Chapter 20
Analyzing Needs for Climate Change Adaptation in the Magdalena River Basin in Colombia

Ad Jeuken, Laurène Bouaziz, Gerald Corzo, and Leonardo Alfonso

Abstract In 2010 and 2011 Colombia was hit by severe floods. After this situation, Colombian government and river basin authorities started developing plans and preparing actions for adaptation to climate change. Together with Dutch institutes a demonstration study and capacity building program was executed in 2013–2014. A systematic analysis of future extreme discharges (as a proxy for the risks of flooding) for the upper and middle Magdalena river basin and water shortages for the Coello sub catchment was done using state of the art downscaling and hydrological modeling tools. In this analysis plausible future projections of climate (based on IPCC fifth assessment), land use and water demand (based on expert workshops and literature) were used to explore consequences of climate change. Recent maps, data and expertise of Colombian partners contributed for necessary input data and to validate the tools used. The study is presenting main results and is discussing its limitations and replicability. Climate scenarios show a persistent increase in the occurrence of extreme rainfall events and that, as a consequence, extreme discharges like during the recent floods in 2011 are likely to increase as well. The return period of the 2011 discharge is already quite high under current climate and might increase by a factor five under climate change. For water shortages the results are more ambiguous showing both the possibility of an increase and decrease of the unmet water demand depending on different future scenarios, the water use category and location within the catchment. The unmet demand is however also under the current climate substantial. The question whether this unmet demand is critical or not could not be answered. The modest length of the reference period in comparison with time period of the ENSO phenomenon, the relatively restricted modeling effort (only using hydrological and no hydrodynamic and damage-cost models) are limitations to keep in mind when interpreting these results. There are no principle barriers for replication the methodology in countries like Colombia that in addition is steadily increasing its data, modeling and

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knowledge capacities. For the adaptation tipping point analysis presented in this study the main challenge is to derive the necessary objectives, sufficiently supported by the relevant stakeholders and policies, as the starting point for a targeted adaptation process.

Keywords Climate change adaptation • Colombia • Adaptation tipping point analysis • Scenarios • Flood risks • Water shortages • Capacity building

Introduction

Likewise many countries do Colombia is preparing for climate change while improving its disaster risk preparedness, response and recovery capacity. The 2010–2011 la Niña (positive phase of El Niño) phenomenon affected four million Colombians, ~9 % of the total population, and caused economic losses of approximately US $7.8 billion, related to destruction of infrastructure, flooding of agricultural lands and payment of government subsidies (Hoyos et al. 2013). The government declared the state of emergency and during the flood situation released resources around 178 million us dollars. This was done while according to local media scientist estimated that the 9 % of the country was underwater.

Compared to an average flood in Colombia more than 70 % extra land was inundated (see Fig. 20.1). Poveda et al. (2001) indicate that there is a strong relationship between the ENSO phenomenon and river discharges in Colombia. Hoyos et al. (2013) in addition show relation between spatially varying flooding, social vulnerability patterns and damages that occurred due to the 2010–2011 floodings. It is only with low to medium confidence that these flooding events can be attributed to anthropogenic induced climate change (Harmeling and Eckstein 2013). Trenberth and Fasullo (2012) suggest that on a world wide scale the climate change induced increase in sea surface temperatures depend the extreme weather events that occurred in 2010 including the extreme precipitation in Colombia.

Within the Colombian territory the climate is however such extremely variable, being influenced by the extreme orography, the Caribbean and the Pacific weather phenomena, that both in observations and model projections trends are difficult to observe. Early climate and hydrological modeling studies (Nakaegawa and Vergara 2010) do not reveal clear trends in river discharges. Recent statistics and scenarios for Colombia give a geographically diverse picture and a large range of potential climate effects over the whole country. For the Andean region including the upper Magdalena basin the 16 model ensemble average however suggests a strong increase of average precipitation (IDEAM et al. 2015).

The National Plan for Adaptation to Climate Change -PNACC- supports the country's preparedness to cope with extreme weather events, and the gradual weather change. It directs the development of priority programs and projects and

