements are expected to increase significantly. This is likely to be a major barrier to adapting the reductions in this region. In addition, predicted water use/discharge is predicted to increase throughout the continent mostly because of population change over climate change (Vorossmarty et al. 2010). A decrease in water availability and increase in demand seems likely for much of Southern Europe. This is supported by model results of predicted irrigation requirements by 2020 (Doll et al. 2002). The widespread adoption of more efficient irrigation systems is certainly feasible and should be a high priority adaptive opportunity to be planned and employed.

The model results of Leemans et al. (1994) predicted a great increase in maize productive land in Northern European Russia and Sweden. The study also predicts a general expansion of agriculturally viable lands north, yield decreases in the south, and increases in the north. The same is true for sugar crops but to a greater extent north. Cereal crops are predicted to increase in productivity in Northwestern Europe and Forestry in the Northeast. Increases in such agricultural land could offset predicted agricultural setbacks of the south and prove to be a great adaptive opportunity. This opportunity overlaps with the feasibility and need to increase irrigation efficiency in central regions.

However, increasing discharges in the north is also a great flood threat. Replacing temperate forest with agricultural land in areas with a predicted increase in runoff could pose serious erosion and flooding problems. A significant barrier to this adaptation opportunity presents becuse crop fraction has been demonstrated to have a profound influence on runoff in a large portion of Northeast Europe and Russia. If new agricultural land-use is to be implemented in these regions, cropland with restored ecosystem services can help increase crop production and regulate water flow simultaneously. This approach also has significant potential to mediate pests and diseases that may expand their range north as climate change progresses (Doll et al. 2002).

Wheat is a major crop cultivated throughout Europe. The IPCC estimates that on average land-use adaptations have high potential to negate the effects of climate change on wheat yield up to increases of 5^{o}C (Easterling, IPCC, 2007). Such land-use adaptations include changes in planting, changes in cultivar and switching from rain-fed-irrigated. A transition to crops requiring less water is not necessary, as Europe has the capability to adjust irrigation as an adaptation effort. However, maize yield is reactive to water increases. It may be advisable to increase maize acreage in some of the northern regions of Europe where precipitation and runoff are predicted to increase.

The heatwave of 2003 highlighted Europe’s agricultural vulnerability to climate change. With temperatures of 6^{o}C above average and precipitation deficits up to 300m, EU losses amounted to 16 billion, 4 billion from France alone. Yield losses included a 36% drop in corn yield in the Italian Po Valley, corn, and grain crop yields reduced 30% in France compared to 2002. In France, winter (wheat) crops almost reached maturity by the time the heat wave hit, yet yields dropped 21% in France in 2003, as compared to 2002 (Easterling, IPCC, 2007).

5.2.2 Lessons for the Rhine

The global perspective does not accurately account for the specific predictions for the Rhine. Global distribution of cropland intensity shows that this region has had a lower cropland intensity compared to other parts of the continent (Ramankutty et al. 1998). Although the basin’s economy is not agriculturally based, there is a significantly higher-concentration of croplands in the Netherlands compared to the rest of the basin (Daamen et al. 1997, Earthtrends). The spatial resolution of the global data does not account for this distribution. Further, the global data suggests drastic precipitation and discharge decrease for most of the basin, especially the headwater regions (IPCC synthesis report, 2007, Easterling, IPCC, 2007). However, for the Rhine, both precipitation and discharge is expecting to increase.

One might think that the discrepancy may be a result of the Rhine's snowmelt discharge regime. However, it is predicted that this regime will shift to a rainfall dominated regime (International Secretariat of the Dialogue on Water and Climate, 2003, Middelkoop et al. 2001). In this case, the global data does not make a sufficient or coherent contribution to the case of the Rhine. However, concerns and predictions of the continent as a whole (derived from the global data) can influence the optimum future land-use of river basins in the north where agriculture will become viable and in the south where irrigation needs are likely to increase and crop production and water availability are expected to decrease.

5.2.3 Future Land-use Adaptive Priorities of the Rhine

The future land-use changes of the Rhine should focus on regulating the flow while preserving ecology and ecological continuity. In the Rhine River Basin, agriculture is not a dominant contributor to the economy (International Secretariat of the Dialogue on Water and Climate, 2003). This increases land-use adaptive capacity greatly as there is greater flexibility in how the land can be used. Creating room for the river can alleviate some flood concerns. Strategically reforesting designated areas con mitigate floods.. Therefore, it is a lower land-use priority. In light of the predicted hydrological changes and societal aspects functions of the Rhine (navigation, 11% urban land use, etc) floods and river flow regulation are primary concerns for the future (Daamen et al. 1997). However, many river structures interfere with ecological continuity and the growing priority of improving the ecological state of the Rhine (IPCR). Further, 33% of the basin is forest, which can, and should be preserved, not only as valued ecosystems, but also as natural flood, flow and erosion regulators.

The first step in this process was setting targets for ecological continuity. Once the detailed targets are achieved, animals may move up and down stream and plants can be carried by currents. Although streamflow regulatory structures may interfere, by-pass rivers and fish-ways or fish passes may help (IKSR 2010, International Secretariat of the Dialogue on Water and Climate, 2003). The 1998 "Action Plan on Flood Defense" focuses on storing water in the catchment, detaining water with natural ecosystems and allowing the river to expand. This should involve spatial reservation of sufficiently large floodplain area and ecological restoration of floodplains (Middelkoop et al. 2001)

Due to an EU food production excess, land-use can be altered to increase natural biomass, which promotes an increase in infiltration and evaporation and reduces runoff (Lundqvist, 2010, International Secretariat of the Dialogue on Water and Climate, 2003). Land-use planning efforts should include mapping of endangered areas and selectively denying building permits. The result will be strategically placed natural retention and detention basins regulating floods and preserving the natural river system. Measures should be carried out in a manner as close to nature as possible and avoid interference with the landscape (Daamen et al. 2007).

In order to safeguard navigation, an increase design discharge of river dikes by 5-8% is planned by 2050. Research is being conducted to investigate the possibility of using alpine lakes to regulate discharge (Daamen et al. 1997, Middelkoop et al. 2001)

5.3 North America

5.3.1 Predicted Threats, Adaptation Opportunities, and Barriers; where are they?

The continental US cultivates copious amounts of maize, soybean and wheat (Leff et al, 2004). North/Central US is a region of intense agriculture and crop export resulting in the area's considerable contribution to global crop production. Model projections indicate that large areas of cultivation will suffer extreme yield reductions in the North Central US due to climate change. This is perhaps the greatest climate change threat to the US. However, Models predict yield increases for a large strip of land to the southeast of this area, which is currently less agriculturally intensive (Leemans et al, 1994).

The east half of the US is well suited to rain-fed agriculture and expected increases in precipitation and runoff will support this production. Further, maize yields respond well to increase in water compared to other crops. Reducing the intensity of agriculture in North Central US and expanding croplands with restored ecosystem services throughout the Eastern half of the US could reduce flood and erosion concerns while maintaining current maize production and healthy river hydrology. Hence, the strip of predicted increased yield could be a successful adaptation option to balance the significant decrease predicted for the North/Central US.

