DOI: 10.7343/as-2018-334

WEAP-MODFLOW Dynamic Modeling Approach to Evaluate Surface Water and Groundwater Supply Sources of Addis Ababa City

Approccio di modellazione dinamica WEAP-MODFLOW per valutare le risorse idriche sotterranee e superficiali della città di Addis Abeba

Behailu Birhanu, Seifu Kebede, Marco Masetti, Tenalem Ayenew

Riassunto: L'integrazione tra i modelli WEAP e MODFLOW accoppiati tramite LinkKitchen contribuisce a creare un collegamento dinamico tra le acque di superficie e le fonti di approvvigionamento idrico della città di Addis Abeba. I possibili impatti degli stress naturali e antropogenici sul volume dei bacini superficiali e sull'immagazzinamento delle acque sotterranee sono stati valutati attraverso scenari di approvvigionamento idrico. Le proiezioni indicano che la copertura della domanda idrica del 100% non sarà raggiunta per proiezioni di crescita della popolazione elevate (4,6%), medie (3,8%) e basse (2,8%), anche con tutti i progetti di approvvigionamento idrico previsti fino al 2025. Lo scenario indica che, poiché i bacini di acqua superficiali sono altamente sensibili ai cambiamenti climatici e alla variabilità, le fonti di approvvigionamento idrico sotterraneo delle città saranno notevolmente interessate dai progetti di approvvigionamento. Se l'estrazione di acqua sotterranea continuerà ad aumentare per soddisfare la domanda, nel 2025 sarà possibile registrare più di 30 metri di abbassamento del livello delle falde.

Il modello è stato testato per prevedere l'effetto combinato degli stress naturali e antropogenici sulle fonti di approvvigionamento idrico della città, sia in condizioni ottimali, sia in condizioni peggiorative. Lo scenario ottimale si traduce in una domanda di acqua completamente soddisfatta nei mesi più umidi fino al 2025, con un probabile calo di circa 6 metri del livello della falda freatica. Lo scenario peggiore mostra che il soddisfacimento dell'idroesigenza sarà potenzialmente ridotto ad un massimo del 35% nel 2025, con una variabilità stagionale e annuale.

Il legame dinamico tra i bacini di acqua di superficie e le fonti di approvvigionamento idrico sotterraneo aiuta a ottenere informazioni sulle potenziali conseguenze delle mutevoli condizioni naturali e antropogeniche in continua evoluzione sulle fonti di approvvigionamento idrico. Di conseguenza, la previsione delle future cospicue pressioni sull'acqua superficiale e sulle falde acquifere della città di Addis Abeba indica chiaramente che la pianificazione e lo sviluppo di fonti alternative di approvvigionamento idrico al di fuori del confine cittadino (bacino Awash) dovrebbero essere immediatamente avviate per rispondere alla domanda sempre crescente. Altrimenti, non solo Addis Abeba continuerà a non poter soddisfare la propria idroesigenza per gli anni a venire, ma anche le locali fonti di approvvigionamento idrico saranno gravemente colpite.

Abstract: *The integration between WEAP and MODFLOW models coupled via LinkKitchen helps to create a dynamic link between surface water and groundwater supply sources of Addis Ababa city. Possible impacts of natural and anthropogenic stresses on surface water reservoirs volume and groundwater storage have been assessed through water supply scenario analysis. Besides, contrary to other surface water hydrological models, the unique nature of WEAP adds water demand assessment by simulating Addis Ababa city near future water demand coverage under three population projection scenarios. The water demand projections of Addis Ababa city indicates 100% water demand coverage will not be achieved for high (4.6%), medium (3.8%) and low (2.8%) population growth rate projections, even with all the emerging and planned water supply projects starting production up until 2025. Supply scenario projections indicate, as surface water reservoirs are highly sensitive to climate change and variability, the city groundwater supply sources will be noticeably affected by the emerging and planned groundwater supply expansion schemes. If groundwater abstraction continues to reach to zero unmet demand, more than 30 meter groundwater level decline can be registered in 2025. To foresee the combined effect of both natural and anthropogenic stresses on Addis Ababa city water supply sources, best case (considering conditions which improve Addis Ababa city water supply) and worst case (considering conditions stressing Addis Ababa city water supply) scenarios were tested. The best case scenario results in zero unmet water demand in Addis Ababa city in most wet months of future projection years up to 2025, with likely decline of about 6 meter on the groundwater level. The worst case scenario shows that Addis Ababa city water demand coverage will potentially be reduced to a maximum of 35% in 2025, with seasonal and annual variability. The dynamic link between surface water reservoirs and groundwater supply sources helps to gain insight into the potential consequences of continuously changing natural and anthropogenic conditions on Addis Ababa city water supply sources. Consequently, the significant predicted near future pressure on Addis Ababa city surface water and groundwater supply clearly indicate that planning and developing alternative water supply sources outside of the boundary (Upper Awash basin) where the city is located should be immediately started in order to endure the pressure from the ever increasing demand. Otherwise, not only Addis Ababa will continue suffering unmet water demand for the years to come, but also the water supply sources will be severely impacted. Nonetheless, wherever the water supply sources, minimizing water loss, waste water recycling and improving water use efficiency should be given at most priority.*

Keywords: *Addis Ababa water supply, WEAPMODFLOW,SW-GW Dynamic modeling, WEAP,MODFLOW, Urban water management.*

Parole chiave: approvvigionamento idrico di Addis Abeba, WEAPMODFLOW, SW-GW Dynamic modeling, WEAP, MODFLOW, Gestione delle risorse idriche urbane.

Behailu BIRHANU ✉
Geology Department
Addis Ababa Science and Technology University
behailu.berehanu@gmail.com

Seifu KEBEDE
School of Earth Sciences
Addis Ababa University
seifukebede@yahoo.com

Marco MASETTI
Dipartimento di Scienze della Terra "Ardito Desio"
Università degli Studi di Milano
marco.masetti@unimi.it

Tenalem AYENEW ✉
School of Earth Sciences
Addis Ababa University
tenalema@yahoo.com

Ricevuto/*Received*: 10 June 2018-Accettato/*Accepted*: 25 June 2018
Pubblicato online /*Published online*: 29 June 2018

Introduction

During the period from 2006 to 2011, the total urban population of the world grew to exceed the total rural population for the first time. The urban population is predicted to continue growing to about 60% of the total global population by 2030, with the increase taking place primarily in the cities of developing countries (UN-HABITAT 2008, 2009). The challenge of providing enough water for the overwhelming majority of the population puts major pressure on the supply of water satisfying the ever increasing demand. The increasing population compounded with climate change and variability amplified the pressure. The complexity of stresses on water supply sources requires more advanced water resource management schemes concurrent with a change in emphasis from resource exploration to resource management (Hellström et al. 2000; Cohen 2006; van der Steen 2009; Mackay and Ewan 2010; Howe and Mitchell 2012) .