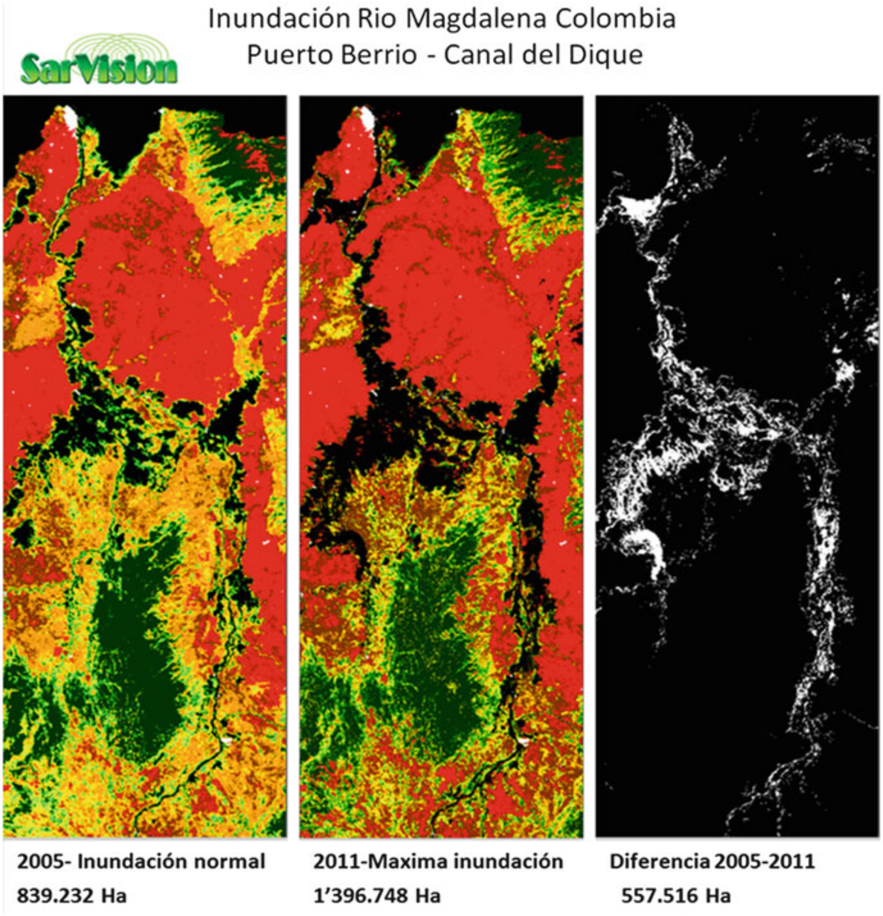

Fig. 20.1 Satellite (MODIS) derived maximum flood extent maps for the Magdalena basin from Puerto Berrio to canal del Dique for a regular year (2005 *left*), 2011 (*middle*) and the difference (*right*) showing how serious the floods in 2011 were (Quinones 2014)

strengthens the actions that are being already undertaken but that need to consider climatic variables in their planning and implementation, in order to reduce the negative consequences in the long term. The main objective of PNACC is to reduce socio-economic risks and impacts associated to the variability of climate. Specifically, the plan aims at generating a better understanding of the potential risks and opportunities, at incorporating climate risk management in planning of sectorial and territorial development, and at reducing the vulnerability of socio-economic and ecological systems to climatic events (Rojas-Laserna 2014).

In Climate Change Adaptation policy making, methods that are promoting a bottom up approach are gaining ground (Ward et al. 2014; Brown et al. 2012; Kwadijk et al. 2010; Wilby and Dessai 2010). Not the Climate Change itself is the leading argument for taking action but the key vulnerabilities of the area, sector, management practices and policies under consideration. Basically the question to formulate is: under what amount of change will we start failing to achieve our objectives or will we start to perform unacceptably?

Aim of this paper is to demonstrate the application of bottom up scenario and impact assessment methods in a case study in Colombia that could further support Colombian institutes involved in adaptation to climate change. The case study was executed from 2013 to 2014. The methodology of adaptation tipping points (Kwadijk et al. 2010) which was originally developed in the Netherlands (with its typical context of high flood protection) is applied in the Colombian management of flood risks and drought risks at two scales: the Magdalena basin upstream of Regidor, (for looking at extreme discharges) and the tributary Coello basin of the Magdalena (for looking at water shortages). Research questions treated in this paper are:

- What are the main results with respect implications of climate change for the areas under study.
- What are main limitations of the study referring both to technical (data and models) and organizational aspects (knowledge level, participation and cooperation)
- What can be said about the applicability and replicability of the methods applied.

Overall Methodology

The adaptation tipping point method as developed by Kwadijk et al. (2010) takes certain performance levels (derived from policy objectives) of the system as a starting point. Imagine for instance a river basin system with a basin authority providing water for consumption and irrigation and managing the flood risks by building and maintaining levees, reservoirs and flood pain management. To do this in a proper way, objectives are defined between authorities and stakeholders for the amount and quality of water that needs to be delivered or the safety level that needs to be maintained. These objectives need to be risk based since we have to deal with large natural variability within we won't be able to cope with all possible extremes. The main underlying question is: what is an acceptable risk? (Fig. 20.2).

Climate change will alter the river's hydrological regime which may lead to an increase of droughts and floods in the future causing at a certain moment that objectives can no longer be met and current management and policy has to be reconsidered, new measures might need to be taken. In scientific literature (Kwadijk et al. 2010; Haasnoot et al. 2012) these certain moments are called *adaptation tipping points*. The timing of occurrence depends heavily on the uncertainty in the speed and amount of climate change and on the definition of a critical level or acceptable risk level which may also change in time due to socio economic development or changing societal risk perception.

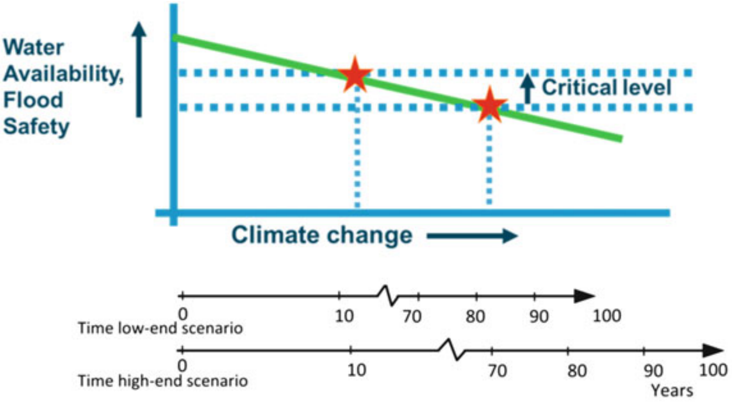

Fig. 20.2 Graphical depiction of adaptation tipping points. With increasing climate the critical or acceptable levels for flood safety or water availability may be threatened. The time range within this might happen is determined by the range of scenarios used. In a high-end scenario extremes are more likely to occur earlier than in a low-end scenario. Socio-economic changes can also alter the critical levels in different ways. For instance converting agricultural land to urban will increase the needed flood protection levels and population growth might increase the demand for fresh water