Extreme increases in precipitation are projected for Alaska and Northern Canada (Bernstien et al. 2007). This translates to increases in runoff for a large region of the East US and almost all of Canada. In general, increases in runoff bring threats of flooding and soil erosion. Future floods and soil erosion could prove to be a significant threat to the North/Eastern US and Canada. The largest changes in river hydrology are expected for snow dominated basins in mid-high latitudes (Nijssen et al, 2001). This could exacerbate concerns in Canada especially when coupled with permafrost melt. The fraction of crop area has a profound influence increasing runoff in a large area of North Central US and South Central Canada. The opposite extreme is seen for The East coast of the US as land-use has a decreasing impact on runoff (Paio et al, 2007). The trend in the East Coast provides a great adaptive opportunity to curb flood concerns with natural vegetation buffers. However, the need for this will be a great barrier to increasing cultivation in the area to compensate losses elsewhere. This highlights the need for compromise between adaptive efforts and stakeholder priorities in the future.

Most of Southern US and Central America are expecting large decreases in runoff. Such decreases represent threats of drought and decrease in water availability. Large barriers in terms of future water scarcity exist for the western half of the US and Mexico as populations in these regions are already putting great stress on river discharges, and discharges are predicted to decrease drastically in the future. Further, only Asia surpasses North America in respect to the greatest irrigated land acreage in the world (Vorossmarty et al, 2010). There are already multiyear droughts in the US and Southern Canada (Kundzewitcz et al, IPCC 2007). The prosperity in the US could allow adaptation in terms of water use efficiency but Mexico may suffer greatly. Water availability is likely to be a major issue in Central America and, to a lesser extent, the US.

Maize is the dominant crop cultivated in Central America. Due to the likely future scenarios of water stress and runoff reduction, the widespread cultivation of Maize in Central America may not be feasible and a shift to drought resistant crops is advisable. As there is large room for improvements and string benefits if such a shift is undertaken, this is represented as an adaptive opportunity in these regions (Figure 10).

5.3.2 Lessons from the Mississippi

The assumptions and trends illustrated by the global data are reflected well in the Mississippi River Basin profile. The basin is characterized by intensive industrialized agriculture in the north, savanna in the west and forest in the east. In addition, the predicted precipitation changes match between both data sets, with increases expected in the northeast and decreases in the southwest. From both data sets it is clear that the western portions of the basin where savanna and croplands overlap, water resources are extremely stressed. However, there are a few critical considerations brought to the table by the global data, mainly, the large area in the central north basin that is predicted to lose its suitability for maize production by 2050 (Leemans et al, 1994). The Basin profile contributes information on the rapid growth and industrialization of agricultural practices (Foley et al. 2004, Donner et al. 2003). Although the effects of land use change and crop fraction on runoff is represented in the global data, the basin profile provides specifics on the influence of wetland degradation and discharge/floods.

5.3.3 Future Land-use Adaptive Priorities of the Mississippi

The agricultural practices of the Mississippi River Basin are unsustainable, especially in light of predicted climate change impacts. However, the basin is an important global provider of several major crops. Fortunately, the east basin is highly suitable for rain-fed agriculture. Great stresses could be alleviated by decreasing the intensity of agriculture in the north, expanding the agricultural area north into Canada where agricultural suitability and productivity is projected to increase, and southeast where climate change is projected to have much less of an effect on irrigation needs and productivity is projected to increase. The drastic increasing effect of crop fraction in runoff in the upper basin compared to the equally drastic decreasing effect in the east highlights the beneficial balancing effects of the above mentioned shift. Such expansion of agricultural lands should be done while preserving and restoring ecological services of the land apposed to the current intensive practices.

It has been demonstrated that the abrupt degradation/deforestation of the wetlands and ecosystems of the Mississippi river has drastically reduced the ability to mitigate floods (Wahaj et al. 2007). The restoration of such ecosystems should be a high priority as the upper basin is expecting increases in runoff and discharge and floods are already a concern.

5.3.4 Lessons form the Mackenzie

Although global projections predict a large increase in runoff for almost all of Canada, nearly all model projection for the basin predict a decrease. However, predictions vary spatially throughout the basin. On of the most significant considerations highlighted by the river basin case study is the use of the basin by indigenous populations who own increasingly more land. This poses complications for the potential development of the land, which could increase significantly as the climate changes. The hydrology of the Mackenzie and the unique social functions of the basin highlight the need to investigate the river basin with precision.

5.3.5 Future Land-use Adaptive Priorities of the Mackenzie

The adaptation to climate change in the Mackenzie River Basin should involve careful hydrological and development balance. Warming temperatures will result in an earlier spring break up affecting the hydrology, ecology, and water resources of the basin. There will soon be a need to develop anthropogenic regulation of the river. However, this will have to be carefully engineered to preserve the pristine natural surrounding by which indigenous people, wildlife and fauna all depend. Warming temperatures will also result in widespread thawing of permafrost. This poses structural limits to the development of the basin and threatens existing structures such as winter roads. Perhaps the most significant effect of climate change is the drastic predicted increase in newly cultivatable lands. This, in combination with the plentiful water resources results in great potential to increase agricultural productivity and economy of the basin. However, land owning indigenous populations who depend on natural ecosystems are a great barrier to this development. The potential of the basin may be too great to ignore. Land use planners, governments, and representatives of these populations will most likely have to compromise over the development of the basin in an aim to expand cultivation while maintaining the essential ecosystem services.

5.4 South America

5.4.1 Predicted Threats, Adaptation Opportunities, and Barriers; Where are they?

A consistency analysis shows that regions of North/West and South/East (excluding south Argentina) are likely to increase in terms of runoff, resulting in likely flood threats in these areas. The same study analysis shows confidence in the drastic decreases in the very southern and northern tips as well as the mouth of the Amazon River where drought is likely to be a major concern (Bernstien et al. 2007). A large Region of the East is threatened by predicted crop yield reductions. The model results of Paio et al. (2007) show a subsection of this area where crop fraction has an extreme increasing influence on runoff in the East/Central region. This is likely to be a major barrier to agricultural expansion in response to yield reductions because natural areas should be preserved as flood buffers. There is a small section in the East where all of the discussed regions overlap. As stress on water resources is relatively low in most of South America (Vorossmarty et al. 2010) floods are a greater concern then drought although shrinking freshwater resources in the Andes will be affected by shrinking glaciers and demands are projected to increase throughout the continent (Kundzewicz, IPCC, 2007, Vorossmarty et al. 2010).

Low latitude regions are expected to experience the greatest reductions in crop yield due to climate change (Easterling et al. IPCC, 2007). Maize and soybean are the major crops of Northern South America, while the South cultivates mostly wheat, soybean, and maize (Leff et al. 2004). Although maize is generally predicted to suffer greatly in low latitudes in the face of climate change, land-use changes have a great potential to negate this especially for this crop (Easterling et al. IPCC, 2007). Water resources are generally under minimal stress in South America. The capacity to negate maize yield losses is high. This is a large adaptive opportunity for a large area of the East, where yields are expected to decrease. The same cannot be said for wheat in low latitudes. The widespread cultivation of this crop should be reconsidered as water resources are more stressed in the South and rainfall and runoff may reduce in Argentina.