Ethiopia is not an exception on the issue of natural and anthropogenic stresses affecting the availability of water supply sources. Based on Population and Housing Census Report of the Central Statistical Agency (CSA) of Ethiopia for Addis Ababa Region, the population of Addis Ababa has grown eightfold from 0.5 to 4 million from 1984 to 2007 and it is expected to rise between 4.5 and 7.5 in 2030 (CSA 1998, 1999; A-Habt 1993; THAHAL 2005). The buildup area of Addis Ababa is also rapidly expanding as a result of urbanization (Van Rooijen 2009). The increasing population compounded with changes in land use put major pressure on the supply of water satisfying the ever increasing demand (Ayenew, et al. 2008; Rae and Ewan 2010). Climate variability and/or change manifested by increased intensity of rainfall, rising temperatures, increased floods and changing seasonality also cause increasing difficulties in efficiently managing scarcer and less reliable water resources (Oljira 2006; Ayenew and Legesse 2007). The challenge of providing overwhelming majority of the population of cities (like Addis Ababa) which has been in a dramatic water intensive change with scarcer water resources signals a need to move from the conventional urban water supply sources management practices towards a new modern paradigm (Mackay and Ewan 2010).

Compared to other parts of Ethiopia, groundwater potential in Upper Awash basin where Addis Ababa city located is well investigated. Groundwater simulation models, litho-stratigraphy, isotope hydrology and hydro-geochemistry were done either for part or for the whole Upper Awash (Kebede et al. 2005; Tsehayu et al. 2005; Oljira 2006; Kebede et al. 2007; Ayenew et al. 2008; Tesfaye 2009; Yitbarek 2009; Yitbarek 2012 Azagegn 2015) to quantify groundwater fluxes and analyze the hydrodynamics of the aquifer system. However, the combined modeling of groundwater resources and surface water supply reservoirs has never been done. This is a key point considering that: a) in Upper Awash basin surface water bodies (reservoirs and rivers) are intimately linked to the productive aquifers systems (Ayenew et al. 2008; Azagegn et al. 2014; Azagegn 2015); b) both surface water reservoirs and groundwater supply sources contribute to supply Addis Ababa city water demand.

For proper utilization of groundwater and surface water resources identified as urban water supply sources, understanding urban hydrology and hydrogeological systems and the study of their vulnerability to natural and anthropogenic stress conditions is very essential (Loiskandl 2006; Masetti et al. 2009; Fletcher et al. 2013; Willem 2013). Hence, in case of Addis Ababa city where there is comparable contribution from both surface water reservoirs and groundwater systems for water supply, the two systems should be integrated. To this end, modeling Addis Ababa city surface water and groundwater supply sources, which could be used as basis for urban water supply management decision support tool has been developed by synchronized simulation of surface water and groundwater supply sources using WEAP-MODFLOW dynamic linkage (SEI 2001). The new methodological approach allows continuous flow of information between the two environments through an interface created by using specially designed software for the purpose called LinkKitchen (Huber 2013).

Although the approach is tested for a case of Addis Ababa city, the problems to be addressed are quite similar to any other big cities where surface water and groundwater supply sources dynamic modeling is needed to help design basis for water supply management decision support tool. For this study, future scenarios are addressed under broad range of "what if" questions. What if water will continuously be abstracted from Addis Ababa city groundwater water supply sources? What if surface water and groundwater resources are fully exploited without physical infrastructure capacity limitation? What if climate change and variability alters the existing hydrologic pattern? What if population growth takes the highest projection rate reported?

Study Area

The study area is located in central Ethiopia bounded by the Blue Nile River basin to the north and the Main Ethiopian Rift system in the south and south east. The area extends from 8° 23' 25" to 9° 18' 42" N latitude and from 37° 59' 9" to 39° 04' 12" E longitude (Fig. 1). Addis Ababa city is the major water user in the basin (Upper Awash) taking potable water from the north (Dire and Lega Dadi dams), from north east (Legedadi well fields), from the North West (Gefersa dam) and from the south (the Akaki-Fanta well Fields).

A number of works to characterize aquifer properties, determine mechanism of groundwater flow and conceptualize the lateral and vertical extent of the aquifers were carried out supported by exploratory drillings, pumping test, hydrochemistry, stable isotopes of water and radioactive isotopes (Tsehayu et al. 2005; Kebede et al. 2007; Ayenew et al. 2008; Yitbarek 2009; Azagegn et al. 2014). There works were very much important to numerically represent the study area.

Data and Methods

To evaluate the supply sources of Addis Ababa city water demand, a dynamic link between surface water and groundwater has been developed using MODFLOW coupled

DOI: 10.7343/as-2018-334

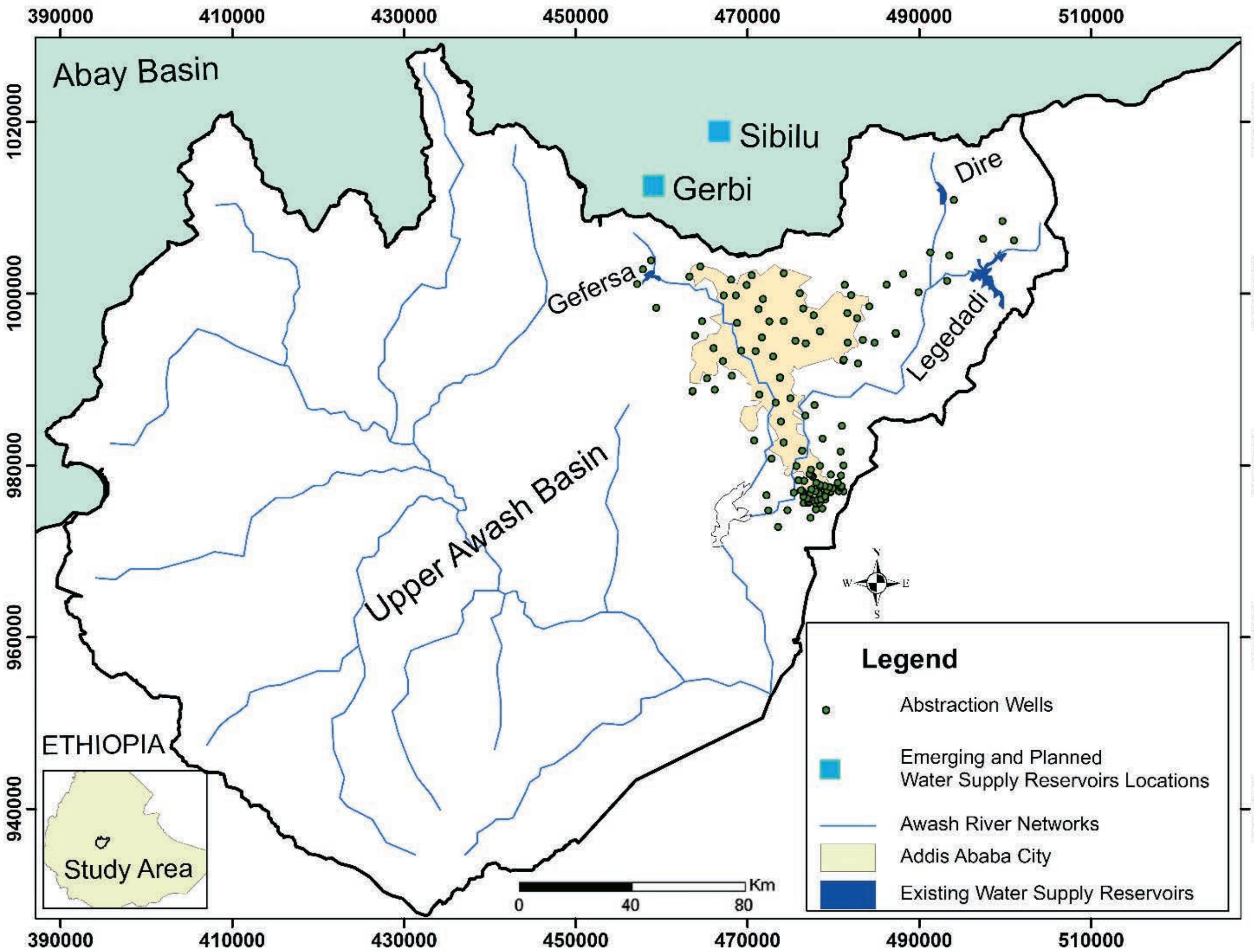

Fig. 1 - Location map of Awash River basin in central Ethiopia where Addis Ababa city is located. Inset shows the location of the basin in Ethiopia.