To determine the adaptation tipping points for the two pilot areas the following steps were taken:

(1) *Determine acceptable risk levels*. Relevant policy documents were analyzed and stakeholders consulted to find out what could be considered as accepted risk levels for floods in the Magdalena basin north of Puerto Berrio and for droughts within the Magdalena Basin. No clear flood protection standards neither clear service levels for water supply in the Coello basin could be found. Past floods however provide good information on hydrologic and hydrodynamic behavior of the flood and the casualties and damages that occurred to support such discussion. It is clear that the floods that occurred in the first half of 2011 are to be avoided in the future (see Fig. 20.1). Therefore we took this flood and it's a return period as a proxy for acceptable flood risks. For drought risks the drinking water supply to the city of Ibague was considered as a critical service.

(2) *Build system models* able to simulate risk variables for the two pilot areas (see Section "Build System Models for the Pilot Basins")

(3) *Derive climate and socio economic scenarios* to stress test the system (see Section "Development of Scenarios")

(4) *Stress test the system* with the scenarios and statistics developed in previous steps (Section "Deriving Adaptation Tipping Points for Flood Risks and Water Demand")

Build System Models for the Pilot Basins

In setting up the system models for this study the use of publicly available supported software and the use of local observational data was a prerequisite in order to really be able to improve and build upon existing capacities among the organizations involved.

To perform a hydrological analysis to estimate current and future discharges of the Magdalena river a hydrological model was built and calibrated using the WFLOW model platform (Bouaziz 2014; Schellekens 2014). The WFLOW model is a fully distributed version of the HBV model (Lindström et al. 1997) with a kinematic wave function for routing. The model was calibrated for the upper and middle Magdalena Basin at the stations of Payande (Coello basin), Puerto Berrio and Regidor. The NashSutcliffe (Nash and Sutcliffe 1970) scores obtained were respectively for each station 0.34, 0.80 (see Fig. 20.3) and 0.70. The input data used was inverse distance interpolated precipitation based on 490 stations measured by IDEAM (Instituto de Hidrología, Meteorología y Estudios Ambientales de Colombia). Minimum and maximum temperatures were also retrieved from IDEAM and interpolated using a lapse rate correction. They were then used in the Hargreaves formula (Hargreaves and Samani 1985) to derive potential evaporation. The point data was interpolated into a gridded product with a resolution of 0.02° (Fig. 20.4).

The unmet water demand under present conditions and under climate change was modeled using the WEAP model for five districts within the Coello basin (Droogers et al. 2014). The model used for the Coello basin is built using the WEAP framework. WEAP is selected as it is designed to work at basin scales and has the level of physical detail needed for this project. A detailed discussion on WEAP can be found in the WEAP manual which can be freely downloaded from the WEAP website (http://www.weap21.org/). An important component of the current project

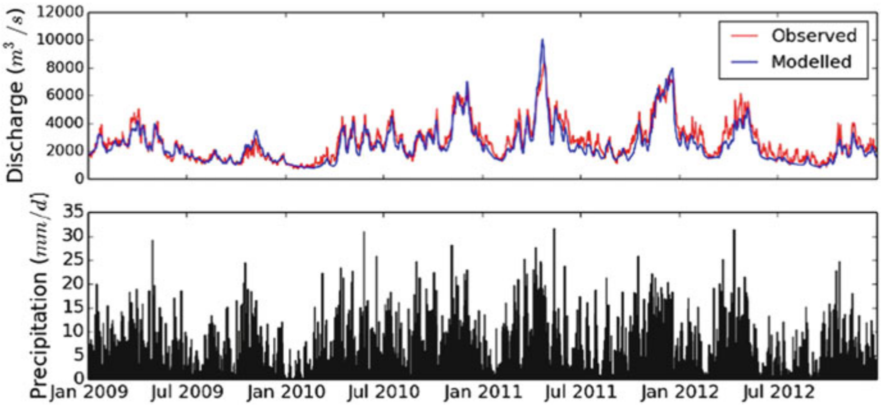

Fig. 20.3 Observed versus modelled discharge (*upper panel*) and observed precipitation (*lower panel*) at Puerto Berrio