Although most of the continent is suitable yet not used for agriculture (especially in the north), Amazonian deforestation cannot continue sustainably. Although crop intensity is very low in South America, the deforestation of the Amazon rain forest is ramped and threatens hydrology, biodiversity, and local and global climate.

5.4.2 Lessons from the Amazon

Although the global data does a good job of characterizing the area it cannot represent the critical role that the Amazon Rainforest plays on the hydrology and climate of the river. This highlights the essential need to preserve its functions. In addition, the river basin profile provides critical information on the driving forces of deforestation. Global predicted climate changes are reinforced by the projections for the basin.

5.4.3 Future Land-use Adaptive Priorities of the Amazon

Most of the deforested land of the Amazon Rainforest is used for cattle ranches. In addition, deforestation rates can be linked to global demands of soy and beef (Coe et al. 2009, Perz et al. 2003). Due to the crucial functions of the Amazon the deforestation cannot continue. A shift from cattle and rain-fed soy to irrigated agriculture could sustain economy and help prevent further reforestation simultaneously. There is a large margin to increase water use (.8% of current resources) and it has been shown that a great range of crops respond well to irrigation over the now common rain-fed agriculture of the region (Earth Trends, Junk et al. 2007). This may conserve land and increase opportunities to reforest areas and buffer floods as well.

5.5 Asia

5.5.1 Predicted Threats, Adaptation Opportunities, and Barriers; where are they?

Unlike any other continent, the entire continent of Asia is consistently predicted to experience significant increases in precipitation and runoff by the end the 21st century (Pachauri et al. 2007, Nohara et al. 2006). It naturally follows that the major threat for the future of the Asian River Basins is flooding. This is likely to be in conjunction with barriers for the large areas of predicted woodland decline with reducing capacity for vegetation as a buffer (Hernandez et al. 2000, Fischlin et al. IPCC, 2007). These are the two most northern barriers depicted in figure 10 below. The Western patch is an area of particularly difficult barrier because it is also a subsection of the larger area in which crop fraction is highly influential on runoff. There are several areas of Asia (West-central Russia, large areas of India, Indonesia, Vietnam, Cambodia, Thailand, Northeast

China, Korea, and Japan) where crop fraction changes have the most extreme influence in increasing runoff world wide (Paio et al. 2007). Permafrost melt and erosion increases will be a major adaptive barrier for the tundra areas of the Himalayas (Foley et al. 2005).

Climate change is not predicted to exacerbate water demands or irrigation requirements as drastically as other regions of the world, with the exception of spotted areas of India expecting the most drastic increases in irrigation needs in the world the precise locations of these spots vary between the two different models (Vorossmarty et al. 2010, Doll et al. 2002). Concerns in India are exacerbated further as large areas of the Northwest and South are already putting great stress on their rivers as sources of fresh water. If these regions coincide, there could be tremendous water shortages (Vorossmarty et al. 2010). Fortunately, most of India is highly suitable for rain-fed agriculture at present (Easterling, IPCC, 2007). This may improve adaptive capacity but it may not be the case in the future. It should be noted that the cultivation of rice in South and Southeast Asia is the most resistant to temperature increases of the major crop cultivated (Easterling et al. IPCC, 2007, Leff et al. 2004). Potential to expand agriculture is very limited in India and Northeast China due to current crop fraction and limited potential agricultural land. However, in the future, there is a consistently predicted large area of expansion of potentially productive agricultural land Asiatic Russia (Ramankutty, et al. 1998, Leemans et al. 1994).

5.5.2 Lessons from the Brahmaputra

The unique characteristics of the Brahmaputra River Basin increase the likelihood that flooding will become a more dramatic concern in this region. The summer monsoon and permafrost melt heighten existing flood and erosion concerns as precipitation, extreme events and temperatures. Deforestation of the upper basin further adds to flood vulnerability. Further, the faunal dispersal and biodiversity of the river is intricately adapted to the existing flood regime. Interference of flow controlling structures with ecology and deforestation promoted by population growth complicates adaptive efforts to future floods. The basin profile also demonstrates that increases in precipitation and runoff do not necessarily translate to an increase in water availability, as glacial melt is likely to lower water storage capacity. In addition, slash and burn agriculture can leave some of the wettest regions of the world in water scarce situations as it increases flow and quickly evacuates water (Lundqvist, 2000). Fortunately, this particular basin does not relay as heavily on the river for water compared to most basins. Global data assumptions of future climate changes of the region are reinforced by the data in the river basin profile.

5.5.3 Future Land-use Adaptive Priorities of the Brahmaputra

The future flood concerns in the Brahmaputra are high while the adaptive capacity is low. Population growth interferes with reducing deforestation and ecology interferes greatly with river flow regulation. It will require careful and strategic engineering to regulate the flow of the river while preserving essential forest and wetlands. The regulating system will have to mimic the natural flood cycles that the ecosystems and wildlife are adapted to or involve highly creative distribution (bypasses and fish-ways) and biodiversity preserving alternatives. Buruah et al. (2002) proposed controlling erosion by phyto-remediation techniques, identify all hydrological processes that influence migration, and maximizing controlled flooding.

The priorities are similar for the Rhine but adaptive capacity is lower. The Brahmaputra does not have as much flexibility as agriculture is more essential to the economy. However, creating alternatives to "slash and burn" practices and restoring ecological functions in crop lands can help mitigate threats, which worsen vulnerability to foods and erosion and water storage. Rain harvesting schemes and rain-fed agriculture will help increase water supplies and reduce demands. The future adaptation of the Brahmaputra will be beyond the sphere of correcting and will rely on increasing ability to adapt.

5.6 Australia

5.6.1 Predicted Threats, Adaptation Opportunities, and Barriers; where are they?

Declining precipitation and runoff had been predicted to threaten currently suitable rain-fed agricultural land in Australia especially (Nohara et al. 2006). The IPCC synthesis report (2007) demonstrated that there is minimal agreement between precipitation models for the end of the 21st century in Australia with the exception of the extreme southwest and southeastern regions. Threats of runoff reduction are also uncertain for most of Australia aside from the significant decreases predicted for regions of the west and the southeast by the end of the 21st century. Drought is a warranted concern for these areas, especially the very southern tips of the east and west. These areas of extremes are also intensely cultivated, which stresses the area but provides adaptive opportunity to reduce water use with irrigation efficiency and the phase out ill-advised crop cultivation. A massive region of Eastern Australia is putting great stress on their rivers for fresh water resources resulting in a significant adaptive barrier.

Wheat yields are predicted to suffer the worst with rising temperatures compared to rice and maize. This is especially true for low latitudes. In addition, wheat is not as responsive to land use adaptations as other crops such as maize (Easterling et al. IPCC, 2007). Being that the Major crop cultivated in Australia is Wheat, expansion of agricultural land and/or shift of crop type cultivation may be beneficial. Savanna expansion replacing of desert is consistently predicted in models for most of central Australia, which could increase opportunities for agriculture but water resources may be a barrier (Monserud et al. 1993, Fischlin, IPCC, 2007). In addition, Leemans et al. (1994) maps a large area of suitable agricultural land in North Australia. Most of this area is suitable for rain-fed agriculture but the future climate is uncertain so cultivating ran-fed agriculture is a risk. Uncertainty is a major barrier here.