Fig. 1 - Localizzazione geografica della città di Addis Abeba all'interno del Bacino di Awash, Etiopia Centrale.

with WEAP modeling techniques. In the dynamic link, both surface water supply reservoirs and groundwater supply sources are represented. Upper Awash River basin where Addis Ababa city is located (Fig. 1) was characterized based on DEM from 30 m spatial resolutions Shuttle Radar Terrain Model (SRTM), land use-land cover and soil classification extracted and modified from FAO land use land cover and soil maps of Ethiopia (FAO, 1984). Hydro-meteorological data collected from National Meteorological Agency (NMA) and Ministry of Water Irrigation and Electricity (MoWIE) were used to estimate recharge annually added into Upper Awash aquifer system and groundwater flux from adjacent aquifer systems.

Main Awash River and its major tributaries together with Addis Ababa city surface water reservoirs were modeled using Water Evaluation and Planning WEAP model (SEI 2001). This unique water resources and planning software was also vital tool to calculate water demand conditions of Addis Ababa city. The groundwater system in the study area is also simulated using three-dimensional finite difference groundwater flow model MODFLOW-2000 (Harbaugh et al. 2000).

To dynamically link surface water and groundwater supply sources of Addis Ababa city, an interface which can be used as a medium to continuously exchange information between WEAP and MODFLOW models has been developed by using LinkKitchen (Huber 2013). Important surface water modeling variables (catchments, rivers, reservoirs, demand sites) in WEAP were coded so that it can easily be read by each cells of the groundwater MODFLOW model. The Processing MODFLOW model has been modified in MODFLOW-2000 format to establish spatial integrity between the models. Discretization (discrit.dat), basic packages (bas6.dat) and block centered flow packages (bcf6.dat) output files are decoded to be compatible with WEAP internal algorithms. Discretization, basic flow package and block centered flow packages are program files where top and bottom of the aquifer system, the various flow packages within the model and active model domain are coded respectively. The coupled models were calibrated using river discharge data to establish realistic surface water and groundwater balances. Finally, the dynamically linked model has been used to test series of future Addis Ababa city water demand-supply scenario projections.

The first step of the analyses started by considering that good management of water resources should be based on an insight into the evolution of past water use, an understanding of current demand, as well as an awareness of possible future trends (Molle 2003). In order to understand the past water use trend, the current water utilization and the likely near future water demand and supply conditions of Addis Ababa city, 'historic' and future scenarios are developed based on plausible projection. There are population projections suggested for Addis Ababa city (CSA 1988, 1989; A-Habt 1993; THATAL 2005). The population projections were established based on some assumptions. For the purpose of accommodating all the uncertainty or to avoid errors due to inappropriate or unintended assumptions, the population projections were systematically categorized into Low Population Growth Rate (LPGR = 2.8%), Medium Population Growth Rate (MPGR = 3.7%) and High Population Growth Rate (HPGR = 4.6%) population projection categories, from which likely future scenarios would develop.

Accordingly, WEAP calculates water demand and supply requirements for Addis Ababa city for the 'reference' scenario (2004-2015) based on the three possible population projections and aggregate per capita water demand which ranges from 50 to 80 l/capita/day (Berhe 2005; Elala 2011; AAWSA 2015). The average of the minimum (20%) and maximum (40%) water loss reported is taken for the reference model simulation (30%) (Berhe 2005). Hence, more water supply than actually demanded is required to satisfy the demand.

The demand and supply requirements for the three population projection scenarios show the possible range of error induced in Addis Ababa city water demand calculations and how significant the error would have been if only one projection scenario had been selected to calculate demand coverage or unmet demand, but it were otherwise. Up to 2 Mm3 to 6 Mm3 difference in monthly water demand among the three population trajectories were registered within the reference model simulation temporal domain. About 65% maximum water demand coverage is observed for LPGR scenario simulation with wet and dry season variation (Fig. 2). The maximum monthly demand coverage for MPGR and HPGR scenarios are 54% and 51% respectively.

Results and Discussion

Water Supply Expansion Schemes Scenarios

There is a renewed interest in water infrastructure in the developing world where there has been a general underinvestment in water related infrastructure (Sadoff 2008; Faures et al. 2007). This is clearly observed in Addis Ababa city. New and planned surface water and groundwater supply sources are being introduced to the already existing supply sources and are expected to be completed up to the 'last year' of model simulation, 2025.

The existing water supply schemes represent the time interval from 2004 to 2015 and already simulated under the reference scenario. Emerging and planned water supply schemes represent near future water supply expansions in Addis Ababa from the current (2015) up to 2025. Accordingly, WEAP-MODFLOW model simulation periods is changed from 2004-2015 to 2004-2025 with aggregate per capita water demand ranging from 80 to 100 l/capita/day with 3.62 aggregate annual per capita growth rate.

To evaluate the likely future impact of Addis Ababa city water supply expansions on the surface water reservoirs and groundwater supply sources, the emerging and planned surface water reservoirs and groundwater sources (Fig. 1) have been introduced in the integrated model distributed in time based on AAWSA business plan up to 2025.

Figure 3 present the results of the model runs with the new water supply schemes (2004-2025) for each of the three population growth rate scenarios. Results show that the planned water supply schemes will manage to take the