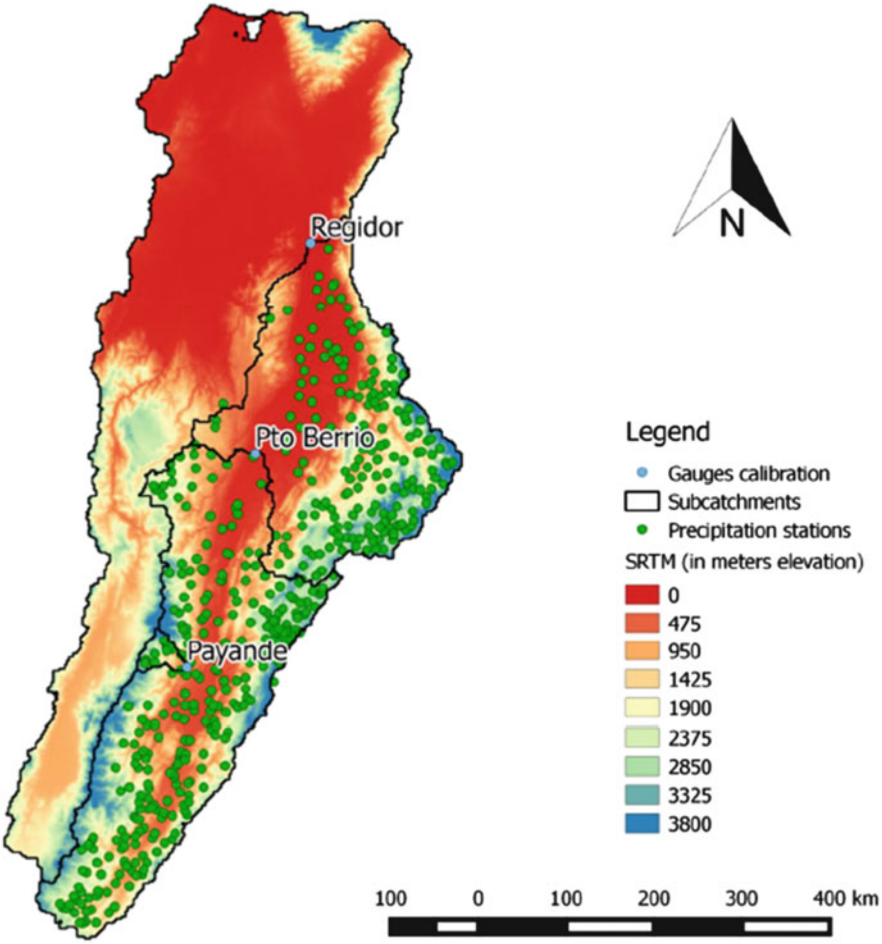

Fig. 20.4 *Upper* and *Middle* Magdalena basin with the location of the three gauging stations (Regidor, Puerto Berrio and Payande) used for calibration and precipitation stations

is the use of a two-tire approach in which data from one model feeds into another. Results from WFLOW model are used as available estimate for inflow in the WEAP model.

This has been done given the better capabilities of the WFLOW model to change the rainfall into runoff, which is determined by the highly-dynamic and complex hydrological processes. WEAP is not able to capture all these complex processes on a daily base and at fully spatial distributed extent. The Coello basin in the model is divided into five sub-basins according to major tributaries (see Fig. 20.5). Within each sub-basin the following water use categories are represented: Domestic (dominant in sub-basin 4 with the capital of Ibague), Industry (including mining dominant in the upper reaches of sub-basin 1–4) and Irrigation (dominant in

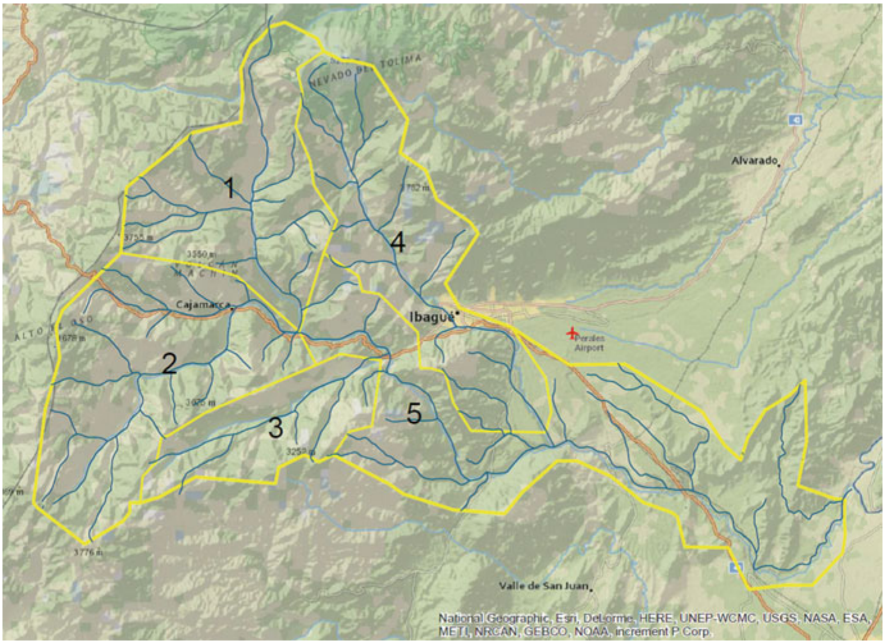

Fig. 20.5 Schematization of the Coello basin into five sub-basins for WEAP

sub-basins 4 and 5 with the extensive paddy rice cultivation). Annual (and in case of irrigation monthly) water demands were estimated using local data sources, expert knowledge and public data (see for more detail Droogers et al. 2014).

Input to both the WFLOW and WEAP model are detailed land cover data based on a map provided by IDEAM presenting the year 2005 (Quinones 2014). Both models were run for a reference period from 1980 until the end of 2013.

Development of Scenarios

To investigate possible impacts of climate and socio economic changes, targeted scenarios were developed. Three particular requirements were put to this scenario development: (1) they should cover a plausible range of uncertainty, (2) they should reflect the high variability key to the flood and drought problem and (3) they should be backed up by a stakeholder process.