5.6.2 Lessons from the Murray-Darling

Many important features of the Murray-Darling Basin (MDB) are not well represented in the global data. Most importantly, the water usage and river regulation have been developed during the “flood dominated regime” which began in 1948 (Beare et al. 2002). Throughout history, the basin has alternated between drought dominated flood dominated regimes. The possibility that the regime could shift back at any time adds greatly to the vulnerability and uncertainty of the basin. Another exclusive phenomenon of the Murray-Darling Basin is the threat of reforestation (which is predicted to increase in the future) to further reduce river discharge. The exceptional water demands of critical marshes and wetlands add again to the competition between agriculture and ecology for water resources. It should also be noted that the Murray-Darling Basin uses a great portion of Australia's freshwater consumption for irrigation and provides a great portion agricultural commodities (Australian Bureau of statistics, Bryan et al. 2004).

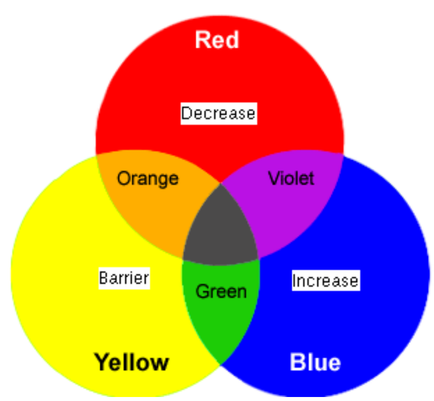
Many of the issues highlighted for Australia by the global data reappear in the Murray-Darling Basin. Mainly, shifts from rain-fed to irrigated agricultural lands, and the drastic, yet ill-advised, expansion of cereal crops in place of sheep. Predictions of the future climate of the Murray-Darling Basin are also uncertain but increases in discharge are said to be highly unlikely (CSIRO, 2002).

5.6.3 Future Land-use Adaptive Priorities of the Murray-Darling

The competition for water between critical ecosystems and agriculture and the negative effects of necessary reforestation on river discharge are major barriers for the Murray-Darling Basin in terms of land-use adaptation to climate change. Reforestation projects must be carefully planned to maximize salinity benefits and minimize stream flow losses (CSIRO, 2002). The assortment of threats to river discharge should create an incentive to reduce the expansion of cereal crops and shift to a less vulnerable and water consuming agricultural practice. The expansion of irrigated land instead of rain-fed agriculture in the Murray-Darling Basin should be reconsidered and the option of expanding rain-fed agriculture in the north should be examined. However, if precipitation and runoff decrease much of this land may no longer be suitable for rain-fed agriculture. Uncertainty of future runoff and precipitation is a barrier to this possible endeavor. No matter what the future holds there is a great need to increase water use efficiency, as the many and most scenarios would lead to reductions in water supplies, which are already difficult to budget. Hafi et al. (2001) estimated that two large areas of the Murrembidgee catchment could reduce irrigation needs by 50% with refurbishment of channels, drip irrigation, and reuse systems. However, yet another potential barrier was presented by Young and McColl (2003): Increases in irrigation efficiency may result in lower return flows to the river both through surface and groundwater systems. Further research is required to confirm this.

5.7 Integration of the results

In figure 10, the major threats and barriers are represented by the three primary colors. Regions subjected to significant threats of reductions in discharge, water resources, agricultural land and/or yield are represented in red, barriers are represented in yellow, and regions subjected to significant threats of increasing discharge are represented in blue. The overlap between them results in new colors based on their influence on each other. Although overlaps result in new colors, the outline if the regions stay the original color to clearly indicate boundaries. Areas where there is significant adaptation potential to the corresponding threats exhibit horizontal lines. More powerful or multiple adaptation potentials will exhibit



lines closer together. Adaptation potential is only represented when it corresponds to a specific threat or barrier. Otherwise, potential agricultural land expansion and/or crop yield increase are not represented.

There where two cases where darker hues where used to represent extreme cases. In the North-central US, a dark red is used to represent unrivaled predicted reduction in crop productivity. In West Russia, a dark green area represents a region where flood concerns are exacerbated by two major barriers of vegetation loss and a profound influence land cover on runoff. Although there are many similar cases, these are the major two. To avoid over cluttering the figure, these are the only cases represented. Similar cases are discussed per continent earlier in the discussion. Inappropriate crop cultivation can be considered an opportunity to adapt as shifts to more suitable crops can improve the situation greatly. Descriptions of the specific threats, adaptation options, and barriers are given in the sections above.

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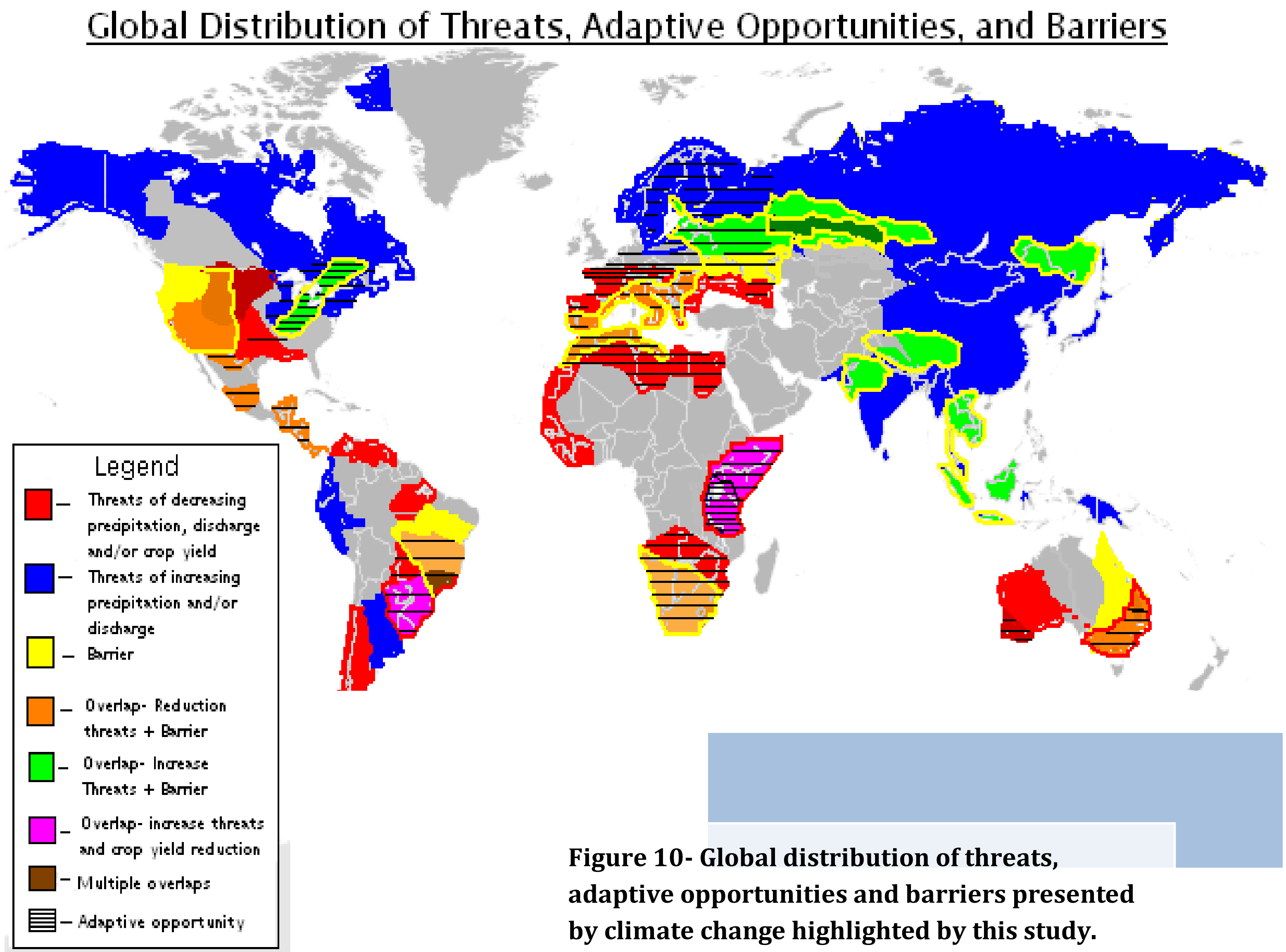