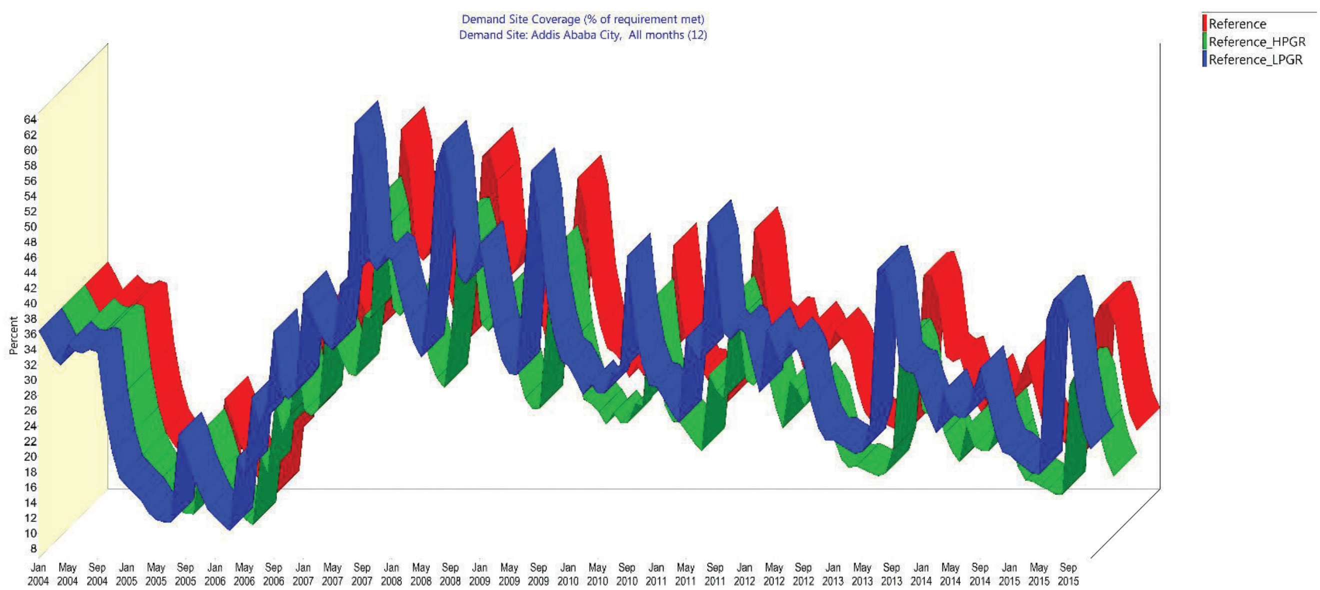

Fig. 2 - Reference model simulation result for Addis Ababa city water demand coverage from 2004-2015.

Fig. 2 - Risultato del modello di simulazione relativo ai dati di idroesigenza della città di Addis Abeba dal 2004 al 2015.

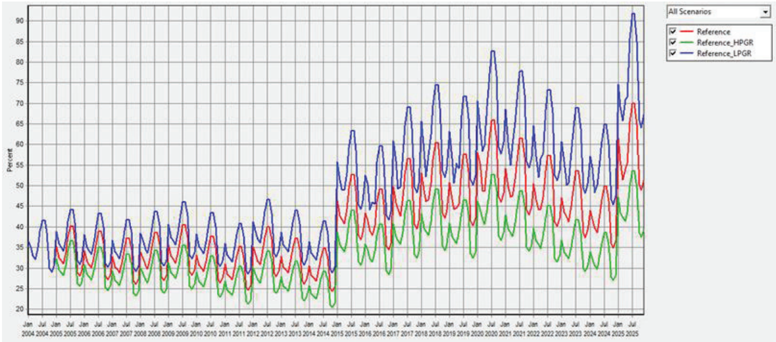

Fig. 3 - Addis Ababa city water demand coverage projections from 2014-2025 for the low, medium and high population projections.

Fig. 3 - Proiezione del soddisfacimento dell'idroesigenza della città di Addis Abeba dal 2014 al 2025 secondo proiezioni di crescita della popolazione bassa, media e alta.

monthly Addis Ababa city water demand coverage to a maximum of 91.2, 70.2 and 54% in 2025 for LPGR, MPGR and HPGR population trajectories, respectively. Shortfalls will still occur in all the population projection scenarios with high seasonal and annual variation until the end of the simulation period, 2025 (Fig. 3).

Together with supplying Addis Ababa city water demand, which is the demand side of the model simulation, the likely impact on the groundwater level has also been evaluated through the supply side model simulation. The contribution of groundwater supply sources has been increasing from about 20% in 2004 to about 40% in 2015. Sharp groundwater level decline is therefore captured right after the last year of the reference simulation period (2015). When emerging and planned groundwater supply schemes will be fully developed, groundwater supply is expected to take the lion share in 2020, about 70%. Due to additional surface water expansions schemes (Gerbi and Sibilu surface water reservoirs, Fig. 1), the contribution from both sources may eventually reach near to proportional contribution: 46% from surface water reservoirs and 54% from groundwater.

As would be anticipated, the increasing abstraction of groundwater results in larger drawdown of groundwater level in wells and near well fields (Fig. 4). The impact is less significant away from intensively exploited well fields. About 8 to10 meter drawdown is observed near to abstraction wells.

The most likely future impact of continuous groundwater abstraction to reach to 100 % Addis Ababa city water demand coverage was evaluated. In order to do that,

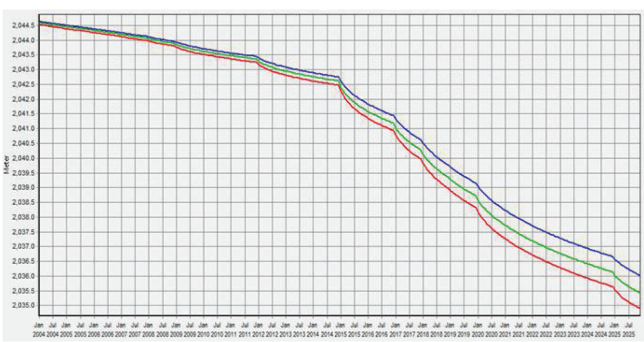

Fig. 4 - Likely impact of the emerging and planned abstractions near well fields if ground water will be abstracted with the existing limited treatment plant capacity.

Fig. 4 - Probabile impatto dei prelievi previsti presso i campi pozzi considerando la limitata capacità dell'impianto di trattamento esistente.

transmission-linking rules joining water supply sources and Addis Ababa city demand site were removed (rule determined by actual treatment plant capacity). Hence, as much water was transferred both from surface water reservoirs and groundwater supply sources until Addis Ababa city water demand coverage reaches to 100 % or zero unmet demand.

The three population projection trajectories (HPGR, MPGR and LPGR) were chosen to test the response of the groundwater system under variable water demand scenarios. Based on the simulation result, , a groundwater level decline of more than 30 meter in wells and near well fields is necessary to satisfy high population growth rate of Addis Ababa city water demand (Fig. 5). A groundwater level decline of 20 meter and 25 meters is expected to occur for the LPGR and MPGR population growth scenarios, respectively. Although smaller, an effect can also be seen far away from wells and well fields.

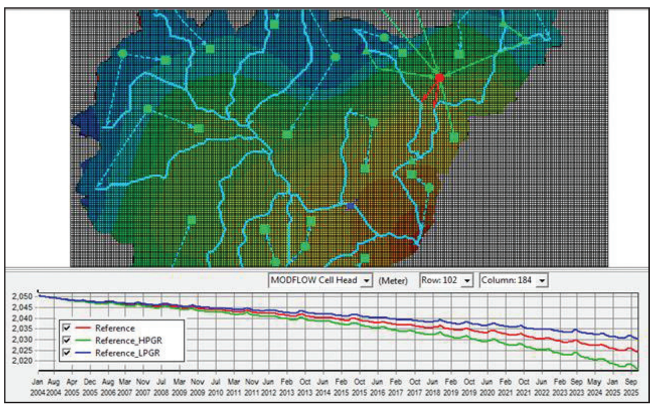

Fig. 5 - Likely future impact of continuous groundwater abstraction near well fields if groundwater will be abstracted without treatment plant capacity limitation.

Fig. 5 - Probabile impatto dei prelievi previsti presso i campi pozzi senza la limitata capacità dell'impianto di trattamento.