To obtain a plausible range of climate scenarios we started with state of the art global available data from the Coupled Model Inter-comparison Project Phase 5 (CMIP5), which provides sets of future climate data by coordinating many institutions to perform climate model experiments (PCMDI 2014). The models in the experiment were driven by predetermined future paths of radiative forcing the representative concentration pathways (RCPs) (IIASA 2013). Model outputs for the RCP 4.5 (second lowest) and RCP 8.5 (highest) pathway were taken from two GCM's (out of 23): MPI-ESM-LR from Max-Planck Institute for Meteorology and HadGEM2-ES from the UK Met Office. These two models were chosen based upon their good reputation and also because their projected climate for Colombia was covering the range of all 23 available GCM's quite well.

Direct downscaling of the relatively course GCM output to a high resolution grid over Colombia would yield insufficient variability of and a bias in the variables under consideration. A solution is to combine GCM information with a reference meteorological time series. Statistics of a GCM control and future climate can be used to scale the values of an observational reference series so that they can be taken as representative for the future climate. This way the GCM signal is incorporated into the high spatial scale reference data that is more suitable for hydrological modeling. The observational data were obtained from IDEAM covering a 30 year reference period from 1980 until 2013. These point data were interpolated into a gridded product with a resolution of 0.02°. In order to assess climate change impacts on discharges of the Magdalena basin, the historical data (precipitation and potential evaporation) were transformed to the future climate as obtained from the two selected models using the advanced delta change method (ADC) (van Pelt et al. 2012) for mid (2036–2065) and end century (2071–2100). This method is especially suited to transform extreme precipitation to drive hydrological models and has been used successfully before for the Rhine Basin (van Pelt et al. 2012).

The results obtained show that an increase of the extreme precipitation values over the Magdalena basin can be expected of about 5–20 % compared to the reference data. This is a significant increase and it will likely affect flooding risks. This finding also appears to be quit consistent over the GCM and RCP projections used. Although these numbers are difficult to compare, since averaged over different geographical extend, the numbers are in line with projections given by IDEAM itself for some departments in the Magdalena valley. For instance values around 12–24 % (depending on timeframe and RCP) are reported for the increase in total precipitation for the departments Huila and Tolima until 2100 (IDEAM et al. 2015).

To develop scenarios for future land and water use in the Magdalena basin a participatory approach was chosen. Instead of extrapolating national and regional trend figures which are often difficult to obtain, experts from different sectors were asked to come up with estimates of water demand and land use in the basin in 2050.

First story lines (see textbox 1) were developed based on two future pathways, which were chosen by their selves as possible and plausible. One of these pathways was the shared socio-economic development path SSP2 and the other was SSP4 (O'Neill et al. 2012). Within each story line global estimates were given by the experts of percentage land use and water demand in the present and 2050 situation in the river basin (see for example Table 20.1). A group of around 12 experts developed the scenarios in a one day workshop. Good sectorial coverage was obtained with the relevant ministries of planning, environment, agriculture, mining and energy and some water management and municipal levels being represented.

Table 20.1 By experts estimated figures for water demand in the Magdalena basin

Sector	Demand in 2050		
	Actual use	SSP2	SSP4
Urban	10	10	20
Cattle	15	10	30
Agriculture	55	40	60
Mining and energy	13	15	18
Industry	7	15	20
Total	100	90	148

The national peace process, development of equality, the development of mining and some major cities were considered as key for the vulnerability to flood and drought risks (Jeuken et al. 2014).

Deriving Adaptation Tipping Points for Flood Risks and Water Demand

The hydrological model for the Magdalena was run for a reference period from 1980 until the end of 2013 and the in total 4 climate projections (see Section "Development of Scenarios") for both mid (2036–2065) and end of the century (2071–2100). An analysis of the effects of climate change on river discharges was done based on mean, minimum, maximum monthly flows and distributions of extreme values.

Extreme values based on a Gumbel distribution were analyzed for the different projections, as shown in Fig. 20.6. In this figure, as well as in Table 20.2, it can be seen that the central estimate of the return period of the discharge of the Magdalena river in the current climate is about 27 years. By the mid and end of the century this return period may be as much as once every 4 years on average.

The study on the impacts of climate change in the Magdalena basin shows an overall increase of the occurrence and the magnitude of extreme events. Additionally, overall mean discharges and especially during the first rainy period (April) are expected to increase. These results seem to be robust over the climate projections used in the study representing two different climate models and emission scenarios.

Based on this analysis of return periods there is good reason to act to improve the flood risks in this part of the basin. One may conclude that critical flood risk levels have already been exceeded in the current climate. The additional climate impact analysis indicates that if actions are taken now, the future climate projections should be taken into account as risks consistently increase over the multiple projections presented here. From Fig. 20.6 it could also be derived that the design discharge in 2050 for infrastructure to adapt to these increasing risks would be around 14.000 m^3/s if a 100 year return period is used as design standard for flood protection systems (like it often is in many countries) (Figs. 20.7 and 20.8).