Figure 10- Global distribution of threats, adaptive opportunities and barriers presented by climate change highlighted by this study.

In the following sections, a general "hypothesized" notion of how the *adaptive potential* of each river basin will react to climate change over time is graphed. On the horizontal axis, climate change is depicted over time in variable manner. The sequence/order of climate change effects varies per basin. From left to right, 1 represents the present situation, 2, 3 and 4 represent the sequence of climate change effects particular to each basin or region. The particular sequences are described in the subsequent sections. This was done for both water management and land-use adaptive potential. The *adaptive capacity* of a river basin is dependent on a broad range of variables. The influence of these variables varies between basins. Four adaptive capacity grades (1-5) are given (y-axis) as the sequence and intensity of climate change effects (threats, adaptive opportunities, and barriers) progress over time (x-axis). The specific predicted reactions to climate change are taken into account for each basin.

5.7.1 Hypothesized Water Management Adaptive Potential

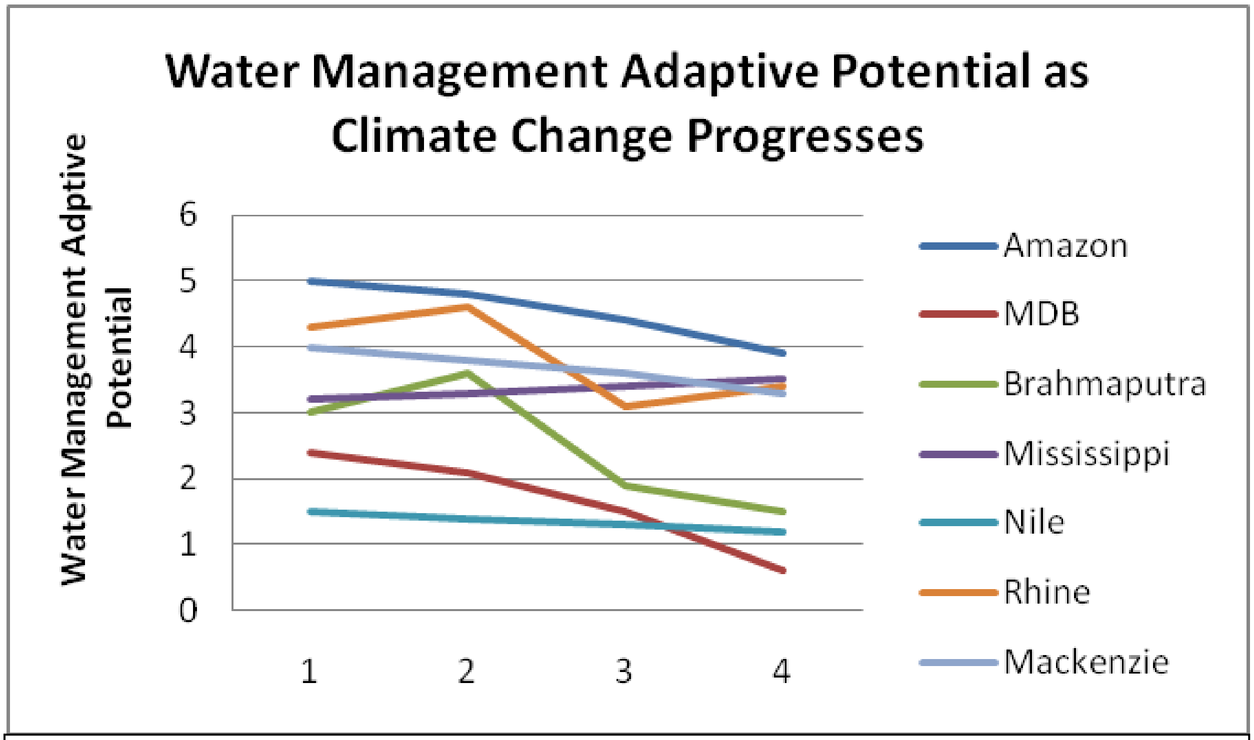

Figure 11- Hypothesized reaction to climate change in terms of water management adaptive potential over time. The estimations are based on both the global data and the river basin profiles.

The Amazon River Basin is home to the largest single fresh water resource (Case, 2010). In addition, water use, especially for irrigation, is very low. The initial water management adaptive potential is at maximum. Climate models consistently project rainfall and discharge reductions. Although the water resources are plentiful, climate change is still a threat of reduction. In addition, the reduction in rainfall is predicted to result in a large increase of silviculture (Fearnside et al. 2005). The required additional deforestation could further reduce water resourced due to the role of the rainforest in hydrology. Rain-fed agriculture is more common in the Amazon River Basin compared to the other case studies. Therefore improving irrigation methods will have a minor effect on increasing resources. The recent shifts to irrigated is likely to accelerate if precipitation reduces as predicted. Thus, the water management adaptive potential of the Amazon River Basin is likely to exhibit steep and steady reductions.

Water resources of are already low and stressed in the Murray-Darling Basin. Agriculture is intensive, consuming a great deal of Australia's water resources. Climate change is projected to decrease discharge and crop yield. Although irrigation efficiency could be improved, ecosystems demand large quantities of water. As resources decline the reducing water use/needs will be limited. As climate change progresses the water management adaptive potential of the Murray-Darling Basin is likely to be lowered drastically. It is important to note that this prediction assumes that the system will remain in the "flood dominated" regime in which the contemporary water use and flow regulation methods have been developed. This trend will be greater if the system reverts to the "drought dominated" regime.