Climate Scenarios

Climate change is defined as a statistically significant variation in either the mean state of the climate or in its variability of global temperature and/or rainfall measurement, persisting for an extended period, typically decades or longer (Christensen et al. 2007). Since influence of climate change on rainfall patterns can have a great impact on water resources and water supply (Kundzewicz et al. 2007), there has been a corresponding acknowledgement of the need to incorporate

DOI: 10.7343/as-2018-334

climate change into water planning, particularly in the planning of water storage (Sadoff and Muller 2009).

Nature of climate change and awareness of the possible impacts of it on water resources has increased in recent years (Mathew et al. 2012). However, across much of sub-Saharan Africa, climate change is given low priority. In many countries, systematic evaluation of the possible implications of climate change for water resources has not been given enough consideration in the planning of future water resources development.

Climate change is likely to cause water supply issues in the future, and at some places it already is (Bates et al. 2008; Evans & Webster 2008; Hedger & Cacouris 2008). Understanding the likely impact of climate on water resources can help plan for the future and be a guide to find appropriate adaptation strategies (WHO & DIFID 2010).

Even though the future will probably give more rain, there will also be extreme weather conditions such as more intense rainstorms and high yearly variation, which would potentially result in more variable, and more frequent dry year extremes (Few et al. 2004; Christensen et al. 2007; WHO and DIFID 2010) which is also the likely scenario in Addis Ababa. Therefore, such climatic conditions would possibly result in extended drier climate sequences.

Consequently, two climate scenarios were developed to analyze the impact of climate change and variability on both surface water reservoirs and groundwater supply sources of Addis Ababa city. To analyze the impact of climate variability two different scenarios were tested without changing the mean values of the existing climate: 1) Extended wetter climate sequence, and 2) Extended drier climate sequence. To evaluate possible future consequences of changes in the mean state of climate, the existing climate sequence is changed by a factor of (0.1, 0.5) and (2, 3) water year type.

Climate sequence is defined by hydrologic pattern resulted from relative annual availability of rainfall.

Existing climate models quantifying IPCC scenarios result in predictions that remain too general for practical decision making. In WEAP model, there is built-in tool 'Water Year Method', which translates such coarse resolution climate model predictions to basin level representations. Before setting up the WEAP model to use 'water year method', it assumed a constant head flow to a river. But, natural variations in hydrology can have major effects on scenario results. The WEAP-inbuilt 'water year method' (SEI, 2001) is therefore applied to explore sensitivity of the linked surface and groundwater systems to historic or natural hydrological variation.

Extended Wetter and Drier Climate Sequence

By altering sequence of each water year type according to predicted effects of climate change, the 'Water Year Method' allows to use historical data to easily explore the effects of future climate variability in hydrological patterns. In this study, responses of surface water and groundwater supply sources to extended wetter drier climate sequence were evaluated by considering likely change in wetter and drier climatic sequence in the future without changing the mean state of the existing climate. Therefore, similar water year type definitions in the water year method are used, except that the water year sequence is changed with wet to very wet for the extended wetter climate sequence scenario and from dry to very dry climate sequence for the extended drier climate sequence scenario for projection period from 2020 to 2025.

Addis Ababa city unmet demand and coverage is either positively or negatively affected by the two likely climate variability scenarios (Fig. 6). Seasonal and annual variation aside, more negative impact due to extended drier climate sequence on Addis Ababa city water demand coverage is projected than positive impact due to wetter climate sequence (which can be attributed to limited surface water reservoirs capacity). About 8% monthly decrease in water demand coverage or about 4 Mm^3 unmet demand can be endured due to drier climate sequence in the future. However, only about 1% increase in monthly water demand coverage or about 1 Mm^3 unmet demand would be recovered due to likely wetter future climate condition.

The variation in unmet demand or coverage in the two scenarios is because of the impact of extended wetter and drier climate sequence on surface water and groundwater storage volume. Up to 2.2 Mm^3 decrease in monthly storage is simulated due to drier future climate sequence on the

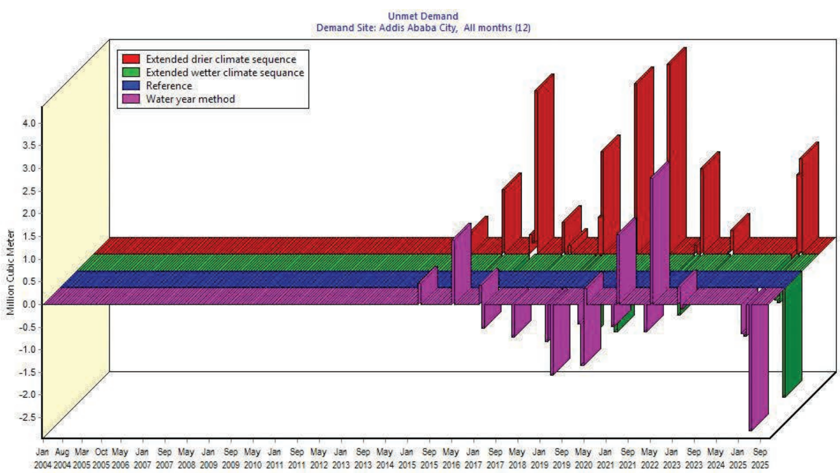

Fig. 6 - Addis Ababa city unmet water demand variation due to climate variability.

Fig. 6 - Non soddisfatta variazione della idroesigenza della città di Addis Abeba dovuta alla variabilità climatica.

DOI: 10.7343/as-2018-334

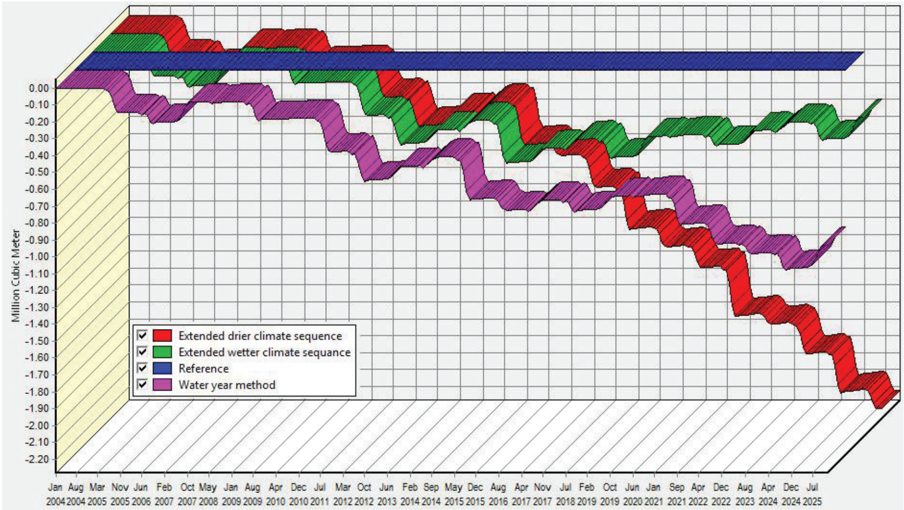

Fig. 7 - Likely impact of climate variability on groundwater storage volume.

Fig. 7 - Impatto della variabilità climatica previsto sul volume d'acqua immagazzinato nelle falde acquifere.