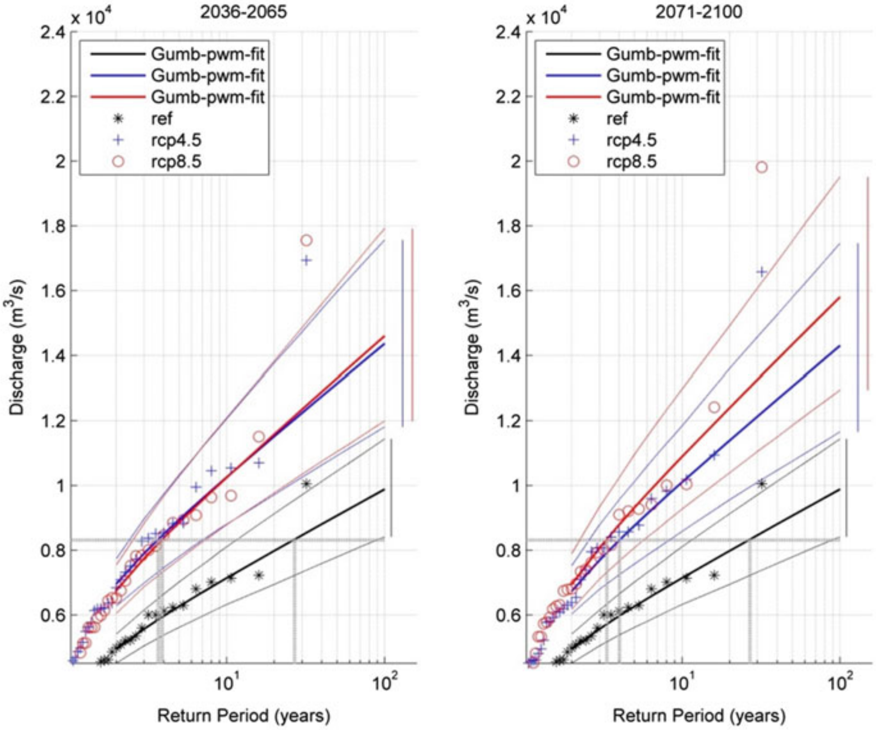

Fig. 20.6 Gumbel extreme value analysis for mid and end century for different RCP's of the HadGEM2-ES climate model. The points represent observations of annual maximum discharges and the *thicker lines* showing the different Gumbel fits for the different scenarios. The *finer lines* around the fits represent the 90 % uncertainty bounds. The *horizontal gray line* depicts the discharge that was measured at Puerto Berrio during the 2011 flooding

Table 20.2 Central estimates of the return period under climate change for extreme discharges at Puerto Berrio based on Fig. 20.6

Discharge (m ^{3}/s)	Current return period (years)	Return period in 2050 (years)	Return period in 2100 (years)
8300	27	5	4
10,000	100	10	10

There are however limitations to the above analysis that urge us to be careful to handle these results with care. There are quite large uncertainty bands associated to the central estimates given. For instance the bandwidth around the estimated return time of the 2011 maximum discharge ranges from 10 to 100 years. Discharges are used as a proxy for flooding using the recent example of the 2011 floods. Every flood situation is however different. Therefore additional hydrodynamic modeling is required to really be able to simulate flooding under different conditions.

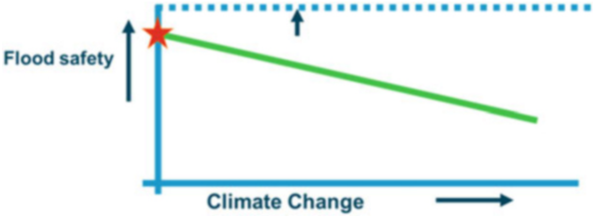

Fig. 20.7 In terms of adaptation tipping points it can be concluded that the current risk level (at which a discharge as occurred in 2011 has an estimated return period of 1/27 years (central estimate)) is already unacceptably high or graphically is below the accepted risk level (*dashed line*) Climate change will only increase the difference between actual flood safety and desired risk level

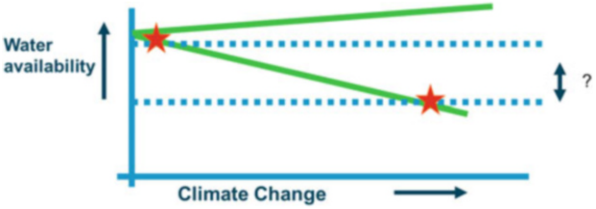

Fig. 20.8 In terms of tipping points for adaptation the situation in the Coello basin is unclear. There is clearly some ambiguity in the climate projections and no clear targets for water availability could be derived from the study due to a lack of clear objectives

The same climate projections were used to stress test the water supply and demand system of the Coello basin (as modeled described in Section “Development of Scenarios”) under climate change. In addition changes in water demand (as suggested by the expert scenarios) were included in the water demand model.

For water availability the analysis gives ambiguous results as only one of the climate projections results in a decrease of water available and increase of unmet demand (see Table 20.3). This projection is the high emission RCP8.5 scenario simulated by the HADGEM2 model for the end of the century. Only under this scenario the total annual water demand for Ibague will increase from 57 MCM/year currently to 128 Million Cubic Meters year around 2100.

The average annual unmet demand will increase from 16 MCM/year to 42 MCM/year. However large variation in annual water shortages will occur. Equally important is to consider the number of months where water shortage occurs. The number of months without any water shortage does not change significantly (47 % currently and 43 % in 2100). However, the number of months with severe water shortages could increase significantly in the future considering this high end climate projection. The analysis by also shows that the influence of socio economic changes on the unmet demand is relatively low on the basin scale but locally could make a difference (Droogers et al. 2014).