Although agriculture is the mainstay of the economy of the Brahmaputra Floodplain Area, the basin does not depend highly on the river for water resources compared to most other basins. The basin mostly depends on ground water but as climate change progresses the basin will develop more use of the river (Mondal et al. 2009). As climate change progresses the water resources provided by the Brahmaputra are highly likely to decrease while the dependence of the basin on them will most likely increase significantly lowering adaptive potential. Similar to the Rhine the initial melting of snow and glaciers may improve water availability. This may help satisfy dry season demands. This also increases the already high potential for land use changes to increase storage capacity (similar to the Mississippi). However, this will eventually reduce storage capacity and water resources. This shift is predicted to be abrupt (Erikson et al. 2008). Climate change impacts on irrigation requirements are extreme in some areas of the basin (Doll et al. 2002). Although discharge is predicted to increase and the monsoon delivers a huge amount of rainfall, deforestation and poor agricultural practices may result in this water being rapidly evacuated from the basin. Improving farming practices, reducing deforestation, the proposed construction of a large barrage, and strategically positioned ecological restoration can mitigate some of the effects, but the impact of climate change on water resources is likely to be drastic and abrupt.

The water stress of the Mississippi River basin is marginal and a great deal is used to irrigate its highly productive and important agricultural lands. Maize cultivation dominates a large portion of this land indicating little potential to reduce irrigation. However, there is great potential to increase irrigation efficiency and some room to use more resources. The future of water resources and use has been proven too difficult to predict due to high spatial variability (Sun et al. 2008, Jha et al. 2004). However, many water resource and management issues have been linked to wetland degradation (Hey et al. 1995). As climate change progresses, the need to restore these wetlands will be increasingly stressed. Despite of an overall increase of decrease in discharge wetland restoration will be beneficial. Therefore, a slight and steady increase in water resource adaptive capacity is feasible. Concrete plans and large investments in ecological restoration and river flow regulation improvements reinforce this possibility (Sparks et al. 2010)

The Nile is by far the most water stressed river base of all the case studies and perhaps the world. Although the projections for future water flow are inconsistent, drastic increases in evaporation and evoptranspiration are certain and likely to reduce water resources and increase demands. While increases and decreases in discharge are both possible future scenarios projections indicate that decreases are more likely. As evaporation increases there will be increasing irrigation requirements and incentive to adopt more efficient irrigation methods. Thus, a slow and steady decline is predicted.

At present time, the Rhine River Basin has plentiful water resources. Because the river is so highly regulated, the initial increases in discharge due to glacial and snow melt are likely to increase water storage temporarily increasing water availability. After the regime has shifted to rainfall, natural glacier and snow storage capacity decreases the water resources of the Rhine are likely to reduce significantly. However, as agriculture is typically the main consumer of river basin water resources and the Rhine River Basin does not depend highly on agriculture for economy (despite the widespread practice), there is a great potential to reduce irrigation. The food stability in Europe creates further agricultural flexibility. In addition, the healthy economy of the Rhine River Basin allows for irrigation efficiency improvements if they do not wish to sacrifice cultivation. As a result, the reduction is not predicted to be extreme. In consideration of the above and the basin's proven ability to regulate the river-flow successfully, it is predicted that the decline in water adaptation will recover and continue to sustain ample fresh water resource.

The water use of the Mackenzie River Basin is quite modest leading to a reasonably high initial water management adaptive potential is fair-high. However, climate change will result in an earlier and disruptive spring break-up, to which adaptation will be difficult. However, in this particular basin, climate change is likely to increase crop productivity and the acreage of cultivatable lands. This will require more water and further reduce potential as climate change progresses. Aboriginal land owners are likely to slow the increase of cultivation resulting in a slow and steady decline.

5.7.2 Hypothesized Land-use Adaptive Potential

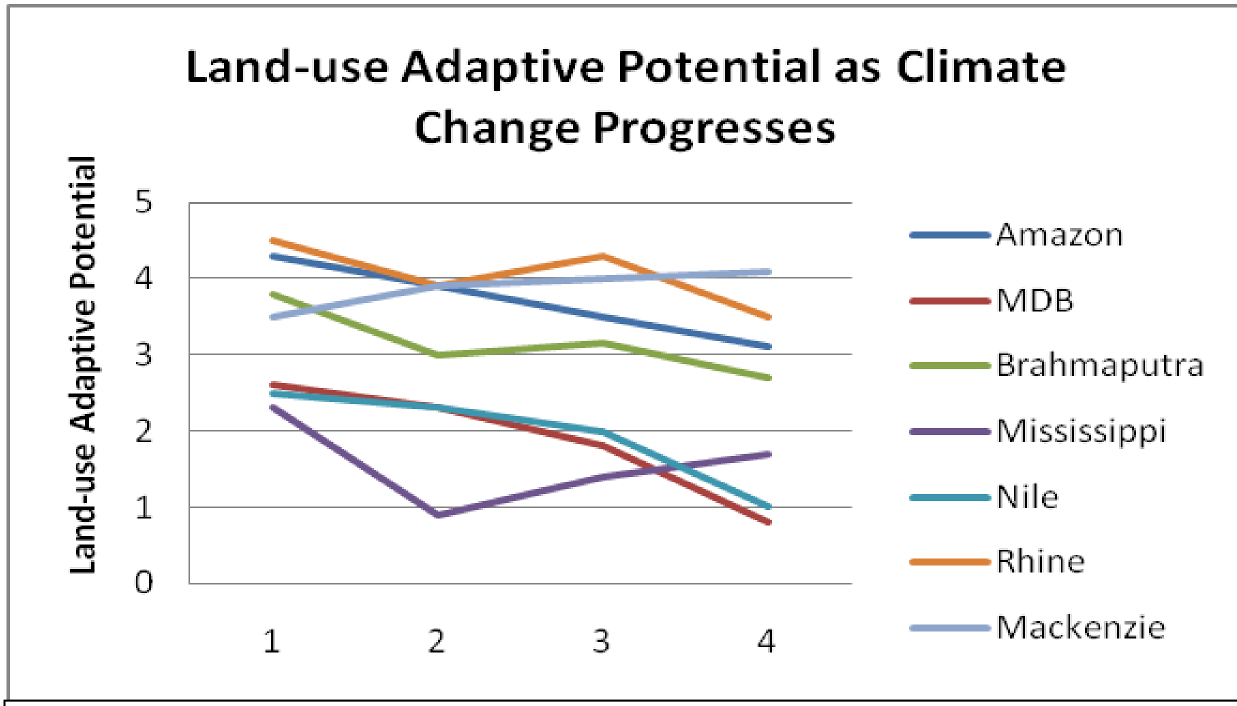

Figure 12- Hypothesized reaction to climate change in terms of land-use adaptive potential over time. The estimations are based on both the global data and the river basin profiles.

As a result of the abnormally high influence of the Amazon Rainforest on the hydrology of the river, the adaptive land-use potential of the basin is relatively high. If deforestation trends can be curbed the ability of the rainforest to mitigate floods is great. Further, irrigation can have a profound influence on crop yields in this particular basin and there are abundant resources to increase irrigation. Reductions in cattle ranching could have great effects but economic considerations may hinder feasibility. The strength of these options will dissipate if they are more widely adopted which is likely as climate change progresses. Climate change is predicted to increase deforestation as rainfall is predicted to declines. This will accelerate the rate at which land-use adaptive potential reduces. Although the initial potential may be high, climate change threatens to reduce at a considerable rate.