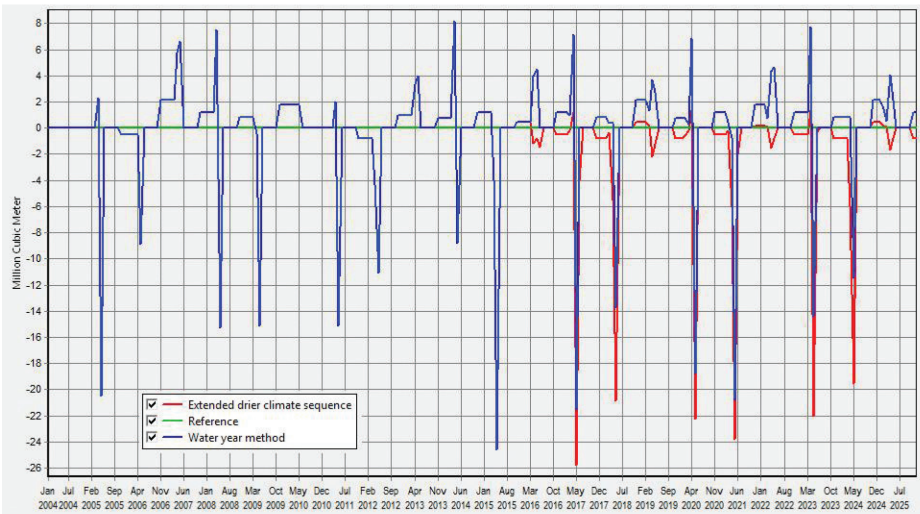

Fig. 8 - Likely impact of climate variability on surface water reservoirs storage volume.

Fig. 8 - Impatto della variabilità climatica previsto sul volume d'acqua immagazzinato nei bacini superficiali.

groundwater storage volume (Fig. 7). Obviously, surface water reservoirs are more susceptible to climate variability than groundwater supply sources. More than 26 Mm^3 of surface water supply reservoirs storage volume can be reduced if the future climate gets drier. Even the natural hydrologic variation simulated using water year method would highly impact surface water reservoirs storage (Fig. 8). Wetter climate sequence may not increase the storage volume in appreciable amount, but would probably play counter acting role in terms of maintaining storage volume without sharp decline (Fig. 7).

To see the implication of climate change on water demand coverage or unmet demand (i.e. if not only climate variability but also its mean state will change) the existing Very dry (0.1), Dry (0.5), Normal (1), Wet (2) and Very wet (3) water year definitions were multiplied by the indicated factors. Nearly double unmet demand and coverage is simulated than climate variability scenario, 16% decrease in water demand coverage and about 8 Mm^3 monthly unmet demand were registered, with seasonal and annual variability within the simulation period up to 2025.

As it was mentioned above, the variation in unmet demand or coverage is manifestation of climate change impact on surface water and groundwater storage volume. Up to 4 Mm^3 and 38 Mm^3 decrease in monthly storage is simulated due to future climate change on groundwater and surface water reservoir storage volume, respectively (Fig. 9). Here again, even the natural hydrologic variation simulated using water year method would highly impact surface water reservoirs storage (Fig. 10).

Best Case Scenario

According to the "WHO Vision 2030 Technology Projection Study", not many systematic assessments have been made regarding the potential impact of climate change on water resources (WHO and DIFID 2010). Based on Praskievicz and Chang (2009), there is a need for more studies that examine the combined effects of climate change and development schemes, because such types of changes are likely to occur simultaneously in many basins, but their interactive effects are still not well understood.

This scenario evaluates what positive impact will be gained if conditions reducing water supply are avoided, or at least reasonably minimized and conditions improving water supply come in effect. The assumptions include: the existing climate

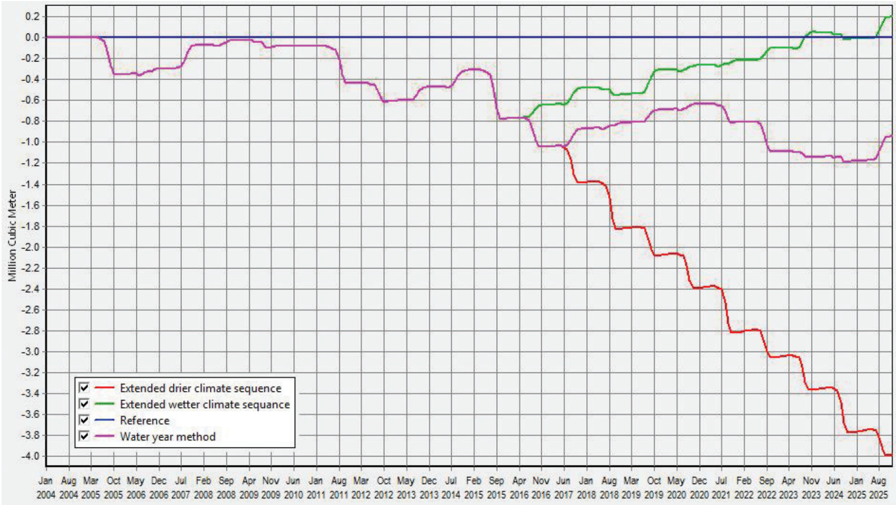

Fig. 9 - Likely impact of climate change on groundwater storage volume.

Fig. 9 - Impatto dei cambiamenti climatici previsto sul volume d'acqua immagazzinato nelle falde acquifere.

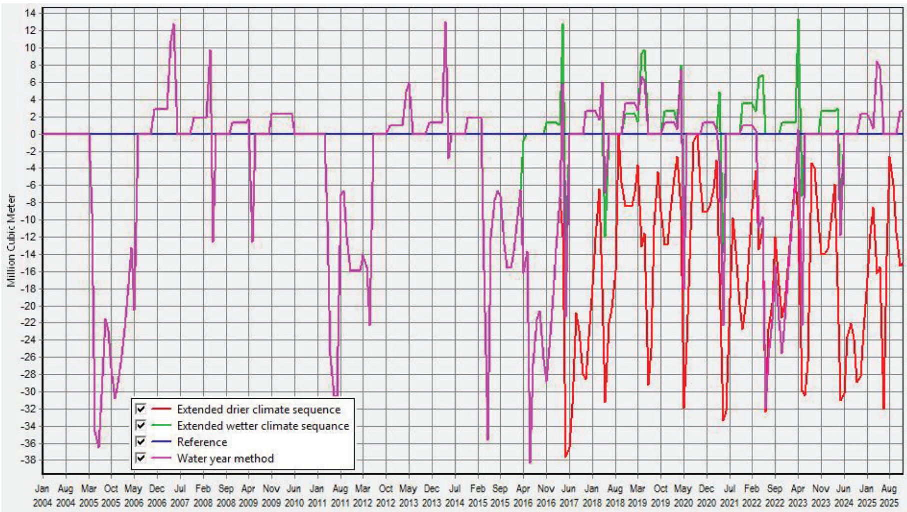

Fig. 10 - Likely impact of climate change on surface water reservoirs storage volume.

Fig. 10 - Impatto dei cambiamenti climatici previsto sul volume d'acqua immagazzinato nei bacini superficiali.