Table 20.3 The unmet water demand in Million Cubic meters (MCM) per year for different projected combination of RCP, climate model and projection period (middle or end of century) and the reference period. Water demand scenarios are not included here

Scenario/GCM	Period	Unmet Demand (MCM/year)
Reference	1980–2013	878
RCP4.5/Hadgem2	1936–2065	509
RCP4.5/Hadgem2	1971–2100	609
RCP8.5/Hadgem2	1936–2065	618
RCP8.5/Hadgem2	1971–2100	1232
RCP4.5/MPI-ESM	1936–2065	608
RCP4.5/MPI-ESM	1971–2100	692
RCP8.5/MPI-ESM	1936–2065	668
RCP8.5/MPI-ESM	1971–2100	801

The analysis of future water shortages has yielded a lot of insight in the performance of the Coello water supply and demand system. However, in order to derive adaptation tipping points for water shortages or unmet demand in the Coello basin there are still too many unknowns and limitations to the analysis done. First of all total unmet demand is a too rough parameter to look at. The question if a water shortage is critical really depends on specific use at specific locations. Therefore a more detailed assessment is needed including locally acceptable service levels. A quick assessment of more local results indicate that for example for the drinking water supply to Ibague (sub-basin 4 a small tributary, with a growing population and upstream mining activities) a critical level will probably be reached earlier than for irrigation in sub-basin 5 (with a much larger base flow). Also to get a better grip on acceptability of water shortages it should be assessed first if the current climate variability already leads to critical conditions being surpassed.

Discussion and Conclusions

This demonstration study has provided a systematic analysis of extreme discharges (as a first proxy for flood risk) and water shortages for the upper and middle Magdalena and Coello river basin respectively. In this analysis plausible future projections of climate and water demand (based on expert workshops and literature) were used to explore extremes in rainfall and discharges, using state of the art downscaling and hydrological modeling tools, and to explore future water shortages using a state of the art water allocation model. Recent maps, data and expertise of Colombian partners were used to provide necessary inputs and to validate the tools used.

In summary the ***main results*** are that climate scenarios show a persistent increase in the occurrence of extreme rainfall events and that, as a consequence, extreme discharges like in 2011 are likely to increase as well. The return period of the 2011 discharge is already quite high under current climate and might increase by a factor 5 to once every 5 years under climate change. For water shortages the results are more ambiguous. One out of eight climate scenarios show decrease in precipitation in one of the growing seasons. Consequently only this one climate scenario leads to an increase of the unmet water demand in the Coello basin. This unmet demand is however also under the current climate substantial. All other scenarios lead to a decrease of the unmet demand. The question whether the unmet demand is critical or not could not be answered and needs additional analysis for specific water use categories at a local level both for the present as possible future situations. For the adaptation process in Colombia these results confirm the need for investments in improved flood risk management in the Magdalena basin that already have been started. In addition they show the need to take into account the potentially serious climate effects in the design of the flood risk management plans.

Being a demonstration project covering a wide range of topics by quick analysis, with the character of a sensitivity analysis more than of a thorough study, also implies that the above results should be handled with care. There are a number of key ***limitations*** to mention here:

Scenarios—In this study only 2 GCM's and 2 RCP's have been used to make downscaled projections of hydrological extremes using one novel statistical downscaling method. IPCC is promoting that a wide ensemble of models should be used. Although the models used in this study are selected to reflect a large range of intermodel variability this has not been tested thoroughly. Different downscaling methods take extremes in precipitation more or less into account. It is important to highlight that ENSO (El Nino Southern Oscillation) and the NAO (North Atlantic Oscillation) have shown to be important indices for climate variability in Colombia. There is a discussion at scientific level if and how these phenomena are affected by anthropogenic climate changes. According to Latif and Keenlyside (2009), Global circulation models do not show consistent indication of either amplification or reduction of ENSO under a warming climate. It is unclear what the implications are of downscaling climate model data using a 33 year data set of past observations. Therefore a critical review of different downscaling methods for the region (and its specific climatic characteristics) and looking at a wider model ensemble is therefore recommended.

From discharges to risks—In this study discharges in combination with past flooding data are used as a proxy for risks. Although this gives a first indication, for a proper risk analysis a much more extensive model and spatial analysis is needed. Such an analysis should include: an improved run off model taking into account the multiple reservoirs and its operations; a hydraulic model able to calculate water depths and two-dimensional flood patterns; flood vulnerability maps to be combined with flood hazards maps; and cost and damage indicator values.

To test the ***replicability*** of methods developed in the Netherlands in the Colombian context was one of the main research questions. The above presented limitations pose no principle barriers for replicability of the methods except that the high climatic variability as discussed provides an additional challenge compared to some other areas. At the moment Colombian authorities are investing in improving its capacity in climate adaptation. For example in the context of PNACC, the planning department (DNP) is aiming to improve its skills in its technical divisions. This includes the review of national and international experiences in adaptation, as well as a review of the relevant legislation framework. There already is a good data infrastructure present which together with modeling capacities are being strengthened at relevant institutions such as IDEAM and the Magdalena river basin authority (CorMagdalena).

The study further revealed that one of the main prerequisites, shared critical thresholds for adaptation needed to perform the adaptation tipping point analyses, were not easily to get. Clear objectives for managing climatic risks could not be derived from the policy documents or obtained during the stakeholder sessions neither at national nor at a more regional policy level. A more systematic participative process supported by proper knowledge and risk analysis studies as suggested above is needed to develop such objectives as a basis for an adaptation strategy.