Many of the agricultural practices and trends of the Murray-Darling Basin are highly ill-advised especially assuming that water resources will become more stressed as projected. As a result, there is a large scale of potential agricultural practice improvements. However, the trend of increasingly more irrigated vs. rain-fed agriculture lowers the initial capacity to further increase yield. Agricultural expansion is a far from feasible option due to limited water resources. As climate change progresses, the initial reduction in land-use adaptation potential may be slow as shifts to more suitable agricultural are hopefully adopted. However, as these improvements get closer to the full potential, the effects of climate change will reduce Land-use adaptive potential more drastically. Negative effects of climate change on water resources will further reduce potential increasingly as climate change progresses.

Many of the threats to the Brahmaputra are intensified by poor land use. Deforestation and poor agricultural practices exacerbate flood concerns and highly reduce the ability to store the great amounts of water delivered to the basin. In terms of physical ability to mediate these treats there is a significant land-use adaptive potential. Discharge is predicted to increase and as a result the reforestation and agricultural effect could have an even greater impact on capturing water for resources but it will be more difficult to mediate floods (to which the basin is highly vulnerable), resulting in a net decrease of adaptive potential. After the glacial and snow-melt increase and storage capacity decreases the potential to capture for resources will diminish, however it will be more feasible to mitigate floods and the adaptive potential will increase slightly. Predicted forest cover gain will improve the potential for reforestation to buffer floods. However, as improvements are made, the room for further improvements will also diminish.

The intensive agriculture (especially in the upper basin) and large scale exports of crops create very limited flexibility in land use of the Mississippi. Climate change is predicted to render a large portion of the Mississippi infertile creating dramatic land use complications. However, crop productivity elsewhere in large areas of less intensely cultivated areas of the basin are predicted to increase (Leemans et al. 1994). This may alleviate some pressures on the upper basin after some time to observe changes, create and implement plans has passed. If this spatial shift in land-use happens, it will increase flexibility to restore wetlands in the upper basin and reduce concerns of flood damage. In addition, the huge influence if land-use/cover on river discharge shows that certain land use changes could have profound results. Pressure for these changes will increase with predicted climate changes. However, the latter increases are unlikely to completely negate the massive impact of the predicted crop yield reductions on the north.

The inappropriate crop cultivation in the Nile River Basin allows great possibilities for improvement. The same can be said for the basin's irrigation system. However, crop production in the basin is very low. As a result, the general influence of agriculture on river hydrology is lower compared to most of the other river basins. The dense urban concentration along the Nile in Egypt eliminates the option of reforestation along the river as a flood buffer in this region. As a result, the present adaptive capacity of the Nile could be described as "fair-poor". As evaporation increases irrigation needs will also increase and the ability for new irrigation systems to negate these effects will decrease. In fact, one can even notice drastic predicted irrigation requirements for the upper basin in the global spatial data. It is likely that climate change will reduce the land-use adaptive capacity. Reduction in cereal crop productivity will add to this trend. After the irrigation improvements and potentially some shifts in crop type, it seems that additional improvement options will be very limited and climate change will have reduced land-use adaptation potential more drastically.

Currently, the land-use adaptive capacity of the Rhine River Basin is promising due to the flexibility resulting from relative independence on agriculture. This flexibility will slightly reduce in the case of increased floods and river discharge because the basin will have to give the river "room to grow" (Asselman et al. 2000). However, this is not likely to have severe consequences and it illustrates the value of land use flexibility. As temperatures rise yields are predicted to increase and cultivation is likely to become more feasible in the higher altitudes of the Alps. This could restore the flexibility previously lost. As climate change continues, the basin will most likely suffer some agricultural losses. It is reasonable to predict that this particular basin could sustainably withstand some losses.

The pristine nature of the Mackenzie River Basin and the potential for significant increase in agriculturally productive land, creates high land-use adaptive potential of the basin, which could increase in the face of climate change. However, natural land owned and utilized by the native population is likely to limit the increase in potential. This is a good example of how unique considerations of river basins can effect adaptive potential. In the future, land needed to buffer potential flood damage will increase as temperatures rise, especially considering the threat of widespread permafrost thaw. The initial increase in LAP will be considerable but as climate change progresses it is likely to dissipate.

6 Conclusion

Climate change presents conflictingly variable threats to the world's large river basins. The results indicate irrigation efficiency improvement, agricultural shifts, natural flood buffers, and regulation that preserves ecological continuity as the major adaptation tools of the future. The study illustrates the influence of climate change on a variety of different basins, how they react differently, and what characteristics determine why they are likely to react in the manner predicted. Although river basin react differently to climate change, there is one major recurring theme; adaptive efforts are often limited by the efforts to mitigate or capitalize on a separate issues that climate presents to the basin. In every situation, different functions, services, and systems will be affected simultaneously.

In many cases, an adaptation in one system may negatively effect or interfere with another adaptive priority. The most illustrative case is the future need for natural flood buffers and agricultural shifts in the North-Central US. The Continental US faces large threats of reduction in water resources and agricultural productivity. In the Eastern US, there are concerns of threats of increasing discharge and flood. The Mississippi River Basin is subjected to both concerns. There is a conflict in the Eastern US between adaptation opportunities leading to identification of a clear barrier. An increase in cultivated land is needed to enhance productivity to counteract losses (in North-central and Eastern US) whereas land is also needed for rehabilitation of wetlands to buffer floods.

Conflicting opportunities and high levels of resource competition limit adaptive efforts and resource allocation. Therefore, the future framework will have to be designed to be capable of balancing inter-limited adaptation efforts and include a compromising resource distribution system. Due to the discussed limitations, the framework will need to determine which sacrifices will be made in order to achieve sustainability. Consequently, balancing compound reactions[3] of a basin, often resulting in the conflict between two or more adaptation efforts/options, will be the fundamental challenge to adaptive land-use planning. In addition, efforts are further limited by the allocation of competitive resources such as water needed for both ecosystems and

[3] Compound reaction refers to a reaction to climate change that calls for multiple courses of action that often conflict with each other, such as for instance increased agricultural cultivation and erosion control.

populations. Dealing with this issue will require the quantification of needs and adaptation limitations along with the ranking of priorities.

The first steps in the process to determine the optimum course and extent of action will be determining what efforts are necessary and quantifying the limitations. Determining the necessary actions is somewhat intuitive based on the most likely reaction to climate change and the needs satisfied by the basin system, similar to what is done earlier in this study. Quantifying needs and limitations will be more difficult. It will require an innovative method to quantitatively assess what agricultural, water resource, and functional services the basin must provide to sustain the local environment as well as the economy. Planners and scientists will have to determine how much water the wetlands and ecosystems need and how much the population needs. Because adaptation efforts and resource allocation have a competitive nature, the limitations they face create a need to determine what actions and resource take precedence over others and to what extent. Therefore, priorities must be ranked before planning can be conducted. First, the adaptive efforts and resource needs that are not expendable must be determined with the corresponding quantifications attributed.

The remaining services and adaptation options should be ranked based on the magnitude of associated risk/profit loss. Based on these quantifications and rankings the most efficient allocation of efforts, resources, and services can be determined. The benefits of such a system are well apparent in the common situation where new agricultural land is feasible while erosion control is an elevated concern in the same region. The approach can be used to determine to what extent the land should be cultivated. The approach can be used to balance the economic incentive for cultivation against the limitation and the risk of erosion control and floods.