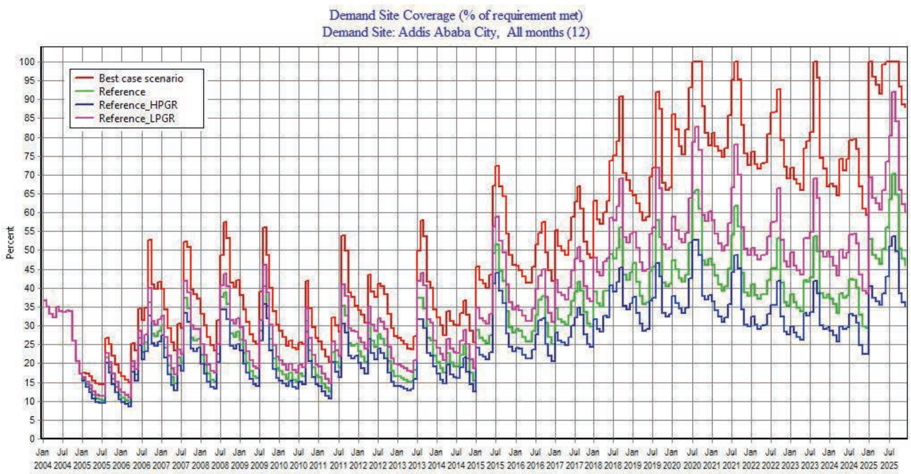

Fig. 11 - Addis Ababa city likely future water demand coverage for the 'best case scenario' projection.

Fig. 11 - Previsione del soddisfacimento dell'idroesigenza futura della città di Addis Abeba relativo allo scenario ottimale.

sequence continues without significant variation, water loss is minimized to 20%, taking the existing attempts into account (AAWSA, 2015), all the ongoing and planned water supply expansions will be completed as per schedule and taking LPGR population trajectory.

Compared with the reference scenario, the best case scenario simulation likely results high improvement with respect to Addis Ababa city demand coverage (Fig. 11). 100% unmet demand can be achieved in almost all wet seasons of the years from 2020 to 2025, with a minimum of 60% coverage registered in dry period of the Year 2024. The highest Addis Ababa city water demand coverage projection was for LPGR trajectory. Because of additional water supply improvement through loss minimization, noticeable improvement compared with water demand projection with LPGR trajectory was observed. The demand coverage for different

DOI: 10.7343/as-2018-334

scenarios in increasing order is: demand coverage for HPGR, demand coverage for MPGR, demand coverage for LPGR and demand coverage for best case scenario.

Worst Case Scenario

In contrary to the 'best case' scenario, this scenario examines what negative impact would be endured if all conditions reducing water supply are prominent and if all situations improving water supply are only partially applied. Some of the assumptions are being felt already and the other are most likely to happen in the future. The assumptions include: extended drier climate sequence, the maximum water loss reported (40%), only 50% of planned surface and groundwater supply expansions (2020-2025) implemented as per schedule and HPGR trajectory.

The conditions will possibly put huge pressure on water demand coverage in the future (Fig. 12). As it may be expected, the combination effect will be much more severe than the individual stress condition. With high seasonal and annual variability, not more than about 35% water demand coverage would be possible for Addis Ababa city.

Conclusions

This study has both practical and scientific importance. Commonly, surface water and groundwater systems are modeled independently and linked through lumped parameter. One parameter output from the surface water mode is used as input for the groundwater model, or vice versa. Besides, most models simulate only supply side (exploiting more) of a system ignoring or giving less emphasis to the demand side (managing the resource). In the current study, both issues were addressed. WEAP model, which is unique in its capability of representing the effects of demand management for ecosystem preservation on surface water and groundwater systems were dynamically linked with MODFLOW. Such modeling approach will support analysis of water allocation and problems involving complicated hydrological, environmental and socioeconomic constraints and conflicting management objectives by adding one perspective to fresh water management challenges. It also allow policymakers and managers to gain insight into the potential consequences of continuously changing conditions and work toward ensuring sustainable development without perturbing the natural environment.

The dynamically integrated model tested on Addis Ababa city water supply has indicted, Addis Ababa city surface water and groundwater supply sources are being stressed and even more likely be highly stressed in the future due to population pressure and continuous groundwater supply abstraction schemes. Likely climate change and variability scenarios will possibly make the city water demand-supply condition unexpectedly worse.

Hence, storage capacity of the existing surface water reservoirs should be improved and new schemes should be immediately developed to benefit from wetter climate and recover from drier climate conditions. Continuous abstraction of groundwater from Upper Awash basin, where the city is located, seems not a viable solution. With the necessary political decision due to the mismatch between Awash basin and administrative boundaries, more vigorous planning and development of water supply alternatives outside of Upper Awash is also recommended. Minimizing the significant water loss, improving water use efficiency and waste water recycling should also be given at most priority. Otherwise, Addis Ababa city water supply sources will potentially be irreversibly impacted.

Acknowledgment: The authors thank Addis Ababa Science and Technology University and Addis Ababa University for the opportunity given to pursue this study. The Swedish Government Development Program (SIDA) is acknowledged for funding part of this work. The authors thank the University of Milan, students and staffs for their support (Gabriele Moioli, Jacopo Terrenghi and Stefania Stevenazzi). The authors would also like to take this opportunity to thank drilling companies, government water works design and supervision enterprises, Ministry of Water, Irrigation and Electricity and National Meteorological Agency for providing relevant data.

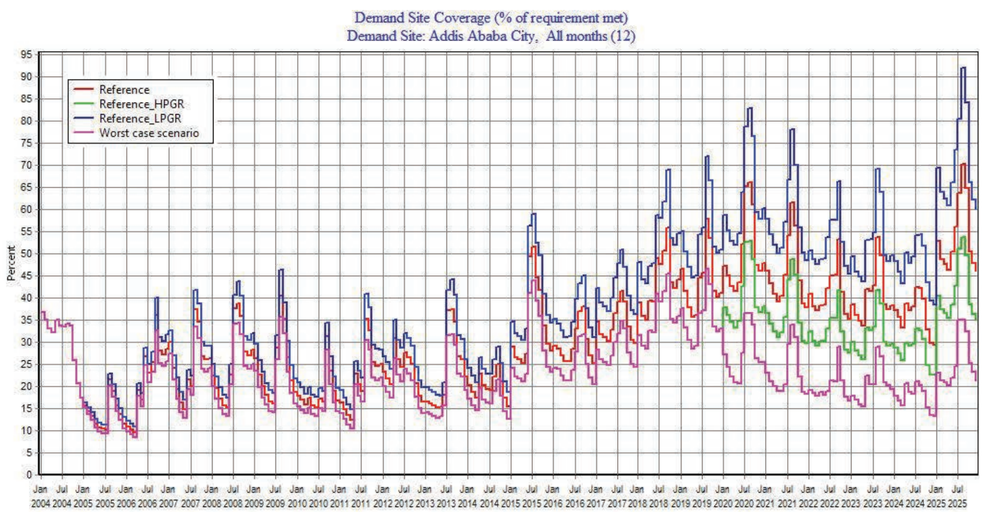

Fig. 12 - Addis Ababa city likely future water demand coverage for the 'worst case scenario' projection.

Fig. 12 - Previsione del soddisfacimento dell'idroesigenza futura della città di Addis Abeba relativo allo scenario peggiore.

REFERENCES

Alemayehu T, Legesse D, Ayenew T, Mohammed N, & Waltenigus S (2006) Degree of groundwater vulnerability to pollution in Addis Ababa, Ethiopia. Groundwater pollution in Africa. Taylor & Francis, London, 203-211.