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References

Bouaziz L (2014) Calibration of the daily openstreams wflow-HBV model for the Magdalena Basin. Report Deltares, Delft

Brown C, Ghile Y, Laverty M, Li K (2012) Decision scaling: linking bottom-up vulnerability analysis with climate projections in the water sector. Water Resour Res 48, W09537

Droogers P, Kraaijenbrink P, Lutz A (2014) Water allocation planning in Coello-Combeima Basin Colombia. Report FutureWater, Wageningen

Haasnoot M, Middelkoop H, Offermans A, van Beek E, Van Deursen WPA (2012) Exploring pathways for sustainable water management in river deltas in a changing environment. Clim Change 115(3–4):795–819. doi:10.1007/s10584-012-0444-2

Hargreaves GH, Samani Z (1985) Reference crop evapotranspiration from temperature. J Appl Eng Agric 1(2):96–99. doi:10.13031/2013.26773

Harmeling S, Eckstein D (2013) Global climate risk index. Briefing paper. www.germanwatch.org/en/cri

Hoyos N, Escobar J, Restrepo JC, Arango AM, Ortiz JC (2013) Impact of the 2010e2011 La Niña phenomenon in Colombia, South America: the human toll of an extreme weather event. Appl Geogr 39:16–25. doi:10.1016/j.apgeog.2012.11.018

IDEAM, PNUD, MADS, DNP, CANCILLERÍA (2015) Escenarios de Cambio Climático para Precipitación y Temperatura para Colombia 2011-2100. Herramientas Científicas para la Toma de Decisiones—Estudio Técnico Completo: Tercera Comunicación Nacional de Cambio Climático

IIASA (2013) RCP Database. http://tntcat.iiasa.ac.at/RcpDb/dsd?Action=htmlpage&page=welcome

Jeuken A, Corzo G, Quinones M, de Keizer O (2014) Adaptation to climate change in Colombia: a tipping point analysis: results of the workshop on socio-economic scenarios. Deltares, Delft

Kwadijk JCJ, Haasnoot M, Mulder JPM, Hoogvliet MMC, Jeuken ABM, van der Krogt RAA, van Oostrom NGC, Schelfhout HA, van Velzen EH, van Waveren H, de Wit MJM (2010) Using adaptation tipping points to prepare for climate change and sea level rise: a case study in the Netherlands. Wiley Interdiscip Rev Clim Change 1:729–740. doi:10.1002/wcc.64

Latif M, Keenlyside NS (2009) El Niño/Southern Oscillation response to global warming. PNAS 106(49):20578–20583. doi:10.1073/pnas.0710860105

Lindström G, Johansson B, Persson M, Gardelin M, Bergström S (1997) Development and test of the distributed HBV-96 model. J Hydrol 201:272–288

Nakaegawa T, Vergara W (2010) First projection of climatological mean river discharges in the Magdalena River Basin, Colombia, in a changing climate during the 21st century. Hydrol Res Lett 4:50–54. doi:10.3178/HRL.4.50

Nash JE, Sutcliffe JV (1970) River flow forecasting through conceptual models part I—a discussion of principles. J Hydrol 10(3):282–290

O'Neill BC, Carter TR, Ebi KL, Edmonds J, Hallegatte S, Kemp-Benedict E, Kriegler E, Mearns L, Moss R, Riahi K, van Ruijven B, van Vuuren D (2012) Meeting report of the workshop on the nature and use of new socioeconomic pathways for climate change research, Boulder, CO. http://www.isp.ucar.edu/socioeconomic-pathways. Accessed 2–4 Nov 2011

PCMDI (2014) Program for Climate Model Diagnosis and Intercomparison: coupled model intercomparison project phase 5. [online]. http://cmip-pcmdi.llnl.gov/cmip5/. Accessed 23 April 2014

Poveda G, Jaramillo A, Gil MM, Quiceno N, Mantilla RI (2001) Seasonality in ENSO-related precipitation, river discharges, soil moisture, and vegetation index in Colombia. Water Resour Res 37(8):2169–2178. doi:10.1029/2000WR900395

Quinones M (2014) Remote sensing products to support the project "Climate adaptation Colombia: Tipping Point Analysis". Report Sarvision, Wageningen

Rojas-Laserna M (2014) Adaptation to climate change in Colombia effective institutional arrangements for NAP formulation and implementation. Presentation at NAP Expo 2014, Bonn. http://unfccc.int/files/adaptation/application/pdf/colombia_mariana_rojas_laserna_session_3.pdf

Schellekens J (2014) Openstreams wflow documentation (Release 1.0-RC3-dev-31-45 M). http://schj.home.xs4all.nl/html/

Trenberth KE, Fasullo JT (2012) Climate extremes and climate change: the Russian heat wave and other climate extremes of 2010. J Geophys Res 117, D17103. doi:10.1029/2012JD018020

Van Pelt SC, Beersma JJ, Buishand TA, van den Hurk B, Kabat P (2012) Future changes in extreme precipitation in the Rhine basin based on global and regional climate model simulations. Hydrol Earth Syst Sci 16:4517–4530

Ward PJ, Jongman B, Kummu M, Dettinger MD, Sperna Weiland FC, Winsemius HC (2014) Strong influence of El Niño Southern Oscillation on flood risk around the world. PNAS 111(44):15659–15664. doi:10.1073/pnas.1409822111

Wilby RL, Dessai S (2010) Robust adaptation to climate change. Weather 65(7):180–185