6.1 Framework Foundation

Before a more precise approach can be designed, there are some major questions that the scientific community must ask. This study highlights the major research topics that need to be explored including; agricultural practices that minimize erosion in high altitudes and latitudes, quantifying a sustainable balance between agriculture and flood buffers for water retention, quantifying the water needs of ecosystems, and engineering river regulation that preserves ecological continuity and natural cycles.

After these issues are better understood, the foundation of the future framework should focus the following principals; quantifying needs and limits, assessing risk, ranking priorities, and innovating accordingly. After the above mentioned topics are better understood, it will be more feasible to quantify the limits relevant to a sustainable design and the services that must be maintained. After new innovative agricultural methods have been determined, and needs have been quantified, it will become more clear how much agricultural land we need to maintain the population and economy as well as how much land is needed to reduce flood concerns to an acceptable risk. Subsequent to this analysis, compromising between the two can commence. Influences on these quantifications will vary by basin and climate change scenario (uncertain). The influences of variables must be modeled precisely and several possible scenarios must be accounted for.

Sacrifice is likely to be necessary in order to implement sustainability. Therefore, it may be necessary to reduce allocations (of efforts and resources) as climate change progresses or if scenarios are worse then predicted. After determining what needs to be maintained for a sustainable basin, the risk of reducing below these determined quantifications must be assessed. The impact of certain allocations reductions and thresholds should be determined. For instance, if there is a lowering of water resources beyond what has been predicted or deemed sustainable; what would be the risk of reducing water allocated to the population versus reducing the same amount reserved for the wetlands? If there is threshold that if passed would result in the complete destruction of the ecosystem, it may be wiser to increase industrial water use efficiency. Based on determined impacts and thresholds, beneficiaries of basin services should be ranked and allocations should be determined for a range of possible scenarios.

After the needs have been assessed, limits have been quantified, and impacts compared, innovation priorities will become apparent. When it is determined that several necessities must be reduced beyond the current sustainable threshold, allocation reduction and innovation efforts must be directed towards the resource beneficiary with the lowest risk/resource ratio and highest feasibility. To illustrate this point, consider the allocation of water for wetlands and agriculture. In a hypothetical situation, lets say a twenty percent reduction in water reserved for wetland restoration could result in the desertification of the entire ecosystem while exposing a fragile population to catastrophic floods. The same reduction in agricultural water reserves would result in the world living with 1% less cashews and some negligible local economic losses. Under these circumstances, the best option would be to allocate less water to agriculture and focus on increasing irrigation efficiency in the future. Innovative priorities will result in new research topics, better understanding of limits and impacts, new allocation structure, and then more innovation. This cycle will optimize the framework until sustainability is achieved. However, it is important to keep in mind that adaptation options eventually dissipate over time and therefore, if climate change continues unabated we could pass a threshold by which a sustainable river basin is no longer an option.

6.2 Trends of Basin Reactions to Climate Change

The previous section addresses the major dynamic challenge of the framework and presents a possible approach. However, there are some more basic insights provided by this study. The more intensely cultivated and agriculturally oriented river basins seem to be the least flexible in terms of land-use change options. Of course, this trend varies depending on several other factors such as particular threats, crop cultivation, irrigation systems and more. This point is supported and highlighted by agriculturally centered basins such as the Mississippi River Basin.

A specifically alarming trend, which emerges from the study, is the tendency of already stressed arid regions to be threatened further by reductions in precipitation, discharge and crop yield. These areas are often arid and developing regions. This concern highlights the need to develop strategies to make sustainably large-scale shifts in cultivated crops in such regions as well as develop methods to increase irrigation efficiency in low economic conditions.

In general, higher altitudes and latitudes are predicted to experience increases in both discharge and agricultural productivity under climate change conditions. The capitalization on increased productivity may be limited by vegetation needed to buffer floods. In addition, new agricultural practices that minimize erosion will have to be explored. This is because permafrost melt and increased discharge will increase erosion concerns and limit new cultivation.

Low latitudes, developing, and arid regions are generally threatened by reduction in water resources and crop productivity. This is often in conjunction with high levels of existing stress on river water resources and hence competition for fresh water. Reactions to climate change vary from basin to basin.

Floods are the major concern for the future of river basins throughout Asia. However, in the large areas of Russia that are predicted to experience an increase in agricultural productivity, conflict will raise with the space needed for natural flood buffers. There are also large areas where crop fraction has a profound influence on runoff (and hence discharge). This increases both the negative effects of agriculture in flood regime and the benefit/need for and efficiency of vegetation to buffer floods. Loss of vegetation predicted for large areas will exacerbate flood threats and the corresponding complications.

The concept worth stressing for the future framework is long-term planning. Although the analysis shows that land-use adaptation potential fluctuate over time, the potential will eventually dissipate in all scenarios.

6.3 Limitations

While the study serves its purpose, it is not without limitations. Each case study river basin is unique. Only one has been chosen to represent each specific major type and location. This prevents the emergence of patterns, correlations, and trends to some degree. Patterns and trends are more likely to become definitive when multiple similar basins for a range of possible cases are analyzed and compared. This study was limited by its broad nature, large scale and the corresponding time constraints. Therefore, results and conclusions are qualitative. However, they still highlight the criteria that should be considered when determining how unique river basins could react to climate change and how the adaptive approach must be developed.

The greatest limitation to the study is the great deal of uncertainty of the effects of climate change especially associated with the specific spatial distributions. However, it is effective in determining the most likely situations based on the resources and knowledge available to date. This method could be extremely effective in its aims if prediction models better incorporated the many dynamic processes involved in the influence of land use on river hydrology. Research better quantifying the effects of a range of land-use/covers on river hydrology could make great strides in the effectiveness of this approach. Cooperation between stakeholders and improving the availability of water resource data that pertains specifically to river basins and the fraction of which is provided by discharge could improve determining optimum adaptation efforts. Additionally, quantifying the needs of ecosystems will not only improve this approach but will also make great improvements to planning efforts in general.

6.4 Post Script

While conducting the research it seemed intuitive, yet perhaps impossible to implement, that land-use adaptation to climate change in large river basin could be more manageable in a globalized civilization. While agricultural and freshwater resources may reduce in some basins, it is increasing elsewhere. In addition, those facing reductions are more often then not in regions where they are desperately needed. The threat of water resource and crop yield reduction in the Nile and Mississippi River Basins are the most extreme of the case studies. Meanwhile, in basins like the Mackenzie, freshwater resources are abundant and agriculturally viable land is likely to increase significantly in a relatively unpopulated area of low agricultural consumption and economic activity. Adaptation efforts can be more beneficial if the services of large river basins were treated more as global commodities.

Future surpluses in certain areas could be used to sooth the reductions elsewhere where adaptation is limited. For example, future agricultural surpluses in the Mackenzie River Basin could help counterbalance the loss of US productivity (crucial for export/ global maize and soybean supply). However, this option is prevented by individual country economic losses. If these crops were regarded as global resources rather then US resources the reduction could be minimized by increases elsewhere and the US would not have to jeopardize land needed to buffer floods. Land-use adaptation to climate change in large river basis would be more efficient if basin efforts are synchronized. Therefore, land-use adaptation to climate change in large river basis should be synchronized. Unfortunately, this option is admittedly not feasible under the current world economic configuration and individual political incentives.

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