Ayenew T, & Tilahun N (2008) Assessment of lake–groundwater interactions and anthropogenic stresses, using numerical groundwater flow model, for a Rift lake catchment in central Ethiopia. Lakes & Reservoirs: Research & Management, 13(4), 325-343.

Ayenew T, Demlie M, & Wohnlich S (2008) Hydrogeological framework and occurrence of groundwater in the Ethiopian aquifers. Journal of African Earth Sciences, 52(3), 97-113.

Azagegn T (2014). Groundwater Dynamics in the Left Bank Catchments of the Middle Blue Nile and the Upper Awash River Basins, Central Ethiopia (Doctoral dissertation, Addis Ababa University Addis Ababa, Ethiopia).

Azagegn T, Asrat A, Ayenew T, & Kebede S (2015) Litho-structural control on inter basin groundwater transfer in central Ethiopia. Journal of African Earth Sciences, 101, 383-395.

Bates B, Kundzewicz Z, & Wu S (2008). Climate change and water. Intergovernmental Panel on Climate Change Secretariat.

Chernet T, Travi Y, & Valles V (2001) Mechanism of degradation of the quality of natural water in the lakes region of the Ethiopian rift valley. Water Research, 35(12), 2819-2832.

Christensen J. H, Hewitson B, Busuioc A, Chen A, Gao X, Held I, & Rueda V M (2007) Regional Climate projections {Book Section} Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change book edts Solomon S., D, M.

Cohen B (2006) Urbanization in developing countries: Current trends, future projections, and key challenges for sustainability. Technology in society, 28(1-2), 63-80.

Desalegn W B (2005, March) Water Supply Coverage and Water Loss in Distribution Systems: The Case of Addis Ababa. ITC.

Evans B, & Webster M (2008) Adapting to climate change in Europe and Central Asia: background paper on water supply and sanitation. World Bank ECCSD.

Faurės JM, M Svendsen and H Turral (2007) Reinventing irrigation. In D. Molden (ed) Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture. London: Earthscan, and Colombo: International Water Management Institute.

Few R, Ahern M, Matthies F, & Kovats S (2004) Floods, health and climate change: a strategic review.

Fletcher T D, Andrieu H, & Hamel P (2013) Understanding, management and modelling of urban hydrology and its consequences for receiving waters: A state of the art. Advances in water resources, 51, 261-279.

Harbaugh, A. W., Banta, E. R., Hill, M. C., & McDonald, M. G. (2000). MODFLOW-2000, The U. S. Geological Survey Modular Ground-Water Model-User Guide to Modularization Concepts and the Ground-Water Flow Process. Open-file Report. U. S. Geological Survey, (92), 134.

Hedger M, & Cacouris J (2008) Separate Streams: Adapting Water Resources Management to Climate Change. Tearfund.

Hellström D, Jeppsson U, & Kärrman E (2000) A framework for systems analysis of sustainable urban water management. Environmental impact assessment review, 20(3), 311-321.

Howe C, & Mitchell C (Eds.) (2011) Water sensitive cities. IWA Publishing. Hydrogeochemistry. Journal of Hydrology, 63(1-2), pp.131-176.

Kebede S, Travi Y, Alemayehu T, & Ayenew T (2005) Groundwater recharge, circulation and geochemical evolution in the source region of the Blue Nile River, Ethiopia. Applied Geochemistry, 20(9), 1658-1676.

Kebede S, Travi Y, Asrat A, Alemayehu T, Ayenew T, & Tessema Z (2008) Groundwater origin and flow along selected transects in Ethiopian rift volcanic aquifers. Hydrogeology Journal, 16(1), 55.

Kundzewicz Z W, Mata L J, Arnell N W, Doll P, Kabat P, Jimenez B, ... & Shiklomanov I (2007) Freshwater resources and their management.

Loiskandl W (2006) Hydrogeology and water utilization in Ethiopia. Beiträge zur Angewandten Geologie–Festband Jean F Schneider. Wien: Schriftenreihe des Departments für Bautechnik und Naturgefahren, 11, 99-110.

Mackay R, & Last E (2010) SWITCH city water balance: a scoping model for integrated urban water management. Reviews in Environmental Science and Bio/Technology, 9(4), 291-296.

Markus H (2013) LikKitchen user manual. The German Federal Institute for Geosciences and Natural Resources (BGR).

Masetti, M., Sterlacchini, S., Ballabio, C., Sorichetta, A., & Poli, S. (2009). Influence of threshold value in the use of statistical methods for groundwater vulnerability assessment. Science of the total environment, 407(12), 3836-3846.

MCIWEM C, Celeste Morgan B A, & BE L (2013) Water-sensitive urban design: opportunities for the UK. Proceedings of the Institution of Civil Engineers, 166(2), 65.

Molle F (2003) Development trajectories of river basins: A conceptual framework (Vol. 72). IWMI.

Nugussa N (2003) GIS Based Groundwater potential and Aquifer Vulnerability Assessment in Akaki River Catchment, Central Ethiopia. Unpublished MSc. Thesis, Addis Ababa University, Addis Ababa.

Oljira E (2006) Numerical groundwater flow simulation of Akaki River catchment. Unpublished MSc. thesis, Addis Ababa University, Addis Ababa, Ethiopia.

Praskievicz S, & Chang H (2009) A review of hydrological modelling of basin-scale climate change and urban development impacts. Progress in Physical Geography, 33(5), 650-671.

Sadoff C (2008) Managing water resources to maximize sustainable growth: a World Bank water resources assistance strategy for Ethiopia (No. 11758). The World Bank.

Sadoff C, & Muller M (2009) Water management, water security and climate change adaptation: early impacts and essential responses. Stockholm: Global Water Partnership.

Sidharno W, Masduqi A, & Lasminto U (2013) Impact of Future Climate Change on water availability in Kupang City. Proceeding ISEE.

Tesfaye A (2009) Steady State Groundwater Flow and Contaminant Transport Modeling of Akaki Well Field and Its Surrounding Catchment (Addis Ababa, Ethiopia). Unpublished MSc Thesis, Addis Ababa University, Addis Ababa.

Tsehayu K, Waltanigus S, Lulu S, and G/Hiwot A (2005) Groundwater management using groundwater modeling: Case study on Akaki well field; Addis Ababa City, Ethiopia.

Van der Steen P, and Howe C (2009) Managing water in the city of the future; strategic planning and science. Reviews in Environmental Science and Biotechnology, 8(2), pp.115-120.

Van Rooijen D (2009, June) Urbanization, water demand and sanitation in large cities of the developing world: an introduction to studies carried out in Accra, Addis Ababa and Hyderabad. In 8th World Wide Workshop for Young Environmental Scientists WWW-YES 2009: Urban waters: resource or risks? (No. 10).

Yitbarek A (2009) Hydrogeological and hydrochemical framework of complex volcanic system in the Upper Awash River basin, Central Ethiopia: with special emphasis on inter-basins groundwater transfer between Blue Nile and Awash rivers (Doctoral dissertation, Poitiers).

Yitbarek A, Razack M, Ayenew T, Zemedagegnehu E, & Azagegn T (2012) Hydrogeological and hydrochemical framework of Upper Awash River basin, Ethiopia: with special emphasis on inter-basins groundwater transfer between Blue Nile and Awash Rivers. Journal of African Earth Sciences, 65, 46-60.